DISSERTATION

SOLVING PROBLEMS: A STATISTICAL COMPARISON OF THREE ROOT CAUSE ANALYSIS TOOLS

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY ANTHONY MARK DOGGETT ENTITLED *SOLVING PROBLEMS: A STATISTICAL COMPARISON OF THREE ROOT CAUSE ANALYSIS TOOLS* BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

The purpose of this quasi-experimental study was to compare the perceived differences between the cause-and-effect diagram (CED), the interrelationship diagram (ID), and the current reality tree (CRT) with regard to causality, factor relationships, usability, and participation. The independent variables were the CED, the ID, and CRT, which are graphical display tools designed for root cause analysis. The specific dependent variables were the perceived ability of each tool to identify causality and relationships between factors. In addition, the researcher was interested in the perceived usability of the tools and the perceived degree of participation.

Using a within-subjects repeated measures design with counterbalancing, participants attempted to solve an organizational problem introduced via a scenario. Participants responded about their experience with each of the tools with regard to the dependent variables using a self-report instrument. Findings of the research indicated that participants could significantly distinguish differences between the tools with respect to usability, but could not perceive differences on causality, factor relationships, or participation. Other interesting findings included differences in process times, the types of questions asked, process observations, and generated tool outputs.

The conclusions drawn from the experiment were that participants' perceptions of usability were driven primarily by the ease or difficulty of the tool use. The CED was perceived easiest to use while the CRT was the most difficult. The ID also emerged as an easy alternative for root cause analysis, but was not perceived differently in other aspects of usability. Another interesting result was that the quality of outputs varied greatly between the tools. Groups using the CED and ID were able to construct the tools with accuracy most of the time, but had difficulty finding specific and reasonable root causes.

In comparison, the groups using the CRT were able to find specific and reasonable root causes over half the time regardless of construction accuracy.

The implications for policy indicate that training, facilitation, and opportunities for group practice are important for all three tools. Varying degrees of training and expertise are required depending on the tool used, the complexity of the problem, and other group factors.

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CHAPTER 1: INTRODUCTION

Creating profound change in organizations requires investment of time, energy, and resources. Most organization professionals would agree that this investment should focus only on areas that will result in the most benefit (DeJarnett, 1993; Jones, 1999). Typically, this means establishing some type of activity to address the fundamental problems that prevent the organization from achieving the objectives necessary for continued existence or profitability. Such change efforts do not approach these issues as a finite problem, but as difficulties symptomatic of deeper structural concerns requiring focused activity. Senge, Kleiner, Roberts, Ross, Roth, and Smith (1999) suggested that the real problem in creating change is not the obvious need to fix something, but the forces that keep people from fixing the problem in the first place. The success of fundamental change depends on the ability of organizational participants to rethink and clearly articulate their basic assumptions, purposes, and processes. Goldratt (1990) postulated that people are unable to solve problems because they have no method of verbalizing their intuition. Both Senge et al. (1999) and Goldratt (1990) agreed that lasting organizational change results from a clear goal; a strategy for achieving the goal; and the use of theories, methods, and tools to guide knowledge towards practices that support the goal.

According to Anderson and Fagerhaug (2000), a problem is a state of affairs, difficulty, or undesirable status that presents a challenge for establishing circumstances that are more desirable. A problem can be of any type or form: personal, work related, organizational, or private. To solve a problem, one must first recognize and understand what the problem is. Goldratt (1990) described this as, “What to change?” To answer this question, one must identify the primary problem that, if solved, would generate the most benefit.

There are many problem solving models described in the literature. The scientific method of problem solving is generally attributed to Galileo, Bacon, and Newton. It is so embedded in the structure of modern thinking that it is the basis for most organizational and post-secondary research in Western society today (Kuhn, 1977). Current problem solving approaches are generally variants of the scientific method and are plentiful (Anderson & Fagerhaug, 2000; Arcaro, 1997; Brightman, 1988; Deming, 1986; Kepner & Iikubo, 1996; Latino & Latino, 1999; Shewhart, 1986/1939; Sproull, 2001; Webne-Behrman, 1998; Wilson, Dell, & Anderson, 1993). This dissertation is an example of an exhaustive exercise in the application the scientific method.

Many analytical problem solving tools are found in literature. They are also well documented and range from data collection tools and flowcharts to intuitive brainstorming techniques and decision matrices (Anderson & Fagerhaug, 2000; Arcaro, 1997; Brown, 1994; Brassard & Ritter, 1994; Brassard, 1996; Sproull, 2001; Mabin & Balderstone, 2000; Moran, Talbot, & Benson, 1990, Wilson et al., 1993). All these methods and techniques are designed to help the practitioner understand the nature and characteristics of a problem. When used separately, they represent a fraction of the total problem solving process and some only verify what was already intuitively known--that there is a real problem here.

Problem Analysis Tools

Tools that assist groups and individuals in identifying the root causes of problems are known as root cause analysis tools. As such, they are designed to find the core cause of a problem and provide the necessary information to produce a permanent solution to the problem. Root cause analysis tools are a significant part of the problem solving process because they attempt to answer the question, "What to change?" While there are many ways to solve problems, the identification of a problem's root cause is preferred because root causes are generally the source of the problem.

Another important characteristic of problem solving is the ability to identify the structure of the problem through the interdependencies between potential causes. Causal interdependency has origins in systems thinking philosophy, which asserts that systems are a collection of interrelated components working towards the pursuit of a common goal. Systems thinkers consider organizational systems in context because they believe that a system interacts with both the external and internal environment. The literature distinguishes causal interdependency from factor interrelatedness such that factor interrelationships represent the interconnectedness between system components while causal interdependency represents the dependent linkages between specific causes that produce effects. This distinction is important because factor interrelationships typically include intermediate factors that connect core causes with effects or to each other, whereas interdependent causes are typically linked only to each other (Dettmer, 1997; Gharajedaghi, 1999, Hitchins, 2002; Lepore & Cohen, 1999; Pasquarella, Mitchell, & Suerken, 1997; Senge, Roberts, Ross, Smith, & Kleiner, 1994). Thus, the causal factors of a system can be viewed as both interrelated and interdependent in terms of overall outcomes. Systems thinkers perceive the effects of a system as being influenced by multiple and related causes. This means that any problem is likely to have been caused by interdependent causes that need identification so all subsequent undesirable effects can be resolved. The reader is encouraged to study Figure 4 in Chapter 2 for a graphic example of causal interdependency versus interrelated independent factors.

Statement of the Problem

Three root cause analysis tools have emerged from the literature as generic standards for identifying the root cause of problems. They are the cause-and-effect diagram (CED), the interrelationship diagram (ID), and the current reality tree (CRT). There is no shortage of information available about each of these tools. The literature provides detailed descriptions, recommendations, and instructions for their construction and use. The literature documents processes and structured variations for each tool. Furthermore, the literature is quite detailed in providing colorful and illustrative examples for each of the tools so practitioners can quickly learn and apply them. In summary, the literature confirms that these three tools do, in fact, have the capacity to find root causes with varying degrees of accuracy, efficiency, and quality (Anderson & Fagerhaug, 2000; Arcaro, 1997; Brown, 1994; Brassard, 1996; Brassard & Ritter, 1994; Cox & Spencer, 1998; Dettmer; 1997; Goldratt, 1990, 1994; Ishikawa, 1982; Lepore & Cohen, 1999; Mizuno, 1979/1988; Moran et al., 1990; Robson, 1993; Scheinkopf, 1999; Smith, 2000; Sproull, 2001;Wilson et al., 1993).

For example, Ishikawa (1982), Anderson and Fagerhaug (2000), and Sproull (2001), advocated the CED as a tool for breaking down potential causes into more detailed categories so they can be organized and related into factors that help identify the root cause. In contrast, Mizuno (1979/1988), and Brassard (1996) supported the ID as a tool to quantify the relationships between factors and thereby classify potential causal issues or drivers. Finally, Goldratt (1990), Dettmer (1997), and Scheinkopf (1999) championed the CRT as a tool to find logical interdependent chains of relationships between undesirable effects leading to the identification of the core problem or common cause. Chapter 2 presents the review of this literature in greater detail.

With the quantity of literature available about these root cause tools, one might wonder why there are still so many unsolved problems. Pasquarella et al. (1997) claimed that individuals and organizations will choose simple methods when confronted with too many choices. Multiple methods and tools create the perception of complexity. Thus, most people tend to use a simple analysis tool that does the job. Unfortunately, simple analysis relies primarily on intuitive methods and is often influenced by emotions or organizational politics. On the other hand, if a tool is too complex, it tends to fail because it often requires a level of expertise not available. In addition, many analysis tools are not effective in solving larger systemic problems unless they are used with other tools in a rigorous fashion. Consequently, the tendency is for organizations to use simplistic tools that do not adequately identify root causes or solve systemic problems.

A fundamental problem of problem solving is that individuals and organizations have little information to compare the tools to each other. The impression is that one tool is as good as another tool. Such is the situation regarding the CED, ID, and CRT. Most organizations and individuals do not understand the similarities or differences between them. While the literature is quite complete on each tool as a stand-alone application and their relationship with other problem solving tools, the literature is deficient on how these three tools directly compare to each other. In fact, there are only two studies that compare them and the comparisons are qualitative. Fredendall, Patterson, Lenhartz, and Mitchell (2002) compared the CED and the CRT using previously published examples of their separate effectiveness while Pasquarella, et al. (1997) compared all three tools using a one-group post-test design with qualitative responses. There is little published research that quantitatively measures and compares the CED, ID, and CRT.

The purpose of this quasi-experimental study was to compare the perceived differences between the cause-and-effect diagram (CED), the interrelationship diagram (ID), and the current reality tree (CRT) with regard to causality, factor relationships, usability, and participation. The independent variables were the CED, the ID, and CRT, which are graphical display tools designed for problem solving. The specific causality measures were the perceived ability of each tool to identify root causes and causal interdependency. A root cause is the core issue or problem that causes an undesirable effect. Causal interdependency is the dependent relationship between causes with respect to the undesirable effect. In addition, the researcher was interested in the perceived ability of the tools to identify factor relationships, and participant's perceptions of tool usability and group participation.

Using a within-subjects repeated measures design, the study counterbalanced the independent variables among subgroups of participants who attempted to solve a fictitious organizational problem presented in a written scenario. The tools were statistically measured in regard to how well they satisfied the dependent variables at the completion of each subgroup analysis using a self-report instrument.

Hypothesis

Root cause and causal interdependency can be combined into a single dependent variable construct called causality. Thus, causality is the perceived ability of the tool to find root causes and the interdependencies between causes. A second construct is the perceived ability of the tool to find relationships between factors or categories of factors. These factors may include causes, effects, or both. A third construct is the overall perception of the tool's usability to accomplish the above and produce outputs that are logical, productive, and readable. The fourth construct is the perception of participation among group members that results in constructive discussion and dialogue about the problem. Therefore, the primary interests of the study stated in the null (H_0) were as follows:

1. There is no difference in the perceived ability of the cause-and-effect diagram, interrelationship diagram, and current reality tree to identify causality.

2. There is no difference in the perceived ability of the cause-and-effect diagram, interrelationship diagram, and current reality tree to identify factor relationships.
3. There is no difference between the cause-and-effect diagram, interrelationship diagram, and current reality tree with regard to perceived usability.
4. There is no difference between the cause-and-effect diagram, interrelationship diagram, and current reality tree with regard to perceived participation.

The secondary interests of the study were to determine the average process time required to construct each tool, the types of questions or statements raised by participants during and after the process, and the nature of the tool outputs generated.

Definition of Terms

Definitions of infrequently and special terms used in this study are found in the glossary located in Appendix A. For operational purposes, the following definitions apply:

Causal interdependency: The interaction of causal factors with each other to form interrelationships and connections resulting in either positive or negative effects (Gharajedaghi, 1999).

Cause: A reason for an action or condition. Something that brings about an effect or a result (*Webster's New Collegiate Dictionary*, 1983, p. 217).

Cause-and-effect diagram (CED): A tool for analyzing process dispersion. It is also referred to as an Ishikawa diagram (named after its developer, Karou Ishikawa) or fishbone diagram (the complete diagram resembles a fish skeleton). The diagram illustrates the main causes and sub-causes leading to an effect (symptom). The cause-and-effect diagram is one of the seven quality control (7QC) tools (Cox, Blackstone, & Spencer, 1995).

Current reality tree (CRT): A logic-based tool for using cause-and-effect relationships to determine root problems that cause the observed undesirable effects of the system (Cox et al., 1995, p. 19). The current reality tree is one of the five thinking processes (TP) used in the Theory of Constraints (TOC).

Effect: Something that inevitably follows an antecedent such as a cause or agent (*Webster's New Collegiate Dictionary*, 1983, p. 397).

Interrelationship diagram (ID): A technique used to define how factors relate to one another. Complex multi-variable problems or desired outcomes can be displayed with their interrelated factors. The logical and often causal relationships between the factors can be illustrated (Cox et al., 1995, p. 40). The interrelationship diagram is one of seven management and planning (7MP) tools developed by GOAL/QPC.

Root cause: An original cause, through a chain of cause and effect, of an undesirable effect (Dettmer, 1997, p. 360).

Undesirable effect (UDE): A symptom of a deeper, underlying core problem. An effect that, in and of itself, is negative or undesirable, without dependence on any other factor (Dettmer, 1997)

Delimitations

The delimitations of the study were:

1. Methods and tools were limited to the CED, ID, and CRT. While there are other specialized methods used in disciplines such as reliability engineering or risk management, the CED, ID, and CRT have general recognition as generic root cause analysis tools.

2. Participants in the study were limited to small groups that represent an authentic application of how the tools would be used in organizations under similar conditions. The purposive nature of the sampling may have decreased the generalizability of the findings.

Assumptions and Limitations

The assumptions and limitations of the study were grounded in the requirements for statistical analysis using the General Linear Model, but also include factors that were beyond the researcher's control. While the researcher attempted to control obvious extraneous variables during the study, participant and organizational cultural attributes, politics, and social climate remained outside the scope and control of the analysis. The additional assumptions and limitations of the study were as follows:

1. Root cause analyses techniques are useful in finding the root causes of problems.
2. The identification of a root cause will lead to a better solution than the identification of a symptom.
3. While it is important to identify root causes, it is also important to identify causal interdependencies that interact with each other.
4. Expertise, aptitude, and prior knowledge about the tools, or lack thereof, was assumed to be randomly distributed within the groups and did not affect the overall perceptions or result of this study.
5. The experimental results reflect the efficacy of the tools in the given context.
6. The tools can be used to solve any type of problem such personal, political, social, or organizational problems. As such, the sample problem scenarios in the study can be considered as having equal complexity.

Significance of the Study

Despite the availability of a wide range of problem solving tools, individuals continue to struggle with problems. Scientists attempt to address recurring economic, social, political, and organizational problems through the expansion of knowledge and theory. Goldratt (1990) hypothesized that every science goes through three phases of development: classification, correlation, and effect-cause-effect. In the classification phase, a phenomenon is logically categorized resulting in a systematic identification. Examples include the location of stars or the phylum names of various plants and animals. In correlation phase, scientists determine *how* the phenomenon works through observations and rough calculations. Early astronomers used correlation to suggest elliptical solar orbits and modern physicists use it to estimate the location of an electron around the atom. When asked about his innovation, the Toyota *kanban* system, Dr. Taiichi Ohno replied, "My system does not make sense at all, but by God it's working" (Goldratt, 1990, p.28). The third phase of effect-cause-effect is characterized by the *why* question. Newton's methods created the science of astronomy and changed forever the way people view the stars. Effect-cause-effect advances logical explanations, predicts future events, and forecasts consequences. Theories and thinking based on effect-cause-effect become recognized science (Goldratt, 1990) and move the field of inquiry from "art" to that of disciplined examination.

In problem solving, the root cause of the problem produces an undesirable effect. Any pursuit that does not seek the root cause leads only to the symptom of the problem and, by definition, solving a symptom will not solve a problem. Problem solvers identify root causes of problems to be able to predict future cause and effect relationships. The tools that problem solvers use to identify root causes were the focus of this study.

The intent of this study was to advance the state of knowledge in the area of root cause analysis to that of a true science. The purposeful application of a root cause analysis tool can address complex problems using scientific methods rather than emotion or intuition. This study compared the tools so that future practice might consider using the tool that best identifies causality and factor relationships. This study can also serve as a starting point for organizational policy such that important decisions will be formulated using rigorous processes rather than educated guesses.

Researcher's Perspective

As a practitioner of Total Quality Management (TQM) principles and tools in the 1990s, the researcher observed promising results of problem solving efforts when applied by empowered, motivated teams. Unfortunately, many of these efforts did not result in sustained improvement over time. Many of the fine individuals the researcher worked with on projects during that time became disenfranchised with TQM although they believed it could make a significant difference.

A held belief of the researcher is that TQM fell into disrepute because of a lack understanding about what continuous improvement means. Individuals tend to repeat mistakes if they do not learn from them and learning implies a change of thinking. Very few structured methods exist to change thinking, except perhaps that one teacher, or a catastrophic, and/or life-changing event. Yet, structure is needed to help people change their thinking and test deeply held assumptions. Practitioners need a way to understand and appreciate multiple perspectives. Without a method to focus effort, people continue to view thinking differences as "you against me" rather than "us against the problem."

Systematic analysis helps professionals make decisions based on logic rather than emotion. The principles of personal growth and development should supercede the personalities. It is held that structured analysis tools level the playing field so that all ideas can be heard, clarified, and potentially implemented. This challenges the supposition that the ability to solve complex problems rests only with a few talented

CEOs or college presidents. Ordinary people become capable of solving difficult problems when armed with sound methods. Nonetheless, the cynic may sneer at the idea that the world's problems can be solved with a few structured methods. The point is that without pertinent information, one rarely makes good decisions while most thoughtful individuals can make a decision when there is unlimited information. The general case is found somewhere between the two extremes. Regardless, any method that helps make better decisions possible is the intelligent choice. The question remains, which method is the best choice?

CHAPTER 2: LITERATURE REVIEW

The first part of this review describes the general problem solving models found in literature, defines the discipline of root cause analysis, and discusses the advantages of graphic language displays for problem solving. The second part of the review characterizes the independent and dependent variables as described by various authors. The third part reports and summarizes studies that compare the analysis tools with respect to the dependent variables and identifies the literature deficiencies.

Problem Solving Models, Root Cause Analysis, and Graphics Language

Problem Solving Models

The scientific method is the generally accepted framework for solving problems in Western culture. No discussion of problem solving models would be complete without mentioning it. The scientific method has no particular inventor; it seems to have evolved over time based on the work of fifteenth-century scholars. It is, however, the basis for most problem solving approaches used today. The basic scientific method is as follows:

1. Define the problem
2. Formulate a hypothesis
3. Gather appropriate data
4. Test the hypothesis
5. Develop conclusions (Wilson et al., 1993, p. 74)

Another problem solving model, PDCA (Plan, Do, Check, Act), was developed by W. Edwards Deming (1986) who derived it from Shewhart (1986/1939). It is a four-step process for continuous problem solving. The four stages of PDCA represent: (1) the analysis and planning of problem solving, (2) the actions taken to resolve the problem, (3) the evaluation of the results, and (4) the modification of activities that either confirm or disconfirm the desired results. In the *plan* step, a strategy for improvement is developed. In the *do* step, the plan is carried out, preferably on a small scale. During the *check* step, the effects of the plan are observed and in the *act* step, the results are studied to determine what was learned and what can be predicted. PDCA is sometimes referred to as the Deming Cycle because he introduced the concept to the Japanese who subsequently named it after him (Cox, et al., 1995). The PDCA model represents a stripped-down version of the scientific method. Unfortunately, its simplicity misleads many problem solvers in that it leaves open the method of accomplishment.

Anderson and Fagerhaug's (2000) problem solving model consists of problem identification, problem definition, problem understanding, root cause identification, root cause elimination, and symptom monitoring. This particular model represents a comprehensive and time-consuming approach to problem solving. As such, detailed models like this should be used only when the problem to be solved is worth the effort to solve them. In other words, they should not be used for easy problems (Brown, 1994).

Latino and Latino (1999) suggested a problem solving model using the acronym PROACT, which stands for: PReserve event data; Order the analysis team; Analyze the data; Communicate findings and recommendations; and Track for results. Arcaro (1997) offered a six-step problem solving model: (1) identify and select the problem, (2) analyze the problem, (3) generate potential solutions, (4) select and plan the solution, (5) implement the solution, and (6) evaluate the solution implementation. Wilson et al. (1993) selected an approach based on the scientific method that includes the following elements: set up appropriate reporting systems; define the criteria for problem selection; select candidates for analysis; select analysis techniques to be used; develop solutions; and test solutions. Finally, Sproull (2001) used ten steps to describe the process: (1)

identify the problem, (2) describe and define the problem, (3) list the symptoms, (4) list the known changes (that occurred prior to the problem), (5) analyze the problem, (6) hypothesize possible causes, (7) test possible causes, (8) take action on the causes, (9) test and implement the solution, and (10) implement the appropriate controls.

While these methods share some common themes, their greatest similarity is that they all represent structured approaches to problem solving. While unstructured approaches such as intuition, networking, and prior experience may be valid for solving problems, they are also more subjective and less repeatable. Problem solving that is not repeatable has a higher potential for failure because practitioners will likely repeat the same mistakes to gain the intuition and experience necessary to solve them again. Likewise, unstructured approaches generally result in outcomes that address symptoms only. Consequently, why should people spend the time and effort to solve the same problems continually? Good problem solving techniques will generally uncover the real reason behind the effect. Otherwise, "If you don't want to hear the answer, simply don't ask the question" (Wilson et al., 1993, p. 72).

Root Cause Analysis

According to Anderson and Fagerhaug (2000), "Root cause analysis is a structural investigation that aims to identify the true cause of a problem, and the actions necessary to eliminate it" (p. 10). It is the process of identifying causal factors using a structured approach with techniques designed to provide a focus for identifying and resolving problems. Root cause analysis provides objectivity for problem solving, assists in developing solutions, predicts other problems, assembles contributing circumstances, and focuses attention on preventing recurrences. Most often, root cause analysis techniques are utilized as input to the decision-making process. If root cause analysis is used in a reactive mode, it provides objective identification of organizational faults. In the proactive mode, root cause analysis identifies and prevents future mistakes. Wilson et al.

(1993) wrote, “Root cause analysis, properly implemented, will tell you the real reasons for problems” (p. 20).

In a study to develop a methodology for describing how emotional and cognitive processes affect group problem solving effectiveness, Khaimovich (1999) found two stages of root cause analysis. The first stage involved the discovery of possible root causes through brainstorming activity. The second stage involved the verification of the generated possible causes by examining the validity of causal links. Khaimovich found the verification of the causes to be problematic. Groups were content with their original ideas and reluctant to scrutinize the integrity of their models. Thus, root cause methods that provide mechanisms for verification are preferred.

Rigorous root cause analysis may involve asking difficult or embarrassing questions about how an organization is managed (Dew, 1991). A characteristic of root causes analysis is to assume that bad decisions are based on erroneous logic, faulty assumptions, or obsolescent systems. The interest of root cause analysis is not who made the error, but why. Analysis methods that focus only on human error are generally not successful due to dwindling participation for fear of repercussions. If the root cause analysis process is flawed, decision errors will continue (Latino & Latino, 1999).

Graphic Displays

The three root cause analysis tools in this study use graphic displays. When viewing graphics, a person first comprehends the overall structure (patterns, symmetry, trends of dots and lines), then focuses on what is interesting. Regardless, of nationality or culture, most people understand pictures. According to Mizuno (1979/1988), human beings go through three stages of development starting as "contact beings" who exchange information through physical contact, such as the contact between an infant and mother. Contact beings then grow into "picture-beings" who understand information through pictures and drawings and finally become "character beings" who transmit information through written characters and symbols. As such, the human capability to understand graphic communication appears to be developmental. Therefore, tools that incorporate graphics emerge as powerful techniques because most people comprehend them quickly.

In 1977, computer theorist Yoshikawa (as cited in Mizuno, 1979/1988) distinguished pictures with language from pictures that contain only drawings with the designation "graphics language." Within this designation, he identified four types: relational, network, column-row, and coordinate. Of the four types, the coordinate and column-row systems are the oldest and most structured. The other two types, relational and network, are more intuitive and allow greater degrees of freedom during use. Not surprisingly, relational and network system tools have become increasingly popular.

> "As we move toward socio/technical systems, this graphic language may be used as a tool to assist the reader in integrating the social and technical requirements of his or her job. Effective communication of relevant data within and between work teams is essential to ensure successful results. ...a strong graphic is worth more than a thousand words" (Moran et al., 1999, p. vii).

Research by Hauser (1991) found that the number of constructs and density of relationships in a causal network display increases the perceived complexity of a system, but does not necessarily reduce understanding. A construct refers to the variables or nodes depicted in the display while a relationship refers to the connections made between the nodes, usually with arrows. In addition, Hauser discovered that clustering or grouping constructs into meaningful sectors and adding additional pictorial information, such as dotted lines, increased overall understanding of the display. Thus, it appears that causal network displays are appropriate for understanding complex problems.

Hitchins (2002) suggested there are three graphic archetypes for displaying cause and effect relationships. The first simply links the two together with an arrow, as shown in Figure 1A, where effect follows cause. The advantage of this display is that it is uncomplicated. The disadvantage is that relationships between multiple causes are not shown; i.e., there is no observable connection between one cause and another. The second archetype in Figure 1B builds relationships between causes and effects to form linear chains. The advantage of this display is that the logic can be traced while the disadvantage is that it does not show system dynamics. The third archetype in Figure 1C shows cause-and-effect with feedback loops. The advantage of this display is that it can describe non-linear and chaotic systems dynamics. The disadvantage is that it may appear counterintuitive and complicated.

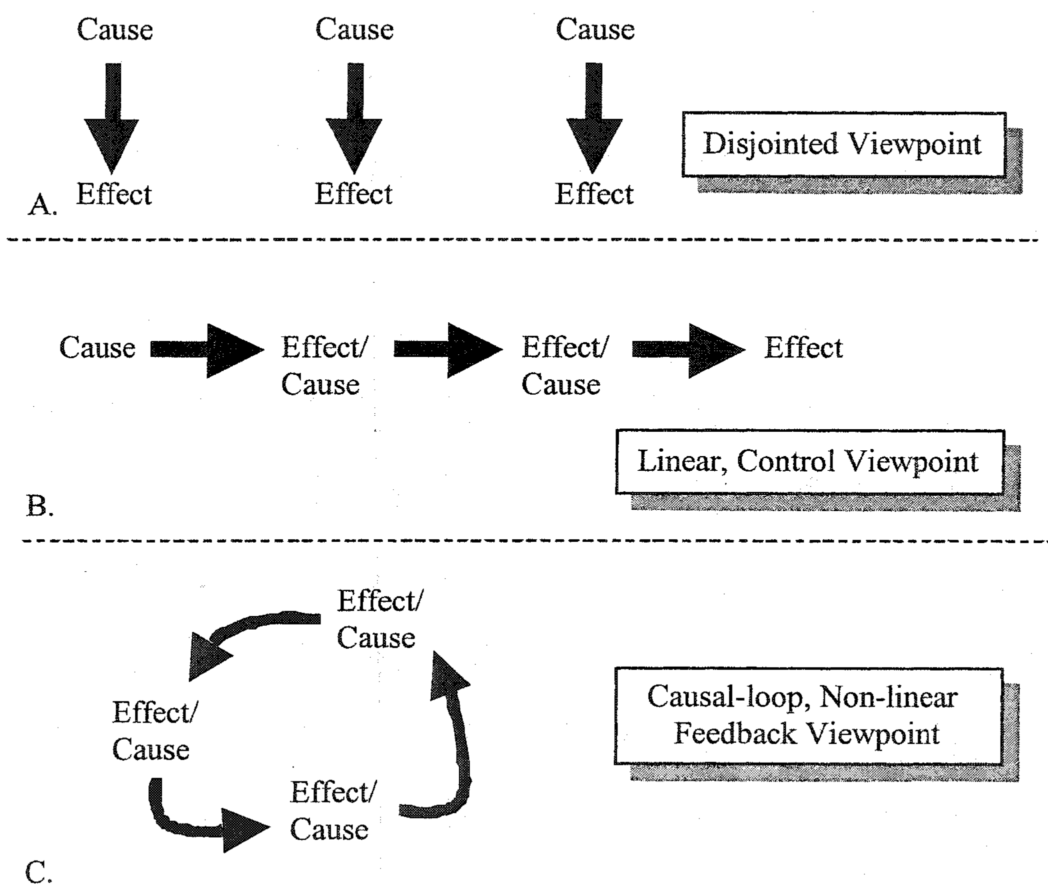

Figure 1. Cause and Effect Linkages

The three tools in this study are all causal network displays that show cause and effect either with or without linearity and feedback. The tool purist may argue the degree of linearity found in each tool. Regardless, the participants in the study determined the importance of linearity and feedback in terms of finding the root cause. The readers are encouraged to draw their own conclusions. The next section of the literature review describes each of the three tools in detail.

Independent and Dependent Variables

Cause-and-Effect Diagram

The cause-and-effect diagram (CED) sorts out the causes of variation in a process and organizes the mutual relationships between them. It was developed by Professor Kaoru Ishikawa of the University of Tokyo in the summer of 1943. He used it to explain how various manufacturing factors could be sorted out and related to a group of engineers at the Kawasaki Steel Works. It later came into widespread use for quality control throughout Japanese industry (Ishikawa, 1982). As its use spread to other countries, it was known by other names such as the Ishikawa diagram, or more informally, the "fishbone" because of its appearance once complete (Arcaro, 1997; Moran et al., 1990; Sproull, 2001).

Brassard and Ritter (1994) asserted that the CED "enables a team to focus on the content of the problem, not on the history of the problem or differing personal interests of team members" (p. 23). Anderson and Fagerhaug (2000) wrote that the CED is "an easily applied tool used to analyze possible causes to a problem" (p. 14) while Wilson et al. (1993) called it a "highly visual technique which aids the process of defining the elements of a problem or event and determining how it probably occurred" (p. 195).

According to Ishikawa (1982), a good CED is one that fits the purpose. Cause-and-effect diagrams are drawn primarily to illustrate the various causes affecting product quality or a particular problem by sorting out and relating the causes, but they can also be used for other tasks such as educating others about a process or problem. The construction and study of a completed diagram stimulates knowledge acquisition and promotes discussion. The CED encourages data collection by highlighting areas of expertise or showing where knowledge is lacking. Fredendall et al. (2002) called the CED process "an exercise in structured brainstorming" (p. 51).

The original intent of the diagram was to solve quality related problems in products caused by statistical variation, but Ishikawa quickly realized it could be used for solving problems of quantity, safety, or personnel. The primary aim was to get results towards the solution of a problem. Thus, the logic of the CED is that one cannot act until the relationship between the cause and effect of a problem is known. Consequently, the CED attempts to show causes so action can be taken.

Ishikawa (1982) outlined the following steps for constructing a CED:

1. Decide on the characteristic to improve or control.
2. Write the characteristic on the right side and draw an arrow from the left to the right side as shown in Figure 2A.
3. Write the main factors that may be causing the characteristic by drawing branch arrows to the main arrow. Major causal factors of variation can be grouped into items such as material, equipment, method, or measurement with each forming a major branch as shown in Figure 2B.
4. For each major branch, write detailed causal factors as twigs on each branch of the diagram. On the twigs, write still more detailed factors to make smaller twigs. For each level of the CED, ask why the variation occurs to show the causes of variation in the characteristic as shown in Figure 2C.
5. Check to make certain all the items that may be causing variation of the characteristic are included in the diagram.

Major cause category branches can be initially identified using the four *Ms*: material, methods, machines, and manpower, or the four *Ps*: parts, procedures, people, and plant. Categories can be tailored depending on the problem (Moran et al., 1990;

Scholtes, 1988; Sproull, 2001). Sometimes measurement or environment is the fifth category. Arcaro (1997) suggested using no more than eight major categories.

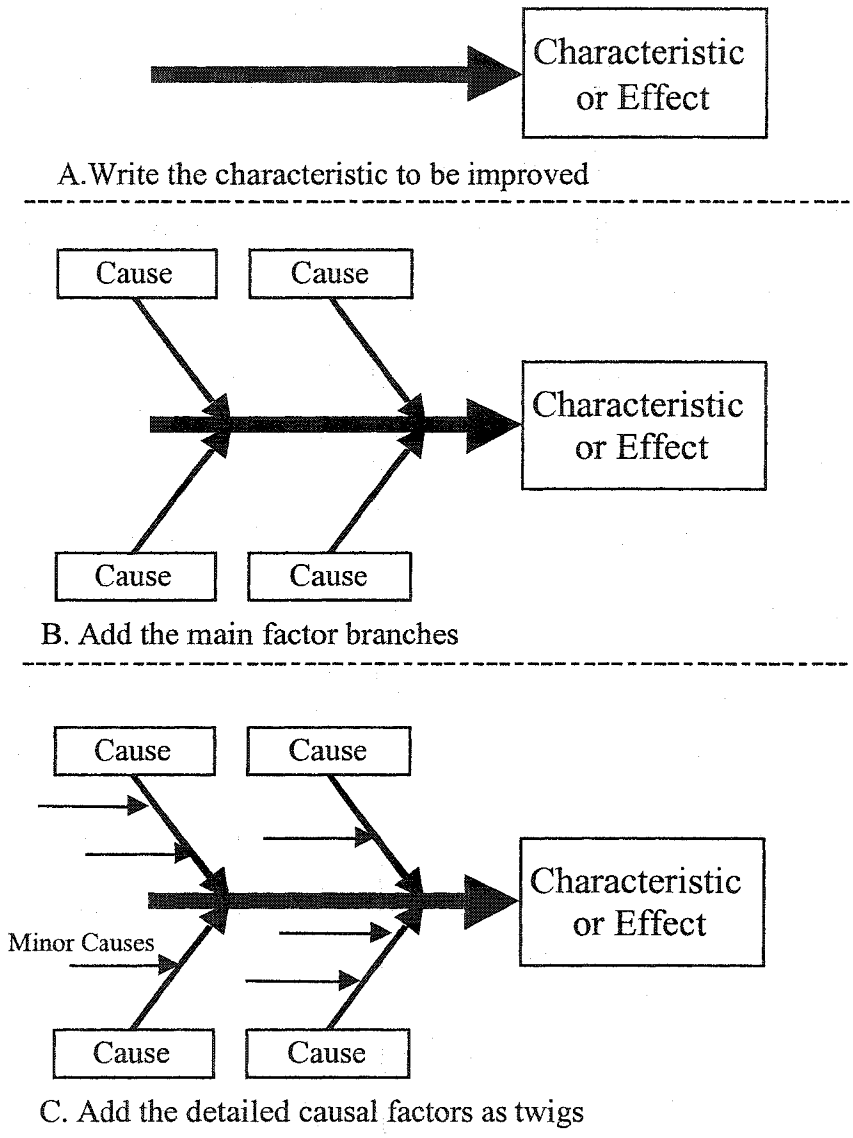

Figure 2. Steps in Building a Cause and Effect Diagram

Anderson and Fagerhaug (2000) listed the following steps for constructing a CED:

1. Clearly describe the problem.

2. Using a whiteboard or some other large medium, draw the problem at the right end of a large arrow. Allow space for the causes. Do not strive for symmetry or graphic effects.
3. Identify the main categories of causes to the problem and write them at branches emanating from the large arrow.
4. Brainstorm and write all possible causes in the applicable area(s) of the chart. Use brief and succinct descriptions. Proceed through the chart one category at a time. Write causes that belong to more than one category in all relevant positions.
5. Analyze the identified causes to determine the most likely root causes (p. 108).

Brassard and Ritter (1994) recommended the following when constructing a CED:

1. Be flexible on the major cause categories that are used.
2. Some causes seem to fit in more than one category. Place them in both categories and see how they work out in the end.
3. Ask "why?" if ideas are slow in coming.
4. For each deeper cause, continue to push for deeper understanding. A rule of thumb is to stop questioning when a cause is controlled by more than one level of management removed from the group otherwise the process becomes frustrating.
5. Use common sense.

There are various types of cause-and-effect diagrams. The dispersion type diagram develops main groups of probable causes as branches and utilizes repeated answers to the question, "Why does this dispersion (or variation) in the characteristic occur?" The reasons for the dispersions are then drawn as twigs on the branches (Ishikawa, 1982; Sproull, 2001). The advantage of this method is that breaking down causes into more detail helps organize and relate the factors. The disadvantage is that the final form is highly dependent on the person or group constructing it and small causes of variation may be overlooked (Anderson & Fagerhaug, 2000).

The process classification type diagram lists all the steps of the process on the main arrow. All of the factors that may affect the main characteristic for that particular process are added as branches or drawn as individual CEDs. This type of diagram can also be drawn like an assembly line with each process step on the main arrow with branches extending from each step. The advantage of this method is that it is easy to understand and construct since it follows the sequence of the process. The disadvantage is that similar causes may appear repeatedly while causes due to interdependency of factors are difficult to illustrate (Anderson & Fagerhaug, 2000; Ishikawa, 1982).

The cause enumeration type diagram simply lists all possible causes of the problem characteristic and organizes them according to their relationship to the problem and each other. The advantage of this method is that all possible causes are listed and solutions are encouraged without confining thinking. The resulting diagram is also quite complete. The disadvantage is that it may be difficult to establish a direct relationship between any given cause and the final effect (Ishikawa, 1982; Anderson & Fagerhaug, 2000).

The cause of a problem generally consists of many complex elements. As a result, a completed CED looks rather complicated with many branches, twigs, and smaller twigs. On the other hand, if the completed diagram has only five or six causes, even through the format is correct, it is not finished. Too simple a diagram indicates that knowledge of the process or problem is still too shallow and that further investigation is required (Ishikawa, 1982). One can test for root causes on the diagram by looking for causes that appear repeatedly within or across major categories. If a knowledge gap is evident, more data can be gathered to determine the relative frequencies of the different causes. As a last resort, the group can select a root cause through unstructured group consensus or a structured technique such as multi-voting or NGT (nominal group technique) (Brassard & Ritter, 1994).

Ishikawa (1982) recommended that when the relationship between the cause and effect is quantitatively known, in exact figures, to put a box around the cause. If the relationship is difficult to show, but exists nonetheless, then underline the causal factor. If there is no real proof that a certain cause is related to the effect, do not mark it in any way. Thus, the more causes with boxes or underlines, the stronger the relationships and the higher the level of technological expertise.

A variation of the tool is to place a large, highly-visible blank CED prominently in a work area and allow everyone to post both potential causes and solutions using self-adhesive notes. This promotes the review and testing of ideas and opens the process to every person in the organization (Brassard & Ritter, 1994). Bhote (1988) recommended a variant of this method using cards that people can update when changes occur to the process. Another variation is to include logic gates from tree diagrams or add notes from other analyses (Wilson et al., 1993).

Overall, the advantage of the CED is that it is easy to use and promotes structure while allowing creativity. It works best when the problem or process is well-defined (Scholtes, 1988). The disadvantage of the technique is that one or a few people may dominate the exercise (Anderson & Fagerhaug, 2000) and that it only identifies possible causes rather than actual root causes (Scholtes, 1988; Sproull, 2001). Bhote (1988) criticized the CED as ineffective, saying it is a hit-and-miss process that may take months or years to find root causes because it tends to emphasize opinions and miss interaction effects.

Interrelationship Diagram

The interrelationship diagram (ID), originally known as the relations diagram was developed by the Society of Quality Control Technique Development in association with the Union of Japanese Scientists and Engineers (JUSE) in 1976. The relations diagram was part of the seven new quality control (7 new QC) tools. It was designed to clarify intertwined causal relationships in a complex problem in order to identify an appropriate solution. The relations diagram developed into a problem solving method from diagrams used in management indicator relational analysis, a method for economic planning and engineering developed by Professor Toshio Senju of Keio Gijuku University. In relational analysis, problems having linked cause-and-effect relationships are numerically analyzed using calculations for each factor (Mizuno, 1979/1988).

In January of 1984, GOAL/QPC, an educational consulting company, formed the Statistical Resource Committee to research, review, and redesign training materials for statistical process control (SPC). The result of the committee's work was a practitioner's handbook, *The Memory Jogger,* created for workers and managers that defined the various SPC tools. These tools are known as the seven quality control (7QC) tools and they include the cause-and-effect (Ishikawa) diagram. During the development of the handbook, the writers became aware of the seven new QC tools as proposed by Mizuno (1972). After translating a working version of Mizuno's book, which was not published in English until 1988, the committee refined these new tools into a set they called the seven management and planning (7MP) tools. The committee developed the term 7MP to indicate that this was not a "new" tool set to replace the "old" QC tools, but rather supplement them and more accurately describe their intended application (Brassard, 1996). As an outcome, GOAL/QPC published the *Memory Jogger Plus+* in 1989 that featured the 7MP tools and included a variation of Mizuno's relations diagram called the interrelationship digraph. A digraph is a combination of the words *diagram* and *graph*

(Moran et al., 1990). Thus, the terms interrelationship digraph, interrelationship diagram, and relations diagram are used interchangeably.

The interrelationship diagram "…takes complex, multi-variable problems or desired outcomes and explores and displays all of the interrelated factors involved. It graphically shows the logical (and often causal) relationships between factors" (Brassard, 1996, p. 5). Anderson and Fagerhaug (2000) stated that the ID is "a tool used to identify logical relationships between different ideas or issues in a complex or confusing situation" (p. 14) and "borders on being a tool for cause-and-effect analysis" (p. 94). Brassard and Ritter (1994) stated that the ID allows groups to identify, analyze, and classify the cause and effect relationships that exist among all critical issues so that key drivers can be part of an effective solution. The ID encourages team members to think in multiple directions rather than linearly and enables critical issues to naturally emerge rather than through dominant or powerful group members. It also systematically surfaces basic assumptions and reasons for those assumptions. In summary, the ID helps a group identify root causes.

The ID is constructed by mapping logical relationships between factors. The intent of the diagram is to provide a broad perspective of the whole problem. It allows the complete mapping of relationships without restricting expression or dictating a specific framework. This open-ended framework is designed to facilitate the conception and development of improvement ideas. To solve problems, the team members draft the diagram several times to generate ideas that may lead to effective solutions. The ID can be used to solve both single and multiple problems (Mizuno, 1979/1988).

The ID uses arrows to show cause and effect relationships among a number of problems and the factors that influence them. Short sentences or phrases expressing the factor or problem are enclosed in rectangles or ovals. Whether phrases or sentences are used is a group decision, but authors recommend the use of at least a noun and verb

(Brassard, 1996; Brassard & Ritter, 1994). Arrows drawn between the rectangles represent the relationship between factors. As a rule, the arrow points from the cause to the effect or from the means to the objective. However, the arrow may be reversed if it suits the purpose (Mizuno, 1979/1988).

The format of the ID is generally unrestricted and several variants of the diagram are discussed in the literature. The centrally converging diagram places the major problem in the center with closely related factors arranged around it to indicate a close relationship. The directionally intense diagram places the problem to one side of the diagram and arranges the various factors according to their cause-and-effect relationships on the other side. The applications format diagram can be unrestricted, centrally converging, or directionally intense, but adds additional structure based on factors such as organizational structure, processes, or systems.

The ID can use both quantitative and qualitative formats. In the qualitative format, the factors are simply connected to each other and the root cause is identified based on intuitive understanding. In the quantitative format, structured numeric identifiers are used to determine the strength of relations between factors and the root cause is identified based on numerical values (Anderson & Fagerhaug, 2000).

Mizuno (1979/1988) recommended the following principles when creating a relations diagram: first, collect information from a variety of sources. Second, concise phrases or sentences are preferred to isolated words. Third, draw diagrams only after group consensus is reached. Fourth, rewrite diagrams several times to identify and isolate critical items. Finally, do not be distracted by intermediate factors that do not directly influence the fundamental factors or root causes. Mizuno recommended asking *why* questions to surface true cause and effect relationships and to slow the process down so participants can critically evaluate, revise, examine, or potentially discard factors.

Anderson and Fagerhaug (2000) asserted that the first step for using an ID is to determine the factors and label them. Next, place the factors on an empty chart or whiteboard in a circular shape and assess the impact of each factor on the others using arrows. After all relationships have been assessed, count the number of arrows pointing into or out of each factor. A factor with more "out" arrows than "in" arrows is a driver while a factor with more "in" arrows than "out" arrows is an indicator. The driver factors form the starting point for analysis.

Brassard (1996) and Moran et al. (1990) agreed that the ID starts by defining the issue or problem. Participants may brainstorm problems using an affinity, tree, or system diagram, or collect data using one of the 7QC tools. Once ideas are generated, the group places these issues on cards or self-sticking notes and lays them out on a work surface, flip chart, or butcher paper. Once all of the cards are laid out, relationship arrows are drawn from each card such that the arrow points from the cause to the effect. The layout of the cards can be pre-arranged or random. Once the relationships are established, the group reviews and revises the diagram selecting important items for further investigation. At this point, it is typical to count the number of arrows going into and coming out of each card. If incoming arrows are dominant, the factor is most influenced by other factors. If outgoing arrows are dominant, the factor affects many other factors or is a basic cause. Thus, the card with the most outgoing arrows might be identified as the root cause of the other cards. The group reaches consensus on the key factors through discussion and evaluation. Finally, the group draws a final diagram with the essential factors highlighted for further action and resolution. An example of a simple interrelationship diagram is shown in Figure 3.

Overall, the ID's strength is that it is a structured approach to problem solving using a graphics language display. The disadvantage is that it relies on the subjective judgements of relationships and can become quite complex or hard to read (Anderson &

Fagerhaug, 2000). Arcaro (1997) estimated that the interrelationship diagram will resolve about 80% of an entire system's issues.

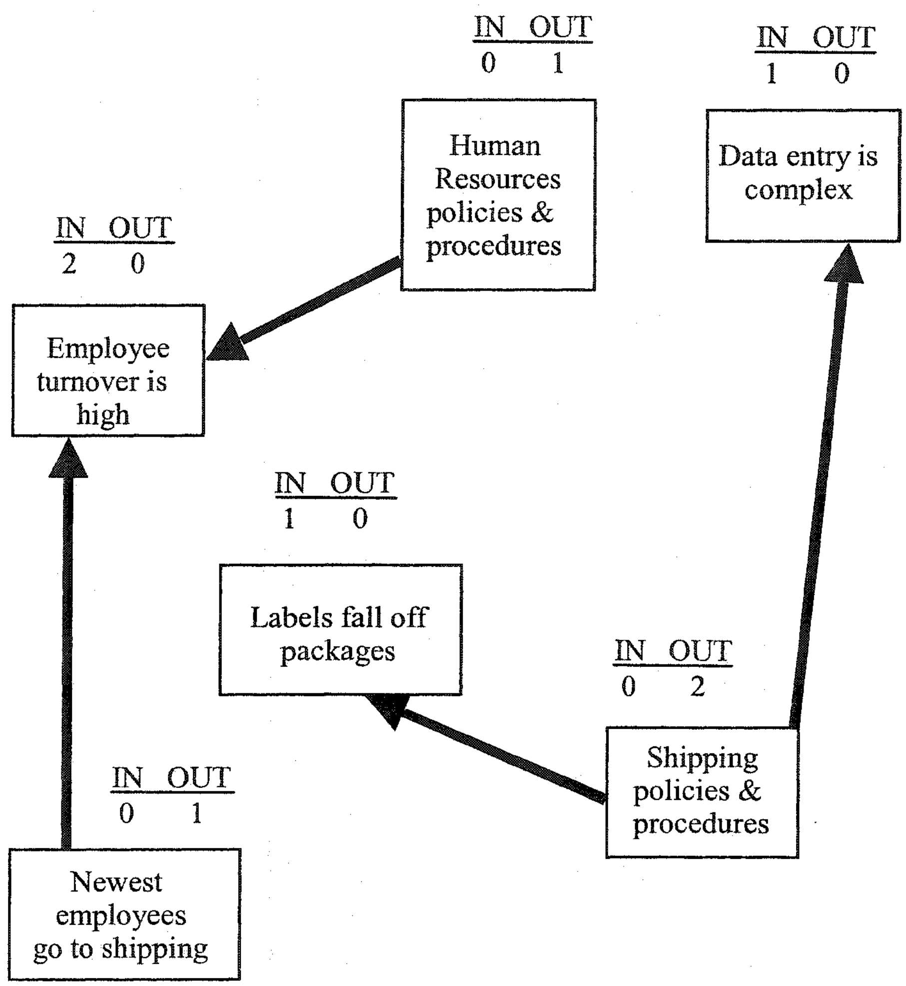

Figure 3. Example of an Interrelationship Diagram

A variant of the diagram is the matrix format, which places all the issues to be addressed on the major axes. This format creates a more orderly display of all the relationships and prevents the tool from becoming too chaotic to read when there are a large number of factors. The strength and direction of the relationships can be represented through symbols or numbers placed in the cells of the matrix. Brassard (1996), and Brassard and Ritter (1994) suggested that users become careless with large, complicated diagrams so the matrix format is a good technique to force participants to look at each factor in a more systematic fashion. If the situation calls for a thorough examination of each factor, the matrix format is best. However, if the situation calls for more creative, innovative thinking, the diagram is the best choice. Ultimately, the format chosen will reflect the group's personality and the problem at hand.

Current Reality Tree

In the book, *What is This Thing Called Theory of Constraints and How Should it be Implemented?* (1990), Goldratt introduced his philosophy of effect-cause-effect logic. He promoted the idea that problems are interdependent and result from a few core problems. In the book, Goldratt said, "We grossly underestimate the power of our intuition" (p. 3); that intuitively, most people know how to solve problems, but are unable because they have no method of verbalizing their intuition. Without a means to verbalize concerns, people will do the opposite of what they really believe and will "...play a lot of games with numbers and words" (p. 3). Goldratt expanded on the idea of problem solving through focused intuition and cause-effect logic in the book *It's Not Luck* (1994). This book introduced the current reality tree (CRT) as one of five thinking process (TP) tools for implementing the Theory of Constraints (TOC). Goldratt's TP tools are a generic set of problem solving tools that address problems as related links of cause and effect, rather than isolated events.

The CRT, sometimes called an effect-cause-effect (ECE) diagram (Walker, Cox, Jordan, & Peterhans, in press) is generally the first TP tool used in TOC. The CRT's purpose is to help practitioners find the cause and effect links between problems, which are called undesirable effects (UDEs) of the core problem.

> "Until these cause and effect connections are established, we don't have a clear enough picture of the situation. The first step then, is to use a very systematic way to build what is called a Current Reality Tree diagramming the cause and effect relationships that connect all the problems prevailing in a situation. Once you do this, you realize that you don't have to deal with many problems because at the core there are always only one or two causes" (Goldratt, 1994, p. 94).

The CRT is a logical structure designed to show the current state of reality as it exists in a system. It reflects the most probable chain of cause and effect factors that contribute to a specific set of circumstances and is the basis for creating an understanding of complex systems (Dettmer, 1997). Schragenheim (1998) wrote, "The current reality tree depicts the current state of an organization with the objective of identifying a root cause..." (p. 19-20), whereas Scheinkopf (1999) stated that the CRT "is used to pinpoint a core driver-- a common cause for many effects" (p. 144).

The CRT attempts to relate the UDEs to each other and identify the core cause of them. Authors define a core cause or problem as the factor that produces between 70% to 80% or more of the system UDEs (Cox, Draman, Boyd, & Spencer, 1998; Dettmer, 1997; Goldratt, 1994; Scheinkopf, 1999). A core cause can also be classified as a core driver, which means that it is beyond the control of the person or group seeking to solve the problem (Walker et al., in press). The identification of a core cause enables problem solving teams to make the simplest change having the greatest positive impact on the system. The CRT assumes that all systems are subject to interdependencies among their components. Therefore, related causes must be identified and isolated before they can be addressed.

Current reality trees use entities and arrows to describe a system. Entities are statements within some kind of geometric figure, usually a rectangle with smooth or sharp-cornered edges. An entity is expressed as a complete statement that conveys an idea. An entity can be a cause, an effect, or both. The linkages formed by the CRT show the relationship between one entity and another and create chains of cause and effect (Dettmer, 1997).

Arrows in the CRT signify a sufficiency relationship between the entities. Sufficiency implies that the cause is, in fact, enough to create the effect. An arrow does not connect entities that do not meet the sufficiency criteria. The cause is positioned at the tail of the arrow while the effect is placed at the tip, similar to the other root cause analysis tools. The relationship between the two entities is read as an "if-then" statement such as "If [cause statement entity], then [effect statement entity]." Every arrow drawn on the CRT is based on underlying assumptions about the system, situation, or laws of nature. If the underlying assumptions change, the result may be a different type of diagram (Dettmer, 1997; Scheinkopf, 1999). The assumptions are tested using rules called categories of legitimate reservation (CLRs). These CLRs will be discussed later in the review.

The CRT adds another unique symbol, the ellipsis, which is also known as the "banana" (Gattiker & Boyd, 1999), lens (Dettmer, 1997), or "and" connector (Scheinkopf, 1999). Its purpose is to show relationships between interdependent causes. Because the CRT is based on sufficiency, there may be cases where one cause is not sufficient, by itself, to create the proposed effect. Thus, the ellipsis shows that multiple causes are required for the produced effect. These causes are contributive in nature such that they must all be present for the effect to take place. If one of the interdependent causes is removed, the effect will disappear. Relationships that contain ellipses are read as "If [first contributing cause entity] and [second contributing cause entity], then [effect entity]."

Dettmer (1997) used the classic example of fire to illustrate the concept of sufficiency. Consider the top graphic in Figure 4; fire requires three simultaneous interdependent conditions or causes: fuel, heat or spark, and oxygen. Using a CRT, the causes are listed as entities connected by an ellipsis to the effect. If any one individual cause is removed, the fire will cease to exist. However, in current reality, oxygen is usually present. The underlying assumption might be that this particular entity need not be shown, unless the system exists in an environment where oxygen is not a given. CRT builders must consider whether the additional contributing factor is relevant to the accuracy of the diagram and either include it or discard it as superfluous. Nonetheless, this example indicates how causal interdependency is represented on a CRT. Causal interdependency is different from additional independent causes that may create an effect as stand-alone entities. These would be represented with additional arrows going into the effect without a connecting ellipsis as shown on the bottom of Figure 4. Arrows drawn from independent causes are known as simple connections (Cox et al., 1998).

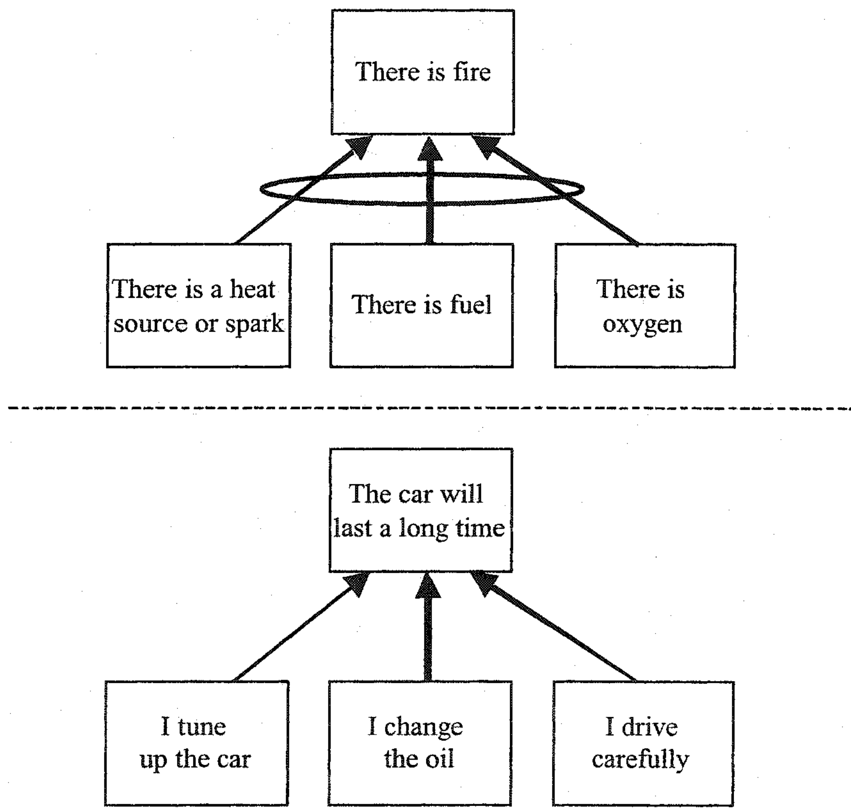

Figure 4. A Comparison of Causal Interdependency versus Causal Independence

The CRT also allows for loops that either positively or negatively amplify the effect. For this situation, an arrow is drawn from the last entity back to one of the earlier causes. If the original core cause creates a negative reinforcing loop, but can be changed to a positive, the entire system loop will be reinforced with a desirable effect (Dettmer, 1997). Although constructed from the top and working down, the CRT is generally read from bottom to top using "if-then" statements. The arrows lead from the causes upward (Gattiker & Boyd, 1999).

The procedure for constructing a CRT was first presented by Goldratt (1994) using a narrative format in the book *It's Not Luck*. Cox and Spencer (1998) later outlined this procedure:

1. List between five and ten problems (UDEs) related to the situation.
2. Test each UDE for clarity and search for a causal relationship between any two of the UDEs.
3. Determine which UDE is the cause and which is the effect.
4. Test the relationship using categories of legitimate reservation (CLRs).
5. Continue the process of connecting the UDEs using "if-then" logic until all the UDEs are connected.
6. Sometimes the cause by itself may not seem to be enough to create the effect. Additional dependent causes can be shown using the "and" connector.
7. Logical relationships can strengthened using words like *some, few, many, frequently*, and *sometimes*.

Goldratt's CRT construction process has been modified and adapted by other authors as well. A few of the alternative approaches are presented.

To construct a CRT, Dettmer (1997) recommended the following steps:

1. Identify the span of control and sphere of influence.
2. Create a list of UDEs.
3. Place the UDEs on a large sheet of paper.
4. Attempt to connect the UDEs using cause and effect logic with intermediate entities that contribute or add to the UDEs.
5. Build the cause and effect chain downward.
6. Identify root causes and the core problem.

Dettmer recommended identifying the span of control and sphere of influence to delimit the scope of the analysis. The rationale is to understand the limits one has over the problem to prevent unnecessary frustration. The initial list of UDEs frames the problem to be analyzed and answers the question, "Why is this a problem?" Dettmer recommended starting with between three to five UDEs and placing them on a large sheet of flip chart or butcher paper using self-stick notes. The connection process begins by looking for UDEs that are related to one another. If there is a direct cause and effect relationship, they can be connected with an arrow. If not, they may be connected using intermediate entities or other contributing causes that tie the two together. In application, this is the most time consuming part of the CRT process, as each relationship must be thoroughly scrutinized using the CLRs.

Once connections have been validated using CLR logic, the process continues as entities are added downward and chained together. At some point, no other causes can be established or connected to the tree. The construction of the CRT is complete when all of the UDEs are connected to very few root causes (Cox et al., 1998; Dettmer, 1997). The root causes do not have preceding causal entities. Thus, if the root causes are eliminated, the UDEs will be eliminated as well. Root causes can be physical or conceptual, such as a deeply held dominant paradigm that drives organization thinking patterns (Schragenheim, 1998). To discover conceptual root causes, it may be necessary to dive deeper by asking the question, "why?" The answer, if valid, will point to the core problem of the system (Cox et al., 1998).

The final step in the construction of the CRT is to review all the connections and test the logic to ensure there are no connection branches that do not lead to UDEs. Branches that do not connect to UDEs can be pruned or separated for later analysis. Root causes can then be evaluated for solutions and, in many cases, simply changed from negatives to positives. The tool for developing solutions is called a future reality tree

(FRT), which "injects" solutions into the CRT to determine their effect on system outcomes. Unfortunately, the FRT is beyond the scope of this study. Occasionally, solutions may not be readily apparent after completion of a CRT. To this, Goldratt answered, "When all else fails, read the Current Reality Tree again. If there is a clue that can pave the way, it is there" (Goldratt, 1994, p. 184).

Scheinkopf (1999) listed the following steps for constructing a CRT:

1. Determine the scope of the analysis.
2. List between five and ten pertinent entities.
3. Diagram the effect-cause-effect relationships between the entities.
4. Review and revise for clarity and completeness.
5. Apply the "so what test."
6. Identify the core causes.

Scheinkopf's approach is similar to Dettmer's, but adds a step called the "so what test." She recommended this step as an exercise to determine what is pertinent on the CRT and what is not. Its intent is to identify and remove entities that do not directly cause the supposed effect or vice versa. In this respect, it is very similar to pruning branches as advocated by Dettmer, but Scheinkopf placed more emphasis on it as a critical part of the process.

The rules used to ensure rigor in the CRT process are called categories of legitimate reservation (CLRs). They are the criteria for verifying, validating, and agreeing upon the connections between the factors and can be used to facilitate discussion, communicate disagreement, reduce animosity, or foster consensus (Scheinkopf, 1999). The CLRs help distinguish the perception of reality from existing reality and consist of eight tests or proofs: clarity, entity existence, causality existence, cause insufficiency, additional cause, predicted effect, cause-effect reversal, and tautology (Dettmer, 1997).

Clarity, causality existence, and entity existence are the first level of reservation. They are used to clarify meaning, question the relationship between entities, or question the existence of the entities themselves. The clarity reservation checks the meaning of statements or relationships and develops mutual understanding of the formulated logic. It is much like a conversation between two people where the listener asks questions of the speaker to clarify communication and surface assumptions. Typically, entities not written as a complete sentence raise a clarity reservation. The intent of the clarity reservation is to make entities clear, concise, and convey the appropriate message (Scheinkopf, 1999).

The entity existence reservation is raised when the entity statement is incomplete, complex, or seems invalid. An incomplete idea does not generally meet the grammatical criteria of a subject and verb, or may include impersonal pronouns such as *it*, *this*, or *those*. The entity should represent a single, simple idea with no compound phrases. The validity of the entity is embedded in the soundness of the statement, its foundation, and reasonableness. Validity means that the statement is true and actually exists in reality (Dettmer, 1997; Scheinkopf, 1999).

Causality existence is the reservation that the cause, in fact, results in the effect. It tests the validity of the arrows between entities. The test for causality is verified using the "if [cause], then we must have [effect]" statement. The causality reservation simply asks if the cause-effect relationship *really* exists (Dettmer, 1997; Scheinkopf, 1999).

The second level of reservation is cause insufficiency, additional cause, and predicted effect. They are classified as secondary because they are used when questions from first level reservations remain unanswered or in doubt. Second level reservations look for missing or additional causes and additional or invalid effects. Cause insufficiency tests the likelihood of complex relationships. It is raised when the stated cause is not enough, by itself, to produce the stated effect. With cause insufficiency, the implication is that the stated cause exists, but is not sufficient to create the proposed effect without some other unstated factor. The focus is on identifying possible missing dependent causes. This reservation allows for the inclusion of multiple interdependent causes and is a powerful feature of the CRT (Dettmer, 1997; Scheinkopf, 1999).

The additional cause reservation tests for an additional independent cause that produces the effect. Additional independent causes represent missing "or" conditions, whereas cause insufficiency represents an incomplete "and" condition. Additional cause addresses concerns about other factors that add to, or increase the magnitude of, the stated effect. Additional independent causes are those factors that would create the effect even if another cause was removed (Dettmer, 1997; Scheinkopf, 1999).

Predicted effect uses the same logic as the additional cause reservation, but applies it by asking for the potential of additional effects. Predicted effect uses the scientific method to speculate about other effects that might invalidate the original effect (Scheinkopf, 1999). Dettmer (1997) wrote that predicted effects can also be based on expectation, coexistence, or magnitude. Expectation considers whether the proposed effect should or should not be present in the stated relationship. Coexistence considers if there is more than one effect and if they coexist. If there is more than one effect, magnitude considers if the effects are more are less than expected. If the actual magnitude is significant relative to the expectation, one or more of the additional causes may be invalid. Furthermore, if causes are not measurable or observable, it is likely that there is another effect yet to be found.

There are two other reservations found in the literature: cause-effect reversal and tautology. Cause-effect reversal is confusion between the cause and the effect. These are typically "chicken versus egg" type arguments. Asking if the stated cause is the source of the effect, or if the effect is really the source of the cause tests cause-effect reversal. The cause may only be an indicator or symptom of the effect, rather than the source (Dettmer, 1997). An example might be the assumption that the economy is good because the stock market is rising, while in actuality, the stock market is merely an indicator of the economy.

Finally, tautology is the test of circular logic where the effect is the rationale for the cause. Tautology is likely to be raised after the causality existence reservation when the cause is intangible; i.e., the cause cannot be measured or observed. Tautology rests on the assumption that if no additional predicted effect is found, it is easier to let the effect provide the rationale for the cause. To test for tautology, the reservation identifies intangible causes, seeks the existence of circular relationships, and asks for additional predicted effects that could substantiate the cause (Dettmer, 1997).

The CLRs provide the rigor for building sound logic and integrity into the CRT and enable individuals to scrutinize the validity of the problem solving process. The CLRs are a mechanism for testing the assumptions of others without creating conflict. They are designed to build consensus within groups to focus attention on the problem rather than each other.

Variations of the CRT include adding other conventions such as the magnitudinal "and" connection to show causal relationships that are neither interdependent (sufficient) nor independent. A magnitudinal relationship is additive where one cause adds to the magnitude of the effect when combined with other causes (Dettmer, 1997). The CRT can also be used discover the core competency or key strength of the system. When used in this manner, the core cause becomes positive rather than negative (Scheinkopf, 1999). Other variations are to use the CRT to identify business constraints as part of the TOC TPs or to persuade others to take a particular course of action (Cox et al., 1998; Goldratt, 1990; Lepore & Cohen, 1999; Smith, 2000). When used as a persuasion tool, it is known as the Communication CRT. When used to identify business constraints, it becomes one of the five focusing methods for the TOC process (Scheinkopf, 1999).

Root Cause

According to Wilson et al. (1993), a root cause is the most basic reason for an undesirable condition or problem, which, if solved, would prevent the undesirable condition. Taken in this context, the root cause is always negative. The root cause may be described in a binary sense (i.e., its existence or evidence to the contrary) or in a qualitative sense, meaning that factors intended to preclude its occurrence may be missing, or less than adequate. Root causes typically create several problems, which have long-lasting effects. Root causes are usually described in terms of specific or systematic factors. Solving root causes has a low cost to benefit ratio and is similar to the notion of leverage as advocated by systems thinkers (Khaimovich, 1999). The root cause is a core cause expressed in terms of a common organizational, personal, or activity denominator.

Beneath every problem lies a cause for that problem. In order to solve a problem one must identify the cause of the problem and take steps to eliminate the cause. If the real cause of the problem is not identified, then one is merely addressing the symptoms of the problem and the problem will continue to exist. Consequently, the core or root cause of the problem must be identified correctly for the problem to be solved. For this reason, identifying and eliminating root causes of problems is of utmost importance (Anderson & Fagerhaug, 2000; Dew, 1991; Sproull, 2001). Symptoms are the tangible evidence or embodiment of the existence of something wrong. Root cause analysis efforts often fail due to their inability to clearly distinguish between apparent and root causes. The relationship between the event or problem and the root cause must be established.

> For the problem solving process to be effective, the evaluation must therefore uncover and correct the condition's root cause, not just the symptom(s). As you remember, root cause analysis is the process of getting at the root of the problem, its source. Like weeds, problems may only appear if not properly removed or treated. Perhaps more ominously, they also can spread to other areas (Wilson et al., 1993, p. 7).

Root causes can be physical, human, or latent. Physical root causes are observable tangibles and most problem solving methods are geared for this level of analysis. Human root causes result from human errors of omission or commission. Latent root causes result from organizational and decision making systems (Latino & Latino, 1999). Reason (1992) defined latent root causes as causes "whose adverse consequences may lie dormant within the system for a long time, only becoming evident when they combine with other factors to breach the system's defenses" (p. 173). Permanent solutions to problems require knowing the root cause (Dew, 1991).

Causal Interdependency

Interdependency is a basic tenet of systems theory and is proficiently documented in literature (Ackoff & Emery, 1972; Forrester, 1961; Senge et al., 1994; Womack, Jones, & Ross, 1990). Gharajedaghi (1999) defined interdependency as a set of variables that are not independent with respect to their impact on the dependent variable. He provided an example of a division within Ford Motor Company that attempted to improve eleven areas of operation over the course of three years. Significant improvement ensued and the division was able to report positive results within eighteen months, but was unable to produce further change even after redoubling efforts for an extended period of time. Gharajedaghi concluded that the division had used up all the available slack (degrees of freedom) in the measured independent variables and was now dealing with the interdependency between them. No further improvement could be achieved until the entire operation was redesigned as an interdependent system.

Schragenheim (1998) claimed that many organizations have an overwhelming number of interdependencies that form the core of system complexity. When coupled with the uncertainty of the environment, the pursuit of optimal performance by all functions, processes, or resources is impossible. This is because there are too many details to consider and each detail has an effect on other variables. Thus, most modern organizations resort to dividing themselves into smaller departmental chunks and make each department responsible for its own performance. Yet, this configuration loses the potential of capturing the whole benefit because a system is more than the sum of its parts.

Gharajedaghi (1999) wrote that the characteristics of interdependent systems are openness, emergent property, counterintuitiveness, multidimensionality, and plurality. Openness is the behavior of a system within the context of its environment. This means that the interactions of the system are influenced by each other such that no single effect can be measured by a single cause. Rather, multiple causes either move the system towards stability or instability. Emergent property is the reinforcing mutual interaction between the parts of the system that produce results greater or less in magnitude than results generated by separate parts. Emergent property describes systems in terms of what they are becoming as opposed to what they currently are. Counterintuitiveness is the phenomenon of an action that actually produces the opposite effect of the intended or desired outcome. Counterintuitiveness is based on the non-linear, iterative nature of systems to form circular logic relationships that either reinforce or balance effects over time. Initial effects may be, indeed, positive, but the long-term consequences are negative. Multidimensionality is the complementary relationship between opposing tendencies to create a feasible effect from unfeasible causes. The mutual interdependence of opposing tendencies is characterized by “and” relationships and is found in pluralistic thinking. Plurality views systems as having multiple structures and functions that are governed by multiple processes. Plurality questions the existence of a single cause and effect relationship within a given structure. This philosophy is very different from the dichotomous approaches of "either/or" relationships in traditional systems (Gharajedaghi, 1999) as typified by the continuing search for "silver bullets" within most modern organizations.

Analysis and Summary of the Literature

This section of the literature reviews and evaluates comparative research on the three tools, summarizes the findings, and identifies literature deficiencies. As of this writing, there are only two studies that compare the tools: Fredendall et al. (2002) and Pasquarella et al. (1997).

Previous Comparative Research on the Three Tools

Fredendall et al. (2002) compared the CED with the CRT by first using a simple example of a car that will not start and then a more complex example of why business process reengineering (BPR) projects fail. The authors stated that the CED and the CRT use much of the same causal logic and that they can be used in tandem. A problem solving group may start using the CED to brainstorm possible causes of a problem and then use the output to develop the list of UDEs for the CRT. There are, however, some critical differences between the two approaches.

The physical layout of the tools is different. The CED is horizontal and is read from left to right while the CRT is vertical and is read from bottom to top. The CRT generally has fewer entities than the CED and allows the use of loops to explore possible non-linear relationships. Fredendall et al. (2002) claimed the CRT is more mechanical and requires less artful construction than the CED. They also stated that the CED needs greater facilitative skills because it requires asking "why" enough times to find the root cause.

The CED does not easily allow the use of "and" statements to indicate multiple causes of an effect. The CRT shows "if-then" logic more precisely. However, Fredendall et al. (2002) admitted that groups may find the strict application of the CRT logic intimidating and resent having to phrase their suggestions and objections as CLRs. They contended that most people view the CED as easier to construct and use because it requires less training and can be put together quickly. The major differences are that the

CED does not quickly identify the root cause of the problem while the CRT visually points to it. The CRT is structured so that it identifies the root cause and what to change, which then leads more precisely to a permanent solution.

Pasquarella, Mitchell, and Suerken (1997) provided a detailed comparison of the tools in a three-part proceedings article; each author wrote a separate section. Suerken did not compare the tools in her particular section, but presented a convincing argument for using the TOC thinking process (TP) tools, including the CRT, in educational settings.

Pasquarella's section of the article compared the TP tools to ten quality control tools (she added three more tools to the 7QC tools) that include the CED. She also compared the TP tools to the 7MP tools, which includes the ID. In comparing both sets of tools, seventeen in all, to the TP tools, Pasquarella made three conclusions: first, organizations will choose simple methods when confronted with too many tools, or if they perceive a tool as too complex. Thus, most people will choose a CED because it fits their perception of a simple analysis tool. Second, simple methods are heavily influenced by emotions and complex methods require familiarity, expertise, and skillful facilitation. Third, the ten quality control tools do not address system-wide problems unless used together rigorously. In other words, they cannot be used individually to solve larger systemic problems. Consequently, organizations tend to use simple tools that do not solve core problems.

Pasquarella claimed the TP tools are superior for the following reasons. They are logical, simple, and there are less of them to consider. The TP tools use intuition and capture emotion without skewing the process because the CLRs force rigor back into the process. Each TP tool can be used as a stand-alone application or together with the other TP tools. Each tool is clearly identified for a specific function so that anyone can use it to solve a particular type of problem. Each tool is designed to consider system-wide application as well as local concerns. As a result, Pasquarella declared that the TP tools (and the CRT) produce the best results because they are more robust, powerful, and simpler then the other tools.

Mitchell, in his section of the article, reported the results of a qualitative study that measured the effectiveness of the CED, the ID matrix, and the CRT. Using students from an advanced quality management course, Mitchell supplied facts about an airline transport accident and asked the group to find the root cause. Mitchell facilitated each of the tool applications, giving students technical information and answering questions as needed. The students applied each of the three analysis tools and then drew comparisons. The results of the study are summarized in Table 1.

Mitchell's students found that the CRT pinpointed the root cause of the airline accident while the CED did not. Mitchell did not indicate whether the ID matrix found the root cause, but stated that the ID matrix is a good tool for keeping groups organized and for sorting out potential causes while exploring and comparing potential cause and effect relationships.

Mitchell's students also reported that the CRT was the only tool that showed interdependencies between causes. While the ID matrix showed interrelationships, it did not show whether the effect resulted from causal interdependency. The CRT was the only tool to show interrelationships and intermediate factors leading to the effect. Both the CED and the CRT were effective in grouping cause categories compared to the ID matrix. Mitchell reported that the CRT caused more discussion than the CED, but did not compare the ID matrix. All three tools were effective in focusing problem solving activities.

In terms of total process time, the CED was the easiest and least time consuming followed by the CRT and the ID matrix. However, the final ID matrix proved somewhat incomplete, which caused extra process time to clarify and correct. Mitchell's students rated the CRT highest for readability because the root cause is located at the bottom of the diagram and the logic flows upward towards the effect. The ID matrix was rated second for readability, although it was easier to read at a glance. The CED was the most difficult to read.

Table 1.

Summary of Qualitative Results From a Study Conducted by Mitchell (as reported in Pasquarella, Mitchell, & Suerken, 1997)

Finding	CED	ID Matrix	CRT
Found root cause?	No	?	Yes
Showed causal interdependency?	No	No	Yes
Showed interrelationships?	No	Yes	Yes
Showed intermediate factors?	No	No	Yes
Identified cause categories?	Yes	No	Yes
Stimulated dialogue?	?	?	Yes
Focused activities?	Yes	Yes	Yes
Total process time	Low	High	Medium
Overall readability rating	Low	Medium	High

Mitchell's students concluded that the CRT was the best of the three tools. The CRT was able to pinpoint root causes while identifying causal interdependency. The common weakness of the CED and ID was their inability to identify causal interdependencies, which Mitchell said are critical to successful problem solving. Mitchell offered the opinion that without a clear understanding of causal interdependency, overlooked negative effects will creep back into the system and create recurrent problems that will need attention again.

Summary of the Literature

There are many problem solving models found in literature; most are based on the scientific method of inquiry. The literature indicated that root cause analysis is the preferred method for identifying problem causes and potential solutions. Authors considered root cause analysis tools that incorporate graphics language and network display structures superior to other types of analysis communication. The CED, ID, and CRT represent three root cause analysis methods that are generally accepted by practitioners as viable techniques for the purpose of finding the root causes of problems.

The literature indicated that the CED is an appropriate tool for developing and classifying possible root causes. The CED assumes the existence of enough knowledge to be able to isolate and identify probable root causes and has the potential to highlight information that is lacking or inadequate. The CED does not identify relationships between categorical factors. Some authors perceive the CED as ineffective.

The literature indicated that the ID is an appropriate tool to help identify root causes and clarify intertwined relationships between multiple factors, although the factors may not be causal. The ID is used to identify, analyze, and classify possible relationships among critical issues and uses a structured problem solving method for gathering information. Authors viewed the ID as a borderline tool for cause and effect analysis.

The literature indicated that the CRT is an appropriate tool for pinpointing root causes and identifying causal interdependency. The literature distinguished between interrelationship and interdependency using sufficient cause logic such that effects due to interdependency are attributed to multiple and related causal factors. The CRT builds a chain of cause and effect logic, starting with effects, to guide the verbalization of intuition in a logical fashion that leads to the identification of a core problem that accounts for more than seventy percent of the undesirable effects. Khaimovich (1999) professed that "Experts rarely look for root causes moving from symptoms backwards along possible causal links" (p. 53). In this respect, the CRT is unique. Of the three root cause tools, the CRT is the only method that has a mechanism for identifying both root cause and causal interdependency. It does this through the use of "and" conventions, which link multiple causes to effect(s) and looping conventions to show reinforcement of causality.

Most of the literature described the three tools independent of each other. Only two studies compared the CED, ID, and CRT to each other and those studies were qualitative. No research has been done that quantitatively measures the CED, ID, and CRT to each other. No research has been done to quantitatively measure the effectiveness of the tools to find root causes or identify causal interdependency. This study attempted to address those deficiencies.

CHAPTER 3: METHOD

This chapter delineates the research method and provides rationale for the design approach. Participants, measures, and instruments are described with their associated validity and reliability. The chapter also provides an account of the research procedures and data analysis used.

Research Approach and Rationale

This study was grounded in the experimental research tradition, but also had sampling and ecological components that could be associated with qualitative research. The design and results of the study were quantitative, but the setting and context were natural and congruent with the participants' normal habitat. Snow (1974) argued that this research approach could be identified as a representative design in that the experiment took place outside a laboratory setting and encouraged the natural behavior of participants. However, another aim of this inquiry was to consider the possibility of generalizing to a larger theoretical population because of the global nature of problem solving activities performed by small, cohesive groups. Anderson (2001) asserted that this type of field science is at least as important as laboratory science because experiments in controlled settings often lose their external validity when generalizing to a social-cognitive context. Field investigations are appropriate for problems involving human behavior because the research results can be more readily applied in authentic field situations.

The specific design was a within-subjects single factor repeated measures study with three levels. The independent variables were the root cause analysis tool (CED, ID, CRT) treatments, which were counterbalanced to reduce carryover effects. The rationale for this design is that it compares the treatments to each other in a relative fashion using the judgments of the participants. In this type of comparative situation, each participant serves as his or her own control making the use of independent groups unnecessary (Girden, 1992).

The advantage of this design is that it required fewer participants while reducing the variability among them, which decreased the error term and reduced the possibility of making a Type I error. This is preferred because a repeated measures design eliminates the variability between individuals by using only the experimental error in the F denominator. This increased the power (β) of the design and the possibility of finding a statistically significant difference. The disadvantage of the design is that it reduced the degrees of freedom (Anderson, 2001; Girden, 1992; Gliner & Morgan, 2000; Gravetter & Wallnau, 1992; Stevens, 1999).

Participants

The selected sample for the research was naturally formed groups, such as those found in organizations, institutions, or classrooms. An international study by the American Quality Foundation found that 53% of manufacturing firms and 33% of service firms have over half of their respective work forces participating in some type of work group (Harrington, 1995). The specific sample for this study was students in intact classrooms. As the participants were likely to have had some previous interaction with one another, the order of the treatments (the CED, CRT, and ID) was randomized. Using three classroom sections, each section of participants drew numbers and were randomly assigned to treatment subgroups. Each subgroup consisted of ten to thirteen participants and was based on the average size of authentic problem solving groups commonly found in work or educational settings. The theoretical population was organizational problem solving groups who are somewhat familiar with a problem and have working relationships with each other. The research design model is shown in Table 2, where *T* represents the treatment, *M* represents the measure, and the subgroup observations are indicated by *O*.

Table 2.

Repeated Measures Design Model

Subgroup	T_1	M_1	T_2	M_2	T_3	M_3
1	CED	$O_{1.1}$	CRT	$O_{1.2}$	ID	$O_{1.3}$
2	ID	$O_{2.1}$	CED	$O_{2.2}$	CRT	$O_{2.3}$
3	CRT	$O_{3.1}$	ID	$O_{3.2}$	CED	$O_{3.3}$

The participants were from three intact class sections of students taking a general education course in team problem solving and leadership in the Department of Manufacturing Technology and Construction Management. The participants were first and second year undergraduate students who had an interest in developing leadership and decision making skills for use in industry, business, or education. Class gender was primarily male; females accounted for only 11% of the sample. The ethnicity of the sample was primarily Caucasian; minorities comprised less than 3%. The age of participants ranged from 18 to 30, but 98% were in their early twenties.

The benefits of this study to participants included an increased knowledge of root cause analysis techniques and the potential to solve problems using structured methodologies. Participants gained experience using structured problem solving and decision making techniques. Participants also gained a greater understanding of alternative problems solving methods for the development of future organizational policy. Other benefits included the development of decision making skills based on rigorous analysis and knowledge that could be applied in future business or educational contexts to increase productivity, quality, and understanding. Participants could also share this knowledge with families, friends, peers, or co-workers. There were other intangible benefits such as an increased understanding of group dynamics, and the role of intuition, emotion, or logic in problem solving.

Measures

The independent variable was the application of the CED, CRT, and ID root cause analysis tools. The dependent measured variables were the perceived ability of the tools to identify causality, specifically: (1) root causes, and (2) causal interdependencies. In addition, the researcher was interested in the perceived ability of the tools to identify factor relationships such as (3) the interrelationship between factors, (4) intermediate factors, and (5) cause categories. The perceived usability of the tools was measured for (6) logic and integrity, (7) productive problem solving activity, (8) ease or difficulty, and (9) overall readability. The amount of group participation generated by the tool was measured through participant's perceptions of (10) amount of discussion, (11) productive dialogue, and (12) active development of participation. During the process, the actual time spent on each tool was observed and documented. The types of questions or statements generated by the participants were summarized along with process observations. The tool outputs were also reviewed and evaluated.

Before the experiment, the researcher held a detailed training session with the treatment facilitators. These facilitators were trained in each of the analysis tools, processes, and experimental procedures. They were instructed to be available to answer questions from subgroup participants during the designated period as well as during the treatment. Upon participant request, the facilitators provided information about the tools, goals, purpose, procedures, or instructions, but did not provide information about the problem scenarios. They were also trained in observational techniques and instructed to intervene in the treatment process if a group was having difficulty constructing the tool or managing their process. The activity of the facilitators was intended to help control the potential diffusion of treatment across the subgroups and measures.

Instrument

To ensure consistency between treatments and subgroups, the treatments were administered using instructional handouts based on published material. Each instructional packet was similarly formatted and included the steps for constructing the tool, a graphical example, and special or unique instructions necessary for successful completion. (See Appendix B for the instrumentation, instructional materials, and problem scenarios.) Each subgroup received the same verbal instructions and had a designated time of ten minutes to ask questions. Each treatment subgroup received the same supplies for constructing the tools: flip chart paper, self-stick notes, pencils, and markers. However, the groups were free to fabricate or develop other supplies at their discretion.

The Flesch-Kincaid grade levels and Flesch reading ease scores of the scenarios, instructions, and instrument are shown in Table 3. The experimental treatment material was designed to be as simple as possible so that participants could focus on the tools rather than the problem. Note that the average grade level for all materials was 8.1 while the reading ease was 56.3.

The dependent variables were measured using a customized participant self-report questionnaire called the Root Cause Analysis Tool Rating Instrument (RCAT-RI). This instrument is found in Appendix B. It consisted of twelve questions representing the constructs presented in Chapter 1. It used a five-point Likert scale with semantic differential phrases added for clarification. Summated responses ranged from 12 to 60 points possible.

Table 3.

Experimental Material Grade Level and Reading Ease Scores

	Instrument	Instructions			Scenarios			
		CED	ID	CRT	Acme	Gizmo	Bob's	*Mean*
Grade Level	10	8	7	7	9	8	8	8.1
Reading Ease	43.8	64.8	62	62.2	49.1	58	54.3	56.3
Word Count	588	272	204	352	264	217	302	314

Reliability and Validity

A group of graduate students familiar with the research judged the content validity of the RCAT-RI instrument to be adequate. Using a pilot study of 42 participants and parallel forms, initial Cronbach's alpha for the instrument was .82. Analysis of variance (ANOVA) determined the instrument was able to discriminate significantly among three of the four instrument constructs: i.e., causality, relationships, usability, and participation. The constructs were measured using two, three, four, and three questions, respectively. The only construct not significant based on the ANOVA was participation. These constructs were congruent with an exploratory principle component analysis except that the usability construct was highly correlated with the causality construct. Thus, the degree of a tool's usability could also be related to its ability to find causality.

Internal Validity

The primary threat to the internal validity of this study was maturation and carryover effects resulting from participants' repeated use of the tools. Participants generally become more mature or proficient in the process through the course of the study. This is because groups tend to operate more efficiently as they establish cohesiveness through established norms of behavior, increased interaction, and repetitive communication (Brightman, 1988; Hersey & Blanchard, 1988; Scholtes, 1988; Webne-Behrman, 1998). Carryover may have resulted because the effects from repeated treatments extended or continued from one treatment to the next. Effects from the sequence of treatments, repeated practice, or boredom were also potential threats (Girden, 1992; Gliner & Morgan, 2000). Therefore, there was a need to counterbalance the order of treatments. Participants were randomly assigned to the treatment subgroups and each subgroup received the treatments in a different order.

Other threats to internal validity included the potential of participants to favor one tool application over another and the statistical regression of scores to the mean with repeated applications. Since the experiment took place in a natural setting, the study was subject to threats associated with outside influences or interruptions, potential interaction between subgroup participants, and increased learning about the study over time. An additional threat to validity was the attrition of participants due to fatigue or time constraints. To counteract these threats, the researcher provided three different problem scenarios to each subgroup in random order to further reduce carryover effects and alleviate potential participant boredom.

External Validity

The most significant threat to external validity was the representativeness of the selected sample since it consisted of intact groups. While the setting was authentic, the administration of the instrument was somewhat unnatural. In addition, the tasks assigned to the participants may have been perceived as new, difficult, or different from procedures previously used or understood. Yet, the study attempted to replicate the settings and types of groups normally found in organizations engaged in this type of activity. Small, highly interactive groups using structured methods are preferable for working problems and achieving consensus toward a solution (Brightman, 1988; Glueck, 1979; Robson; 1993; Van de Ven & Delbecq, 1971). In a between-groups design, the generalizability of the research would be based on the assumption of random subjects or observations against a well-defined theoretical population. However, in a repeated measures design, this is not possible. The assumption of generalizability for this research is based on a judgment about the similarity between the empirical design and an ideal situation in the field (Anderson, 2001). Thus, from a pure experimental standpoint, the external validity of this study might be considered low, but from a representative design standpoint, the validity is high.

Procedure

This section describes the detailed methods and procedures used in the study. The researcher followed this process to support the design rationale and ensure the integrity of the study. The time line for the procedure is shown in Figure 5. The collection of the data for the study was as follows:

1. The participants were randomly assigned to one of three subgroups.
2. Prior to each session, the facilitators drew numbers and were randomly assigned to a subgroup.
3. The researcher provided simultaneous verbal instructions about the experiment, problem scenarios, and instructional materials to all subgroups.
4. Each subgroup was given a problem scenario and written instructions for the root cause analysis tool to be used. Five minutes were allowed for the participants to review their respective scenarios and instructions.
5. Each group was given ten minutes to ask their facilitator questions about the goals, purpose, procedure, tool, or instruction. The facilitators were also available to answer questions about the tool or process throughout the treatment.

6. Participants analyzed and attempted to find the perceived root cause and causal dependencies of the predetermined problem. The problem consisted of one of three randomly selected problem scenarios developed by the researcher based upon published information (see Appendix B).
7. Upon completion of the root cause tool treatment, the participants completed the RCAT-RI. Participants created and used a unique reference code so their responses could be tracked across treatments.
8. This process was repeated until all subgroups applied all three root cause analyses to all three randomized problems. Each subsequent treatment application and measurement was administered across seven days to reduce participant fatigue, attrition, and experimental carryover effects. Once the treatments were complete, the instrument was discarded and only reference codes tracked the individual data.

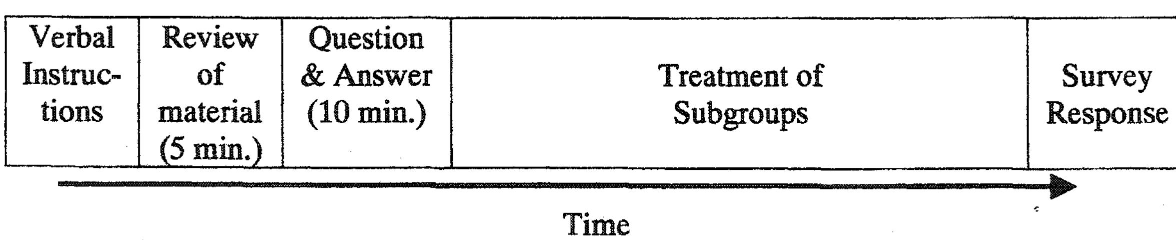

Figure 5. Experimental Procedure Time Line

Data Analyses

The primary purpose of the research was to determine if there was a perceived difference between the CED, CRT, and ID in regard to their ability to identify causality and factor relationships. Also of interest was how participants perceived the tool's usability and ability to facilitate participation. The appropriate tool for analyzing within-group differences of an independent variable with three levels using repeated measures is a repeated measures ANOVA (Gliner & Morgan, 2000; Stevens, 1999). All analyses were performed using the Statistical Package for Social Sciences™ (SPSS) software.

The secondary purpose of the study was to determine the average process time for each tool, to capture the types of statement or questions raised by participants during the study, and to evaluate the tool outputs. The secondary questions were addressed using descriptive statistics and qualitative reporting. All data was collected using the instrument, except the process time data, individual questions, and tool outputs, which were observed and collected by the researcher and the trained treatment facilitators.

Treatment of Data

The assumption of measurement independence was applied through individual self-report rather than group report and each subgroup constructed the analysis tools independently of the other subgroups. Data were pre-screened for violations of normality. As in between-groups ANOVA designs, homogeneity of variance is important, but in repeated measures design, each measure is somewhat correlated with the previous measurement. This correlation of measurement is known as circularity or sphericity. Sphericity measures the equality of variance between the scores of any combination of measured pairs. While repeated measures ANOVA is robust to violations of normality, it is not robust to violations of sphericity.

SPSS uses Mauchley's to test for the condition of sphericity. If Mauchley's test is significant, then sphericity is measured by using a calculated estimate of ε. If ε is equal to one, the assumption of sphericity is valid. If the assumption of sphericity is violated, it can be adjusted using Box's Epsilon. However, estimates can also be corrected using formulas developed by Greenhouse and Geisser (1959) or Huynh and Feldt (1976) that adjust the degrees of freedom. Another option is to take the average of the corrected ε estimates and calculate a new F value based on the adjusted degrees of freedom. Still another option is to use multivariate statistics, but authors disagree on whether this is more powerful than using univariate approaches with adjustments (Anderson, 2001; Field, 2000; Girden, 1992; Stevens, 1999). Thus, the researcher tested for statistical significance using both univariate and multivariate approaches.

A two-tailed .05 level of significance was chosen as the alpha level for this study. The repeated measures ANOVA tested the differences between tool treatments with respect to the dependent variables. Post hoc tests identified the best tool under conditions of significance with either assumed or adjusted sphericity. If sphericity was violated, the degrees of freedom were adjusted using Greenhouse and Geisser (1959) for ε less than 0.75 or Huynh and Feldt (1976) for ε greater than 0.75 (Field, 2000; Girden, 1992; Stevens, 1999). Three types of post hoc tests were run for each significant variable: a paired *t* test, a *t* test with Bonferroni adjustment, and an omnibus *F* test. The researcher then compared *p* values between the post hoc tests to validate statistical significance.

Effect size (*d*) was calculated for significant differences found between treatments. The rationale for using effect size was as follows. First, effect size measures the magnitude of a statistical difference in standard deviation units that can be compared or combined with other studies. Second, effect size is an alternative to null hypothesis testing and provides additional information on the extent or strength of significant findings. Third, the American Psychological Association Task Force on Statistical Inference states that effect sizes should be reported in primary results. (Gliner & Morgan, 2000). For repeated measures, the effect size for *d* is calculated the same as independent measures (Cortina & Nouri, 2000). Interpretation of effect size was based on the works of Cohen (1988), and Morgan, Griego, and Gloeckner (2001).

Using the data analysis methods, the researcher was able to analyze differences between the three root cause analysis tools in question. Given the limitations presented in Chapter 1, this analysis method was capable of any discovering significant differences if the assumptions of the General Linear Model (GLM) were not markedly violated.

CHAPTER 4: FINDINGS

This chapter will present the findings of the research by showing the descriptive data, then examining the statistical results for the specific dependent variable constructs of causality, relationships, usability, and participation. Finally, the chapter will summarize qualitative information provided by the participants or observed during data collection.

Descriptive Data Findings

An initial sample of 107 participants took part in the study, but the actual sample size was 72 participants. The difference between the initial and actual sample was due to attrition among the three sections and non-responses on the Root Cause Analysis Tool Rating Instrument (RCAT-RI). Using Cohen's power tables for this sample size and alpha level (.05), the statistical power was sufficient enough to find medium to large differences between treatment groups (Stevens, 1999). The sample data were screened for missing values, outliers, and normality. Cases with missing values were eliminated and the outliers were checked for validity. Screening indicated the data were normally distributed and met all assumptions for parametric statistical analysis. Mauchley's test showed that sphericity was valid for most data. For violations of sphericity, the researcher used Huynh and Feldt (1976) corrected estimates for cases where ε was greater than 0.75 (Girden, 1992). Box and multivariate adjustments were not required. After all responses, the overall Cronbach's alpha for the RCAT-RI was .93. The reliability table for the instrument and dependent variables is found in Appendix C.

Descriptive statistical data for the research constructs and the individual question responses are shown in Tables 4 and 5, respectively. In Table 4, the reader will note that the mean for the CED is either the same or higher on all constructs and that the standard deviations are all less than one. In Table 5, the reader will observe that the means for the CED are higher on eight questions, while the means for the ID are higher on four questions. The CRT had the lowest means for all questions and constructs.

Table 4.

Descriptive Statistics for Constructs

	CED		ID		CRT	
Construct/Dependent Variable	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Causality	3.41	.62	3.41	.89	3.30	.79
Relationships	3.38	.67	3.24	.67	3.19	.78
Usability	3.37	.69	3.35	.70	2.97	.73
Participation	3.11	.69	3.06	.82	2.99	.83

Quantitative Dependent Variable Findings

The dependent variables consisted of four constructs: causality, relationships, usability, and participation. Each construct was measured using two, three, or four questions on the RCAT-RI. The findings for each of the constructs and questions are presented below.

Causality

As defined in the previous chapters, causality was the perceived ability of the tool to find root causes and the interdependencies between causes. The null hypothesis (H_0) tested was that there is no significant difference in the perceived ability of the cause-and-effect diagram, interrelationship diagram, and current reality tree to identify causality. The following questions were submitted for hypothesis testing of this construct:

Table 5.

Descriptive Statistics for Individual Questions on the RCAT-RI

		CED		ID		CRT	
#	Specific Question	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
1.	Identified Root Cause	3.46	.69	3.35	1.13	3.29	1.00
2.	Identified Causal Interdependencies	3.36	.86	3.47	.87	3.32	.77
3.	Identified Interrelationships	3.22	.89	3.47	.86	3.31	.96
4.	Displayed Intermediate Factors	3.43	.92	3.18	.88	3.33	.95
5.	Identified Cause Categories	3.50	.87	3.06	.99	2.94	1.03
6.	Assesses Logic and Integrity	2.97	.92	3.18	.91	3.10	.89
7.	Facilitated Productive Activity	3.32	.80	3.17	.89	2.99	.91
8.	Difficulty or Ease of Use	3.75	.82	3.78	.83	2.75	.92
9.	Overall Readability	3.43	.95	3.26	1.01	3.07	.91
10.	Stimulated Discussion	3.14	.83	3.08	.93	3.10	.98
11.	Promoted Productive Dialogue	3.14	.70	3.04	.85	3.04	.83
12.	Actively Developed Participation	3.07	.81	3.07	.97	2.82	.95

Question 1. Did the tool identify the root cause(s) of the problem? The data for this question violated the assumption of sphericity and ε was greater than 0.75 so the degrees of freedom were adjusted using Huynh-Felt. However, there was no significant statistical difference between the tool treatments.

Question 2. Did the tool identify interdependencies between causes? Data indicated that the assumption of sphericity was valid, but there was no significant statistical difference between the tool treatments.

Based on the results above, no statistical difference was found among the three tools for causality. Therefore, the null hypothesis (H_0) was retained and there does not appear to be a difference in the perceptions of the participants concerning the ability of the tools to identify causality.

Relationships

Relationships included the perceived ability of the tool to find relationships between factors or categories of factors. The factors might include causes, effects, or both. The null hypothesis (H_0) tested for this construct was that there is no difference in the perceived ability of the cause-and-effect diagram, interrelationship diagram, and current reality tree to identify factor relationships. The following questions were submitted for hypothesis testing of this construct:

Question 3. How well did the tool identify interrelationships between factors (such as causes, effects, and intermediate factors)?

For this question, the results indicated the assumption of sphericity was valid, but there was no significant statistical difference between the treatments.

Question 4. Did the tool display intermediate factors? (Intermediate factors link the root cause(s) with the effect.)

The assumption of sphericity was also valid here, but there was no significant statistical difference between the tools.

Question 5. Based on your experience, how well did the tool identify categories of causes? (Example: equipment, procedures, etc.)

Data indicated that the assumption of sphericity was valid. The data also indicated a significant statistical difference between the tool treatments ($F\,(2, 74) = 7.839, p = .001$). Three post hoc tests were run on significant variables to validate statistical significance: a paired t test, a t test with Bonferroni adjustment, and an omnibus F test. Results of the post hoc tests found that the individual variables remained statistically significant regardless of the type of post hoc test. The paired t test was the most liberal, followed by the omnibus F test, with the Bonferonni t test being the most conservative. The researcher selected the omnibus F test for reporting purposes because it was neither the most conservative nor liberal, and because the main effects for a repeated measures ANOVA are also calculated as F statistics. The comparison of the three post hoc tests is found in Appendix C, Table C9. Thus, a post hoc test using F found that the CED was perceived as statistically better at identifying cause categories than either the CRT ($F\ (1, 71) = 15.754, p < .001$) or the ID ($F\ (1, 71) = 7.520, p = .008$). Effect size was 0.59 and 0.47 respectively, a medium effect. The results are shown in Table 6.

Table 6.

Repeated Measures Analysis of Variance (ANOVA) for Cause Categories

Source/Contrast	*SS*	*df*	*MS*	*F*	*p*	*ES*
Within-Treatments	12.84	2, 74	6.42	7.839	.001	
CED vs. CRT	23.52	1, 71	23.52	15.754	.000	.59
CED vs. ID	13.65	1, 71	13.65	7.520	.008	.47

While the responses to Question 3 about cause categories were significant, the combined responses for all of the relationship questions produced no statistical difference among the three tools. Therefore, the null hypothesis (H_0) was retained and there does not appear to be a difference in the perceptions of the participants concerning the ability of the tools to identify factor relationships.

Usability

Usability was the overall perception of the tool to produce outputs that are logical, productive, usable, and readable. The null hypothesis (H_0) tested for usability was that there is no difference between the cause-and-effect diagram, interrelationship diagram, and current reality tree with regard to perceived usability. The following questions were submitted for hypothesis testing of this construct:

Question 6. Did the tool provide a method for testing the logic and integrity of the process? (This would be a way to verify that the construction of the tool is correct or valid.)

The assumption of sphericity was valid for this question, but there was no significant statistical difference between tools.

Question 7. How well did the tool facilitate productive problem solving activity? For this question, sphericity was valid and data indicated a significant statistical difference between the treatments ($F\,(2, 71) = 3.650, p = .028$). Within-group post hoc tests found that the CED was perceived to be statistically better at facilitating productive problem solving activity than the CRT ($F\,(1, 71) = 9.161, p = .003$). The result was a small-to-medium effect size of 0.38. The results are shown in Table 7.

Table 7.

Repeated Measures Analysis of Variance (ANOVA) for Productive Problem Problem-Solving Activity

Source/Contrast	*SS*	*df*	*MS*	*F*	*p*	*ES*
Within-Treatments	4.01	2, 71	2.01	3.650	.028	
CED vs. CRT	8.00	1, 71	8.00	9.161	.003	.38

Question 8. In your opinion, was using the tool easy or difficult?

Participants responded significantly to this question and indicated that there is a difference between tool treatments for both the CED and ID with respect to the CRT. However, a violation of the assumption of sphericity prompted the use of the Huynh-Feldt corrected estimate ($F\,(1.886, 71) = 38.395, p < .001$). A post hoc comparison revealed a large statistical difference between the CRT and CED (F (1, 71) = 67.263, $p <$ .001, ES = 1.15) as well as between the CRT and ID (F (1, 71) = 45.020, $p <$ .001, ES = 1.18). Thus, the CRT is perceived as being much more difficult than either the CED or ID. The results are shown in Table 8.

Table 8.

Repeated Measures Analysis of Variance (ANOVA) for Ease or Difficulty of Use

Source/Contrast	*SS*	*df*	*MS*	*F*	*p*	*ES*
Within-Treatments	49.37	1.866, 71*	26.46	38.395	.000	
CED vs. CRT	72.00	1, 71	72.00	67.263	.000	1.15
ID vs. CRT	76.06	1, 71	76.06	45.020	.000	1.18

*Huynh-Feldt adjusted *df*

Question 9. What is your perception of the overall readability of the tool when complete?

Participants found the overall readability of the tools to be significantly different (F (2, 71) = 3.480, p = .033). Assuming sphericity, post hoc tests indicated the CED was significantly preferred over the CRT for overall readability (F (1, 71) = 7.697, p = .007) with a small-to-medium effect size of 0.39. The results are shown in Table 9.

Table 9.

Repeated Measures Analysis of Variance (ANOVA) for Readability

Source/Contrast	*SS*	*df*	*MS*	*F*	*p*	*ES*
Within-Treatments	4.70	2, 71	2.35	3.480	.033	
CED vs. CRT	9.39	1, 71	9.39	7.697	.007	.39

As three of the four survey questions on usability had significant differences, the overall usability between the three tool treatment was statistically significant using a Huynh-Feldt corrected estimate (F (1.881, 74) = 9.156, $p < .001$). Post hoc comparisons showed that both the CED (F (1, 74) = 20.144, $p < .001$) and ID (F (1, 74) = 9.333, p = .003) were perceived as more usable than the CRT with medium effects sizes of 0.56 and 0.53, respectively. The overall results for usability are shown in Table 10. Therefore, the null hypothesis (H_0) was rejected. There is a significant difference between the CED, ID, and CRT with regard to perceived usability.

Table 10.

Significant Within-Group Differences for Usability

Source/Contrast	*SS*	*df*	*MS*	*F*	*p*	*ES*
Within-Treatments	6.80	1.881, 74*	3.62	9.156	.000	
CED vs. CRT	11.41	1, 74	11.41	20.144	.000	.56
ID vs. CRT	8.84	1, 74	8.84	9.333	.003	.53

*Huynh-Feldt adjusted *df*

Participation

Participation was the perception among group members that the tool stimulated discussion, productive dialogue, and active participation during the process. The null hypothesis (H_0) tested was that there is no difference between the cause-and-effect diagram, interrelationship diagram, and current reality tree with regard to perceived participation. The following questions were submitted for hypothesis testing of this construct:

Question 10. How much did the tool stimulate discussion between participants? Data for this question violated the assumption of sphericity and ε was greater than 0.75

so the degrees of freedom were adjusted using Huynh-Felt. However, there was no significant statistical difference between the tool treatments.

Question 11. To what degree did the tool promote productive dialogue among participants?

The responses to this question also violated the sphericity assumption and were corrected using Huynh-Felt. Nonetheless, there was no significant statistical difference between the treatments.

Question 12. Did the tool actively develop participation?

The assumption of sphericity was valid for this question, but there was no significant statistical difference between the treatments.

Based on the above, no statistical difference was found among the three tools for participation. Therefore, the null hypothesis (H_0) was retained and there is no difference in perceptions regarding discussion, dialogue, and active participation.

Summary of Statistical Findings

As shown previously in Table 10, the only construct of statistical significance was usability. The statistical results were primarily due to significant differences on three of the four questions for this construct. A significant and medium effect was found to exist between both the CED ($F(1, 74) = 20.144, p < .001$) and the ID ($F(1, 74) = 9.333, p = .003$) compared to the CRT. This difference was driven by a large effect size between the CRT and the other tools in response to Question 8, ease or difficulty of use. The CRT was deemed much more difficult than the other two tools. Thus, the null hypothesis (H_0) was rejected for usability and retained for causality, relationships, and participation. The other significant statistical finding was that the CED was perceived as better at identifying cause categories than either the ID or CRT. However, this finding did not change the participants' overall perception of the ability of the tool to find factor relationships. The detailed tables for individual questions and comparisons are found in Appendix C, Tables C1 and C2.

Process Times and Qualitative Findings

The secondary interests of the study were to determine the average process times for constructing each tool, the types of questions or statements raised by participants, and the nature of the tool outputs generated. This section is divided into three subsections: process times, participant responses, and researcher observations. The participant responses were taken from an open-ended question on the RCAT-RI. The observations were made by the trained treatment facilitators during each group session. The observations include questions or comments made by the participants during the sessions, a general characterization of the treatment process, and a qualitative evaluation of the tool output.

Process Times

The process times for each tool in each group session is shown in Table 11. The mean times for the CED, ID, and CRT were 26 minutes, 26 minutes, and 30 minutes, respectively. The CED had the smallest standard deviation at 5.59 and the CRT had the largest standard deviation at 9.47. The standard deviation for the ID was 8.94. Thus, the CRT took the longest amount of time to complete with greatest variability. The CED and ID were near equal for process time, but the CED had much less variability while the variability of the ID was closer to that of the CRT.

Qualitative Findings: Participant Responses

Participant responses were captured using a single open-ended question at the end of the RCAT-RI. Participants were asked to write additional comments about the tool, procedure, or experience. Comments received were generally about the groups, the process, or the tools. The complete list of participant responses and comments is found in Appendix D. Comments received about the groups were typically about either group size or the amount of participation. Comments received about the process were typically complaints or comments about the tools and were generally either positive or negative depending on the participant's experience. Comments about the CED and ID were either favorable or ambiguous. Most of the comments made about the CRT concerned its degree of difficulty.

Qualitative Findings: Researcher Observations

During each session, the treatment facilitators captured the types of questions raised by participants during the sessions and made specific observations about the group process. The list of detailed questions and observations is found in Appendix D. The researcher sorted the questions and observations by searching for key words in context to discover any emergent themes or categories. This qualitative sorting resulted in the questions falling into one of three categorical types: process, construction, or root cause. The observations were also sorted into the same three categories and a fourth category called group dynamics.

The types of questions raised by participants tended to be different depending on the root cause analysis tool used. Questions raised during the development of the CED were about the categories and if multiple root causes could be identified. Questions about the ID were primarily about the direction of the arrows. Questions during CRT development were the most varied, but were generally about the tool process or construction. CRT questions ranged from asking about how to start the construction of the tool to inquiries about CRT-specific conventions such as the "and" connector, ellipse, UDEs, CLRs, and intermediate factors. Even though participants were instructed to find the perceived root cause, a common question from participants among all three tools was whether their assignment was to find a root cause or to determine a solution to the problem.

Table 11.

Process Times

Group	Section 1	Min.	Section 2	Min.	Section 3	Min.	*Mean*	*SD*
M_1								
1	CED	23	CED	33	CED	22	26	6.08
2	ID	20	ID	43	ID	16	26	14.57
3	CRT	24	CRT	25	CRT	36	28	6.66
M_2								
1	CRT	45	CRT	40	CRT	27	37	9.29
2	CED	33	CED	25	CED	24	27	4.93
3	ID	37	ID	23	ID	27	29	7.21
M_3								
1	ID	25	ID	25	ID	17	22	4.62
2	CRT	21	CRT	17	CRT	36	25	10.02
3	CED	33	CED	23	CED	18	25	7.64

Grand Means and Standard Deviations

	Section 1		Section 2		Section 3		Tools		
Group	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*		*Mean*	*SD*
1	31	12.17	33	7.51	22	5.00	CED	26	5.59
2	25	7.23	28	13.32	25	10.07	ID	26	8.94
3	31	6.66	24	1.15	27	9.00	CRT	30	9.47

Each treatment facilitator answered participant questions, observed each group's process, and made qualitative assessments of the session. Most facilitator observations were about group dynamics or the overall process. Typical facilitator comments about group dynamics were the degree of participation or leadership roles. Approximately one-quarter of the process observations concerned the participants' confusion over finding causes or solutions to the problem. Overall, the types of observations made by the facilitators were relatively consistent regardless of the tool used, except for the CRT. The observations for the CRT were different in that there were no root cause observations and the construction observations were much higher than for the other tools.

The researcher critically evaluated the construction of each group's treatment output using several methods. For the ID and CRT, the researcher counted the number of entities/factors and the number of connections or arrows between them. For the CED, the researcher counted the number of major categories and detailed causes. The tool outputs were also qualitatively evaluated for accuracy, root cause, and integrity of the root cause. This qualitative evaluation was based on the criteria defined below:

1. *Technical accuracy*. This was the level of constructed accuracy of the tool output based on the written instructions. The researcher looked for characteristics that indicated the correct construction of the tool. Characteristics evaluated were (1) directionality of the cause and effect relationships; i.e., Did arrows point from cause to effect? (2) specificity of the factors; i.e., Were the factors clear and specific? (3) format; i.e., Did the output resemble or was it recognizable as the assigned tool? and (4) use of conventions; i.e., Were symbols, lines, and devices correctly used? If all the above characteristics for technical accuracy were met, a rating of high was assigned. If more than one, but less than all of the above characteristics were

met, a rating of medium was assigned. If none of the characteristics was met, a rating of low was assigned.

2. *Root cause identification*. This was whether the group, through some means, either visually or verbally, identified a root cause or causes on the tool output. A "yes" for this criterion indicated the group was able to identify a root cause. A "no" indicated the group was not able to identify a root cause. The groups that were unable to identify a root cause either disagreed about the root cause or indicated to the facilitator that a root cause could not be found.

3. *Integrity of identified root cause(s)*. This was the specificity and reasonableness of the root cause identified. If the group could not identify a root cause as in the example above, a rating of low was assigned. If the group selected a root cause, but the cause was not specific enough to act on, a test of reasonableness was made. An example of lack of specificity would be if the group identified the root cause as "the organization" or as "management." While this root cause might be technically accurate, it would be impossible to correct without further analysis. Reasonableness was defined such that someone not familiar with the process would state that the root cause seemed rational or within the bounds of common sense. An example of lack of reasonableness would be if the group identified the root cause as an emotion or as a factor that, after examination, could not be logically associated with the problem. If the root cause or causes met the criteria of both reasonableness and specificity, a rating of high was assigned. If the root cause met either reasonableness or specificity, but not both, a rating of medium was assigned. If the root cause met neither reasonableness nor specificity, and rating of low was assigned.

A summary of the questions, observations, and tool output evaluations is shown in Table 12. The specific researcher evaluations of each group session and tool output are found in Appendix D with specific participant questions and facilitator observations. These specific findings are also detailed in Appendix D, Tables D2 through D5.

Summary of Qualitative Findings

A quantitative analysis of the summary data yielded some interesting findings. First, the technical accuracy of both the CED and the ID were high in eight out of the nine outputs, whereas the technical accuracy of the CRT was mixed. However, groups using the CED were able to identify a specific root cause only two times. The groups using the ID faired better, identifying a root cause eight out of nine times.

Table 12.

Summary of Questions, Observations, and Tool Outputs

	Output Evaluations			Questions and Observations			
Tool	Technical Accuracy	Root Cause?	Integrity of Root Cause	Process	Root Cause	Construction	Group Dynamics
CED	1M, 8H	2Y, 7N	8L, 1H	17	11	11	17
ID	1M, 8H	8Y, 1N	3L, 4M, 2H	14	5	16	22
CRT	3L, 2M, 4H	8Y, 1N	2L, 2M, 5H	23	1	19	22

H = High, M = Medium, L = Low
Y = Yes, N = No

Because groups using the CED could not identify a specific root cause, the integrity of their selections also suffered. Only one CED group found a root cause that was both specific and reasonable. While the ID groups found a root cause most of the time, the integrity of their selected root causes was mixed. In contrast, the CRT groups found a root cause in eight out of nine outputs and their integrity was high in over half the cases. In addition, the CRT groups were able to do this using about half of the factors and connections as compared to the other tools. The number of factors and connections constructed for each tool is shown in Table D1, Appendix D.

Second, the number of root cause questions and observations for the CED was twice as high as the ID and ten times greater than the CRT. The CRT generated more process and construction questions/observations than the ID or CED. In summary, the CED produced the greatest amount of questions and discussion about root causes, whereas the CRT produced the greatest amount of questions and discussion about process and construction. In comparison, the ID and CED produced about the same number of process and construction questions/observations.

CHAPTER 5: DISCUSSION

This chapter will interpret the data findings from the previous chapter, draw conclusions, address potential policy implications, and critically analyze the emergent limitations of this study while making recommendations for future research. First, the chapter interprets the statistical findings and draws conclusions based upon the literature. Second, the chapter explores the potential meanings of the qualitative findings. Third, the implications of this research for use in the business and academic community are presented. Finally, a review of this study's shortcomings along with recommendations for future research completes the chapter.

Interpretation and Conclusion of the Statistical Findings

The results of this research indicate that there is no perceived difference in the three root cause analysis tools with respect to causality, factor relationships, or participation. For these three constructs, the null hypothesis (H_0) tested should be retained. However, the results of the research also indicate that there is a significant perceived difference in the tools with regard to usability. Therefore, the null hypothesis (H_0) for usability should be rejected and the alternate hypothesis (H_1) accepted. The reader will recall that usability was measured using four questions about the ability of the tool to produce logical, productive, usable, and readable outputs.

The CED was specifically perceived by participants as better than the CRT at facilitating productive problem solving activity, being easier to use, and more readable. Interestingly, the readability perception refutes Mitchell's (1997) findings that the CED is *less* readable than the CRT. The ID was perceived better than the CRT for being easier to use only. Concurrently, none of the tools was perceived as being significantly better for assessing the logic and integrity of the outputs. It is striking to note that while CED participants perceived themselves as engaging in productive activity, they could not perceive that the tool had better mechanisms for validating the correctness of their analysis efforts. The ID was different only in ease-of-use, but the perception of the ID for productive activity or readability was no different from any of the other tools. Also, the lack of perceived difference in the ID with regard to finding factor relationships is surprising because this characteristic is supposed to be a defining feature of the tool.

One might conclude from this that the CRT had no merit because both the CED and ID were considered more usable. However, in the literature, several authors criticize the CED and other simple analysis methods like the ID because they tend to be influenced by group emotions and are thought to be incapable of addressing complex systemic problems. The fact that participants selected the CED supports the claim that people will choose this method because it fits their perception of a simple analysis tool (Pasquarella et al., 1997). The participant's responses also support Anderson and Fagerhaug's (2000) claim that the CED is an easily applied tool for analyzing *possible* causes to a problem. However, a lingering question remains--if a tool is easy to use, is it also capable of finding root causes (not just possible causes), especially if the integrity of the root causes cannot be verified? Considering the effect sizes, participants defined usability depending on whether the tool was easy or difficult to use. The important difference for usability was the fact that the CRT was perceived by participants as too complex and that it did not fit their definition of a user-friendly analysis method.

The CED was also identified as being statistically better at identifying cause categories than either the ID or CRT. This finding supports Ishikawa's (1982) original description for the CED--as a method for sorting potential causes into major and minor categories. Thus, this result is not surprising. Ishikawa also thought that factors on the CED could be related by problem solving groups, but the results of the study did not support this. Ishikawa's primary aim for the CED was to get results towards the solution of a problem. As such, he never claimed the tool would identify root causes. Rather, he claimed that it would drive groups to establish relationships between the cause and effect of a problem. In this study, the groups had difficulty relating the factors using *any* of the tools. Consequently, the results add very little to what was already known about the CED.

In contrast, this study suggests that the ID is another simple, easy-to-use alternative for root cause analysis. While it was not judged as being either better for productive problem solving activity, overall readability, or testing logic, it was at least as good as the CED for ease of use. The data also support that the ID, because of the way its connections are counted, leads groups to more specific root causes in about the same amount time as the CED. Regardless, it is speculation to claim that the ID is more effective than the CED until this can be affirmed statistically under various conditions with various types of groups. What is known now that was not known previously is that the ID is statistically comparable to the CED in terms of ease of use and practitioners should consider it as a viable alternative for simple root cause analysis.

This study supported the literature in that the CED is an easy-to-use tool to classify and categorize causes, but not necessarily the relationships between the causes. This study did not support the literature regarding the CED's readability, the ability of the ID to identify and clarify interrelationships between factors, and the ability of the CRT to find causal interdependencies. In summary, do the statistical findings indicate that the CRT is not a suitable tool for root cause analysis? This study neither supports nor refutes the value of the CRT other than to verify that it is, in fact, a more complex method. Again, this is not surprising given the amount of detailed literature about its process and construction.

From a practitioner's perspective, this research raises more questions because none of the tools was statistically different in finding causality or identifying factor relationships. Authors and scholars can reasonably argue that a basic requirement for root cause analysis is to be able to identify root causes and cause-effect relationships. It is the position of the researcher that until this basic requirement can be measured, one cannot definitively claim the superiority of one analysis method over another. It is not a great leap of abstraction to say that some tools are easier to use than others, but finding root causes still appears to be an elusive measure subject to circumstance, emotion, and personal interpretation.

Interpretation and Conclusion of the Qualitative Findings

The secondary interests of the study were to determine the average process times for each tool, the types of questions or statements raised by participants during and after the process, and the nature of the tool outputs generated. This study supports the literature that the CRT requires less factors and connections for construction. The process times for this study support the literature such that the CRT did take longer, on average, to construct than the CED. Since there was no previous research on process time for the ID, the reader now knows that the ID was near equal to the CED for construction time. However, both the ID and CRT times were highly variable with times ranging from approximately 20 to 40 minutes.

It is postulated that the difference in average process time was due to the relative construction complexity of the CRT. Nonetheless, this does not explain its high process time variability. If one reviews each session, the overall variability of the ID improved over time while the overall variability of the CRT deteriorated. If any conclusion can be reached from this, it is perhaps that as groups gain experience, the learning curve for the ID becomes less. Still, this does not explain why process time variability increased on the CRT. Perhaps experience is detrimental to the CRT because it uses a different logic system. The CRT process starts by identifying effects (UDEs) and moves to causes, whereas the CED and ID processes start by identifying potential causes.

The participants' questions and statements show that the complexity of the CRT was a major source of frustration during the study. Participants used words such as *difficult*, *confusing*, and *hard* to describe the CRT. In comparison, participants used words such as *easy*, *good*, and *best* to describe both the CED and ID.

Most of the questions raised during CRT sessions were about its process or construction. Participants wanted to know how the symbols and conventions of the CRT were constructed and how the categories of legitimate reservation (CLRs) supported the process. Specific observations indicate that more extensive facilitator intervention was required in the CRT process than on the other tools. Facilitators had to intervene more often because the groups had more difficulty building the CRT without making construction errors or process mistakes. This finding refutes Fredendall et al. (2002) claim that the CRT requires less facilitation than the CED because the CRT is more mechanical to construct.

Most interestingly, in spite of difficulties, groups using the CRT were able to identify a specific and reasonable root cause over half the time as compared to the CED and ID. This was one of the distinguishing findings of the study. For the CED and ID, groups identified specific and reasonable root causes only once and twice, respectively. This difficulty in finding root causes was verified by the number of questions asked by participants during CED construction. They kept asking for guidance on how to find root causes because they could not find a root cause easily using the CED. With the ID, groups were able to identify root causes, but only because ID construction requires a count of incoming and outgoing arrows. By simply looking at the ID factor with the most outgoing arrows, most groups declared that a root cause had been found and stopped any further any critical analysis.

So why were the participants unable to recognize the difference between the three tools with respect to the quality of their root causes? First, because the participants were asked only to identify a root cause, not a root cause that was reasonable and specific enough to be acted upon. Second, if participants thought they were making progress towards finding a root cause (i.e., constructing the tool per the instructions and agreeing on a root cause) they gave little thought towards critically analyzing their decision-making process.

Nothing undermines critical analysis more surely than certainty. This phenomenon was also described by Khaimovich (1999) in a study where problem solving groups were reluctant to scrutinize the validity of their models. They settled and were content with their original ideas. Once participants felt they had an answer, all motivation to question their own thinking disappeared. Third, because people tend to dislike confrontation and conflict, most of the groups avoided creating the tension that might have produced better results. To quote Senge (1990), "Great teams are not characterized by an absence of conflict. On the contrary, one of the most reliable indicators of a team that is continually learning is the visible conflict of ideas" (p. 249). Although the majority of the CRT groups were uncomfortable during the process, the quality of their outputs was better. The groups that successfully used the CLRs were able to build chains of logic and pinpoint a root cause. Their outputs support the literature in this regard. Conversely, their responses to questions on the instrument reflected their frustration of learning a difficult tool while analyzing a problem at the same time. As per Fredendall et al. (2002), the groups found the strict application of the CRT logic intimidating and rated the tool accordingly.

The groups were not able to sufficiently differentiate tool causality or factor relationships because they were (1) learning the tools for the first time, (2) emotionally involved in the group process, or (3) engaging in what Scholtes (1988) called the "rush to accomplishment." Each of these factors prevented group members from thoroughly evaluating their progress. Because many participants were learning and doing, they did not have time to assess or reflect on the meaning of each tool and logically think about what was happening. Their reflection was also impaired by the emotionally laden group processes. To think, act, and interact effectively is difficult with peers. This difficulty was probably accentuated by a Hawthorne Effect of the treatment facilitators watching and taking notes. Finally, participants were instructed to work on the problem scenario until they had identified a root cause. This created goal-specific behavior, which in some groups was manifested by the need to achieve that goal as quickly as possible.

Implications for Future Policy and Practice

Because the tools differed greatly in degree of difficulty and integrity, there are several implications for ensuring their effective use in future practice. First, the type and amount of training needed for each tool varies. This study supports the literature that the CED and ID can be used with little formal training, but the CRT requires comprehensive instruction because of its logic system and complexity. However, in contrast to the literature, the CED and ID both appear to need some type of supplemental instruction in critical evaluation and decision making methods. The CRT incorporates that evaluation system using the CLRs, but the CED and ID have no such mechanism and are highly dependent on the thoroughness of the group using them. Therefore, training for the CED and ID should include some type of structured mechanism for assessing the logic and integrity of group decisions. If groups actively use evaluation mechanisms during the process, the results are generally better. This was true for the CRT. Nonetheless, some of the groups chose to ignore the CLRs and their results were mixed.

Second, serious practitioners should strongly consider using facilitators during root cause analysis. The facilitators should be familiar with the specific tool being used.

The CRT should definitely not be used unless facilitated by someone familiar with its mechanics, construction, and rigor. For the CED and ID, a critical evaluation of identified root causes is most important. For all three tools, the facilitator needs to be capable of recognizing when the group is off-track, rushing the process, or becoming socially dysfunctional.

During this study, observations indicated that most of the groups had a few individuals who either dominated or led the process. In the groups where leadership took place, individual contributions were carefully considered with a mix of discussion and inquiry. Group leaders did not attempt to convince others of their superior expertise or content knowledge and conflicts were not considered threatening. In contrast, the dominated groups did not ask for or encourage discussion and differences of opinion were viewed as disruptive. For these types of situations, the challenge for the facilitator is to be able to distinguish between behaviors that help or hinder the analysis. The facilitator's primary role should be to help the group maintain ownership of the process and outcome without becoming a "rescuer." He or she must encourage group members to raise difficult and potentially conflicting viewpoints so that the best ideas can emerge.

Third, these tools cannot be used to their greatest potential without repeated practice. Like other developed skills, the more groups use the tools, the better they become with them and the more value can be extracted. Yet, current protocol is that groups rarely have opportunities to practice using analysis skills together for any extended period. For many participants in this study, this was the first time they had used a root cause analysis tool. Indeed, for some, it was their first experience with *any* structured group decision-making method. Their experience, participation, and observations created insights that could be transferred to other analysis activities simply with repeated practice.

The complexity of today's business and educational issues require approaches that are more sophisticated. Brainstorming generates only the most obvious causes or solutions. Just as the professional athlete or classical musician needs repetition and practice to achieve peak performance, teams need repeated skill development to find the causes of recurring problems. Regardless, a popular view is that if enough minds are put to the task, an answer will be found, sometimes sooner, usually later. Bhote (1988) criticized unstructured processes because they put too much emphasis on opinions, take too long, and don't produce lasting results. Leaders need to establish standards and policies for training, facilitation, and practice with organizational problem solving groups. The alternative is to continue to assume that existing efforts will somehow produce different results. A policy of assuming that groups can work together on a problem without standards, structure, or critical evaluation is a policy doomed to fail.

Discussion and Recommendations

This study attempted to focus on the application of root cause analysis rather than group dynamics. As one might imagine, this was difficult because the impact that human beings have on their surroundings and each other is extremely strong. Throughout the data collection process, the social component of working groups was evident and influential. Both the positive and negative effects of human interaction on the process were conspicuous in the participants' comments and the facilitators' observations. In any case, this was not a study about human factors; it was about human perceptions.

Emergent Limitations of the Research Design

One of the shortcomings of this study was that by measuring perceptions, the importance of group effectiveness on the analysis process was probably overemphasized and the tools underplayed. Human interaction in problem solving groups is a double-edged sword because participant's reactions are often influenced by past experience, recent conversations, and level of motivation. Teams that use dialogue and discussion effectively within a supportive context might overcome the restrictions of a mediocre tool, but even the best analytical tool cannot turn a mediocre team into a great problem solving group. However, this was not the intent of this research. The limitation was an inability to isolate the tools from the users themselves.

This inseparability of the tool from the participant is a classic example of aptitude-treatment interaction (ATI) as identified by Cronbach (1957). Aptitude is generally defined as any personal characteristic that affects a participant's response to the treatment. In this study, the nested nature of the human factors with the treatment factors (or vice versa) resulted in complex interactions between the measurement constructs. As the reader will recall from Chapter 3, an initial factor analysis showed a potential relationship between participation and causality. Subsequent correlation, analysis of covariance, and regression models verified that, in fact, all the constructs were marked by various degrees of confounding interactions and co-linearity (see Tables C3 through C6 in Appendix C). As such, the results about the treatment effects are misleading because they are potentially dependent on other factors yet to be defined. Cronbach (1975) argued that, "An ATI result can be taken as a general conclusion only if it is not in turn moderated by further variables," which if attended to, lead the researcher to "enter a hall of mirrors that extends to infinity" (p. 119). In this study, the interactions between the participants and the treatments swamped the generalized effect of a specified tool.

Another limitation of the design was the differing degrees of motivation among the participants. For this study, all the participants took part voluntarily, but not necessarily willingly. Just like other groups in business or industry, they were asked to be a part of an effort that may or may not have been meaningful to them. Unlike business or industry, there were no consequences for lack of participation or cooperation. Their class standing was not adversely affected if they chose not to attend the sessions. Unlike real problem solving groups, these participants knew the problem scenarios were fictitious. There was no penalty, loss of prestige, or inquiry into personal competence for selecting a questionable root cause. In addition, the groups did not have any emotional stake in the problem. Collectively, these factors may have affected their effort, interaction, motivation, responses, and quality of output.

Recommendations for Future Research

Because of the strong effect that participants have on root cause analysis outcomes, future research needs to consider ways of further isolating the human component from the methodology component. This might be accomplished through an analysis of covariance (ANCOVA) design using informal group leadership as a covariate. As observed, the degree of group openness to discussion and dialogue appeared to have some influence on the integrity of outcomes and the degree of group openness appeared to be related to the informal leadership style. An ANCOVA study would address the intentional or unintentional impact of a person (or group of people) has on the problem-solving process and partial out those effects. Other potential covariates might include the participant's perceptions of group effectiveness, individual motivation, and previous analysis experience. Any factor that might correlate strongly with the performance of a root cause analysis tool in finding a logical and specific root cause is a potential covariate. Because of the nested nature of these ATIs, one might consider the use of structural equation modeling. However, unless the researcher can specifically define the factors (which potentially extend to infinity) and their relationships with each other, this would likely be an exercise in futility.

Another fair conclusion is that the participants were too close emotionally to the process to be able to give accurate and unbiased accounts of their experience or the results. Consequently, a research design that uses multiple observations from multiple raters has merit. This approach would assume that participants are not capable of making dispassionate judgments about their perceptions or the activity itself. Just as Deming (1993) believed that a system cannot understand itself and needs an outside view; so too would analyses groups need an outside perspective in order to gain an understanding of their methods. Multiple raters and observations would offset some of the noise introduced by group dynamics and other human factors. The challenge of this type of design would be to establish a reliable interval rating system for process dynamics and tool outputs.

Still another approach would be to design an associative study that measures the influence of human factors against tool outputs or explores how group factors such as leadership style, group size, and individual experience relate to the frequency of root cause discoveries. Of course, an associative design could also relate various tool attributes such as the number of potential causes listed and the length of cause descriptions to the frequency of root causes as well. An important consideration for future research is the degree to which participants or observers are involved in the measurement of root cause analysis. Both measurement methods are subject to bias depending on the design.

Discussion and Conclusion

The intent of this research was to be able to identify the best tool for root cause analysis. This study was not able to identify that tool. However, greater insight was gained into the characteristics that make certain tools better under certain conditions. Practitioners can appreciate that the CED is an easy tool for identifying many potential causes and productively getting the causes into readable categories. As such, this tool is good for beginning problem solving groups who do not have much experience or time working together. The ID is another easy tool for identifying the suspected causes of a problem and showing the potential relationships between them. The ID has a mechanism for isolating potential root causes, but is subject to errors of reason depending on the group dynamic. However, it is a good tool for more experienced groups that have developed sound ground rules for evaluation and decision making.

Finally, the CRT is a difficult tool that should be used only with advanced groups working on complex problems. The CRT has the evaluative mechanism built in, but needs a facilitator to ensure the integrity of its process and construction. For any of these tools, finding the root cause seems to be related to the group's familiarity with the problem and how effectively they can work together to test their assumptions.

A large portion of this study revolved around issues of actual versus perceived characteristics. Future research in this area will struggle with how to capture and test what people say about the tools versus how the tools are actually performing both during and after the process. Groups may claim usefulness, but is the output useful? Groups may struggle with construction and conflict, but does the output or experience offer opportunities for growth and higher levels of thinking? Each group put its own personality into the effort such that each tool output was different in some aspect. With such varied results, can a researcher find a single root cause analysis tool that works better under all conditions? Perhaps the answer lies in the interaction between the participants and the tool. The value may not rest on the actual result as much as it does on the process. This is because the process has the potential of developing new ways of thinking. While the quantitative researcher is likely to become frustrated in the pursuit of measuring thoughts, the qualitative researcher would likely have sufficient material for a comprehensive emergent analysis. The most interesting study is the psychological perspective of how people think and articulate their basic assumptions during group settings. The tools are simply a starting mechanism for how groups interact and react in problem solving or decision-making situations.

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APPENDIX A: GLOSSARY OF TERMS

Glossary of Terms

Business process reengineering (BPR): A procedure that involves the fundamental rethinking and radical redesign of business processes to achieve dramatic organizational improvements in such critical measures of performance as cost, quality, service, and speed. Any BPR activity is distinguished by its emphasis on (1) process rather than functions or products, and (2) the customers for the processes (Cox et al., 1995, p. 10).

Just-in-Time (JIT): A philosophy of manufacturing based on planned elimination of all waste and continuous improvement. It encompasses the successful execution of all manufacturing activities required to produce a final product, from design engineering to delivery and including all stages of conversion from raw material onward. The primary elements of JIT are to have only the required inventory when needed; to improve quality to zero defects; to reduce lead times by reducing set-up times, queue lengths, and lot sizes; to incrementally revise the operations themselves; and to accomplish these things at minimum cost. In the broadest sense, it applies to all forms of manufacturing, job shop, and process, as well as repetitive. It is also known as short-cycle manufacturing, stockless production, and zero inventories (Cox et al., 1995, p. 42).

Kanban: A method of Just-in-Time production that uses standard containers or lot sizes with a single card attached to each. It is a pull system in which work centers signal using a card that they wish to withdraw parts from feeding operations or suppliers. The Japanese word *kanban*, loosely translated, means *card*, *billboard*, or *sign*. The term is often used synonymously for the specific scheduling system developed and used by the Toyota Corporation in Japan. It is also known as moved card or production card (Cox et al., 1995, p. 42).

Nominal group technique (NGT): A technique, similar to brainstorming, used by teams to generate ideas on a particular subject. Team members are asked to come up with as many ideas as possible silently, writing them down. Each member is then asked to share one idea, which is recorded. After all the ideas are recorded, they are discussed and prioritized by the group (Cox et al., 1995, p. 53).

Scientific method: Principles and procedures for the systematic pursuit of knowledge involving the recognition and formulation of a problem, the collection of data through observation and experiment, and the formulation and testing of hypotheses (*Webster's New Collegiate Dictionary*, 1983, p. 1051).

Seven management and planning (7MP) tools: Also known as the seven new quality control tools. They were developed by the statistical resource committee of GOAL/QPC to assist managers in planning and problem solving activities. The tools are the affinity diagram, interrelationship diagram, tree diagram, prioritization matrices, matrix diagram, process decision program chart, and activity network diagram (Brassard, 1996).

Seven quality control (7QC) tools: Tools that help organizations understand their process in order to improve them. The tools are the cause-and-effect diagram, check sheet, control chart, flowchart, histogram, Pareto chart, and scatter chart (Cox et al., 1995, p. 78).

Statistical process control (SPC): The application of statistical techniques to monitor and adjust an operation. Often, the term statistical process control is used interchangeably with statistical quality control (Cox et al., 1995, p. 81).

System: A regularly interacting or interdependent group of items forming a unified whole toward the achievement of a goal (Cox et al., 1995, p. 84).

Theory of constraints (TOC): A management philosophy developed by Dr. Eli M. Goldratt that can be viewed as three separate but interrelated areas: logistics, performance measurement, and logical thinking. Logistics include drum-buffer-rope scheduling, buffer management, and VAT analysis. Performance measurement includes throughput, inventory and operating expense, and the five focusing steps. It is also known as constraints management or constraints theory (Cox et al., 1995, p. 85).

Thinking process (TP) tools: Tools developed by Dr. Eli M. Goldratt for generic problem solving and for implementing TOC. The tools are used for identifying the root problem (current reality tree), identifying and expanding win-win solutions (evaporating cloud and future reality tree), and developing implementation plans (prerequisite tree and transition tree) (Cox et al., 1995, p. 85).

Total quality management (TQM): A term coined to describe Japanese-style management approaches to quality improvement. A management approach to long-term success through customer satisfaction and the participation of all members of an organization in improving processes, products, services, and the culture they work in. The methods for implementing this approach are found in the teachings of quality leaders such as Philip B. Crosby, W. Edwards Deming, Armand V. Feigenbaum, Kaoru Ishikawa, and J. M. Juran (Cox et al., 1995, p. 86-87)

APPENDIX B: INSTRUMENT, INSTRUCTIONAL MATERIAL, AND PROBLEM SCENARIOS

Root Cause Analysis Tool Rating Instrument

YOUR REFERENCE CODE __________

NAME OF TOOL ____________________________________

Based on your experience with this particular tool, rate the tool in terms of how well it did the following:

1. Did the tool identify the root cause(s) of the problem? Remember that the root cause is the core or ultimate cause of the problem. (Circle the number that best describes your perception with 5 being the highest rating.)

DID NOT IDENTIFY MAYBE FAIR HIGH IDENTIFIED CLEARLY
-------1---------------------2-------------------3------------------4----------------------5-------

2. Did the tool identify interdependencies between causes? Keep in mind that interdependent causal factors interact with each other to create the effect. (Circle the number.)

DID NOT IDENTIFY MAYBE FAIR HIGH IDENTIFIED CLEARLY
-------1--------------------2-------------------3-------------------4----------------------5-------

3. How well did the tool identify interrelationships between factors? (Interrelationships between factors might include causes, effects, and intermediate factors.)

DID NOT IDENTIFY MAYBE FAIR HIGH IDENTIFIED CLEARLY
-------1------------------2--------------------3-------------------4----------------------5-------

4. Did the tool display intermediate factors? Intermediate factors link the root cause(s) with the effect.

DID NOT DISPLAY MAYBE FAIR HIGH DISPLAYED CLEARLY
--------1-----------------2-------------------3---------------------4--------------------5--------

5. Based on your experience, how well did the tool identify categories of causes? (Example: equipment, procedures, etc.).

DID NOT IDENTIFY MAYBE FAIR HIGH IDENTIFIED CLEARLY
--------1-----------------2-------------------3---------------------4--------------------5--------

6. Did the tool provide a method for testing the logic and integrity of the process? (This would be a way to verify that the construction of the tool is correct or valid.)

NO METHOD SOME METHODS FAIR METHODS GOOD METHODS VERY GOOD METHODS
--------1-----------------2-------------------3---------------------4--------------------5--------

7. How well did the tool facilitate productive problem solving activity?

NOT PRODUCTIVE	SOMEWHAT PRODUCTIVE	FAIRLY PRODUCTIVE	HIGHLY PRODUCTIVE	VERY HIGHLY PRODUCTIVE
1	2	3	4	5

8. In your opinion, was using the tool easy or difficult?

VERY DIFFICULT	DIFFICULT	SOME EFFORT	EASY	VERY EASY
1	2	3	4	5

9. What is your perception of the overall readability of the tool when complete?

NOT READABLE	SOMEWHAT READABLE	MEDIUM READABLE	HIGHLY READABLE	VERY HIGHLY READABLE
1	2	3	4	5

10. How much did the tool stimulate discussion between participants?

DID NOT STIMULATE DISCUSSION	STIMULATED SOME DISCUSSION	FAIR AMOUNT OF DISCUSSION	HIGH AMOUNT OF DISCUSSION	VERY MUCH DISCUSSION
1	2	3	4	5

11. To what degree did the tool promote productive dialogue among participants?

DID NOT PROMOTE PRODUCTIVE DIALOGUE	PROMOTED SOME PRODUCTIVE DIALOGUE	FAIR AMOUNT OF PRODUCTIVE DIALOGUE	HIGH AMOUNT OF PRODUCTIVE DIALOGUE	VERY MUCH PRODUCTIVE DIALOGUE
1	2	3	4	5

12. Did the tool actively develop participation?

DID NOT DEVELOP PARTICIPATION	DEVELOPED SOME PARTICIPATION	DEVELOPED FAIR PARTICIPATION	DEVELOPED HIGH PARTICIPATION	DEVELOPED VERY MUCH PARTICIPATION
1	2	3	4	5

Please write any additional comments about the tool, procedure, or experience:

Definitions

ASSESSMENT OF LOGIC AND INTEGRITY: The ability to assess the validity of the logic used to construct the tool. A mechanism for verifying the integrity of the results.

CATEGORIES OF CAUSES: Major reasons for causes (e.g., machines, methods, etc.) that may include causes that are more detailed.

CAUSE (CAUSAL FACTOR): A reason for an action or condition. Something that brings about an effect or a result.

EFFECT: Something that follows or is produced by a cause.

INTERDEPENDENCIES BETWEEN CAUSAL FACTORS (OR CAUSAL FACTORS): The interaction of causal factors with each other that result in an effect. Two or more causes that work together to produce an effect.

INTERMEDIATE FACTORS: Factors that link root causes with the effects of the problem.

INTERRELATIONSHIPS BETWEEN FACTORS: Linkages or relationships between factors regardless of whether they are causes, effects, or intermediate factors.

PRODUCTIVE PROBLEM-SOLVING ACTIVITY: The amount of activity that was directly related to describing, identifying, understanding, and analyzing the problem.

READABILITY: The ability to be read and understood. The readableness or legibility of the tool.

ROOT CAUSE: An original, core, or basic cause of a problem.

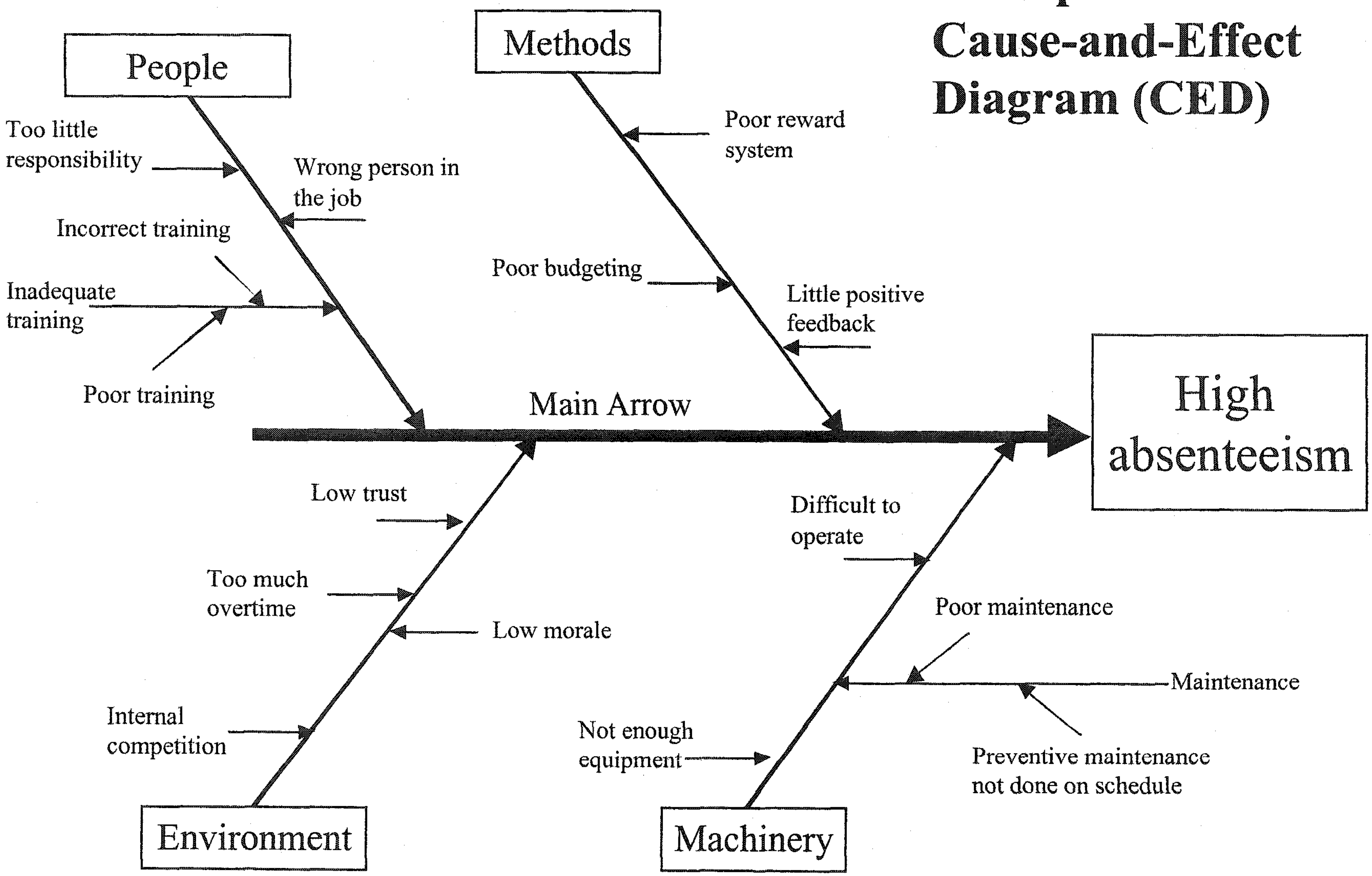
THE STEPS FOR CONSTRUCTING A CAUSE-AND-EFFECT DIAGRAM (CED)

1. From the scenario you just read, as a group decide on the problem to be improved or controlled.
2. Using a whiteboard or flip chart paper, write the problem in a rectangle on the right side and draw a main arrow from the left side pointing to the problem rectangle on the right side.
3. Write the main factors that may be causing the problem by drawing branch arrows to the main arrow. Major causal factors can be grouped into items such as material, equipment, method, or measurement with each group forming a major branch.
4. For each major branch, brainstorm and write causal factors on small branches of each major branch on the diagram. On the small branches, write detailed factors making twigs. If a cause belongs in more than one major branch, write the cause in both places.
5. Check to make certain all the items that may be causing the problem are included in the diagram.
6. Analyze the identified causes to determine the most likely root cause(s).

SPECIAL INSTRUCTIONS

- Be flexible on the major cause branches used.
- Ask "why?" if ideas are slow in coming.
- If the completed diagram has a total of five or six detailed causes on the entire diagram, it is not finished, even though the format is correct. The group needs to ask more "why?" questions.
- Test for root causes on the diagram by looking for causes that appear repeatedly within or across major categories.
- Select a root cause(s) through unstructured group consensus or a structured technique such as multi-voting.

Example of a Cause-and-Effect Diagram (CED)



THE STEPS FOR CONSTRUCTING AN INTERRELATIONSHIP DIAGRAM (ID)

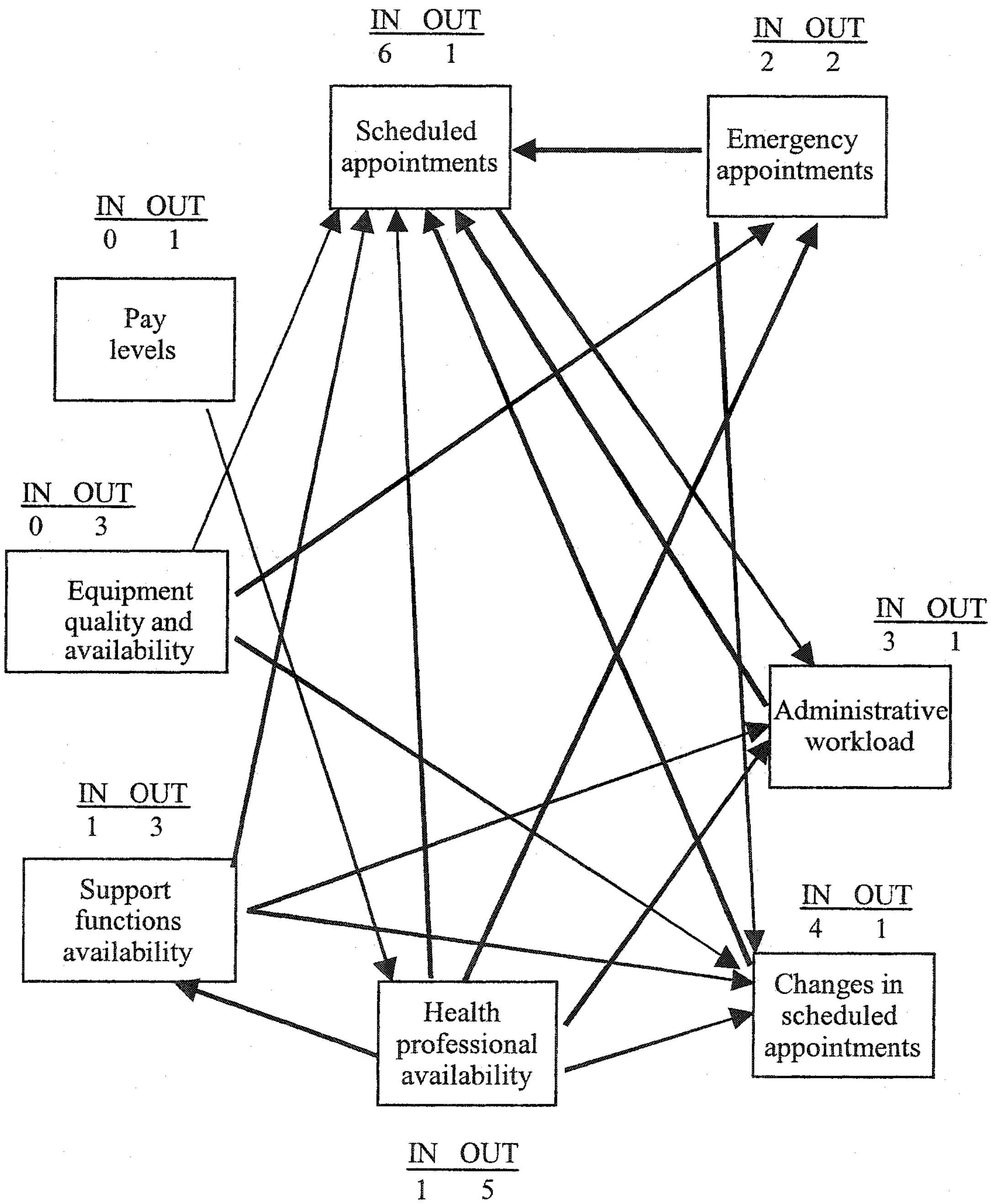
1. From the scenario you just read, as a group determine the factors to analyze for possible relationships and write them down using complete sentences if possible.
2. Place the factors on an empty space such as a whiteboard or flip chart paper.
3. Assess the relationship between each factor and the other factors by drawing an arrow from the cause to the effect. If no relationship exists, do not draw an arrow.
4. After all relationships have been assessed, count the number of arrows pointing into and out of each factor. Write this information next to each factor.
5. Factors with more arrows coming in: a possible effect.

   Factors with more arrows going out: a possible cause.
6. Analyze the factors to determine the most likely root cause(s).

SPECIAL INSTRUCTIONS

- Show arrows moving in one direction only. Do not draw arrows that go in both directions.
- The layout of the factors can be pre-arranged or random.
- Ask "why?" questions to surface cause and effect relationships.
- Test for root causes on the diagram by looking for factors that have many outgoing arrows.
- Select the root cause through discussion and evaluation.

Example of an Interrelationship Diagram



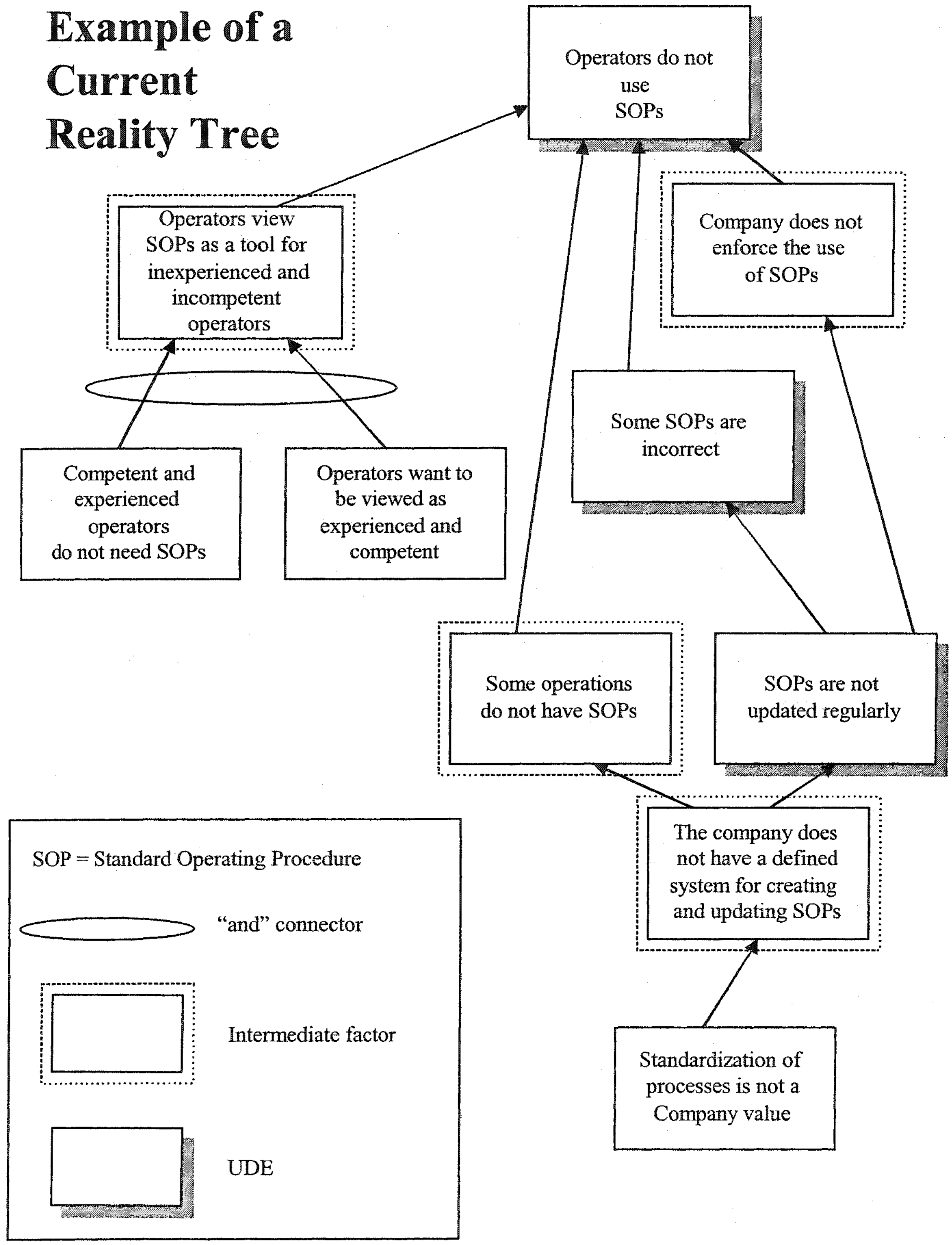
THE STEPS FOR CONSTRUCTING A CURRENT REALITY TREE (CRT)

1. From what you just read, work as a group to develop between three to five problems or undesirable effects (UDEs) related to the scenario. Put them in squares or rectangles at the top of an empty space such as a flip chart or white board.
2. Search for a causal relationship between any two factors. Determine which factor is the cause and which is the effect. Connect the causal relationships with an arrow that points from the cause to the effect with the cause on the bottom and the effect on top.
3. Insert intermediate factors as needed to connect the UDEs, building the cause-and-effect chain downward, connecting the factors using "if [cause] then [effect]" logic until all the original UDEs are connected. Reinforcing loops may be added if necessary.
4. Sometimes the cause by itself may not seem to be enough to create the effect. Additional dependent causes can be shown using the "and" connector (the ellipsis).
5. Test the integrity of the diagram using the categories of legitimate reservation (CLRs) as a guide. See the special instructions below. Use CLRs A, B, and C first, then if any of the A, B, or C CLRs are unsatisfied, use CLRs D through H as needed.
6. Search for root causes by looking at factors that do not have arrows going into them.

SPECIAL INSTRUCTIONS: <u>Categories of Legitimate Reservation (CLRs)</u>

a. IS IT CLEAR? Is the meaning clear, unambiguous, and understandable? Is it complete?
b. DO(ES) THE FACTOR(S) EXIST? Does it make sense? Is it valid?
c. IS THERE REALLY A CAUSE-EFFECT RELATIONSHIP? Is there a logical connection between the cause and effect? Does the "if-then" connection really exist?
d. IS THERE A MISSING CAUSE? Is there a missing dependent cause that produces the effect? Does the relationship require an "and" connector?
e. IS THERE AN ADDITIONAL CAUSE? Is there a missing independent cause that produces the effect? Is another cause with a separate arrow required?
f. DOES THE EFFECT REALLY EXIST? Is there a missing or additional effect?
g. CAUSE-EFFECT REVERSAL: Does the arrow point in the wrong direction?
h. CIRCULAR LOGIC: Is the effect offered as rationale for the cause?

Example of a Current Reality Tree



Bob's Technology Services

You are the manager of a department that supplies drawings and technical information to various manufacturing companies. The department keeps up-to-date versions of all original equipment drawings, specifications, and requirements documents and ships them to customers upon request. The customers use these documents to ensure they are meeting all the technical requirements.

DEPARTMENT PROFILE

- New employees typically work for this department as their first job with the company, turnover is high.
- Hot (high priority) orders are expedited ahead of all others.
- The department focuses on output as a measure of performance.
- The service area is small, new incoming documents are co-mingled with out-going orders.
- Keeping track of orders is difficult and complex. The paperwork is slow.
- The company frequently changes blueprint companies, based on cost.

SCENARIO

Last week your boss, Bob, received a call from a customer who had not received their order. He then visited your department to demand an explanation why order #787 had not been shipped. He said that the order, for a highly valued customer, was seven weeks late, and the customer was producing product without any drawings and specifications. He threatened to fire you if order #787 was not shipped within twenty-four hours.

Where is order #787? It must be somewhere in the department. You order an intensive search for the order. During the search, one of the workers noticed an unlabeled box in the corner. She opened it and inside was order #787. The worker then noticed a whole stack of boxes in the same condition. All the labels appeared to have fallen off. You saved your job and shipped the order, but vowed to fix the problem of missed deliveries permanently. You must now find the root cause of this problem in order to fix it.

Acme Industrial Products

You are the chief executive of a large industrial company. Your company is having trouble introducing new products. Many of the marketing managers complained that they do not have enough information to make effective decisions about introducing new products. Sensing an important problem, you sought help from the information systems group.

COMPANY PROFILE

- The information systems group reports to the manager of operations.
- The marketing department reports to the manager of sales.
- Technology and innovation is highly valued throughout the company.
- The cost of introducing new products has significantly increased over the last few years and budgets have been tight.
- Marketing managers sign off on their own new product introduction decisions.

SCENARIO

Information systems told you that the cause of the problem was technical. They said the marketing managers do not have the correct information system and proposed three new computer systems. All three systems are very expensive and require large amounts of training. Although you had some doubts, you decided to approve one of the systems.

During system installation, the marketing managers showed little enthusiasm, but you still expected the system would work. Now, a year later, less than 50% of the marketing managers have attended the training sessions and few of them actually use the new system. The new system has not affected the way marketing managers make decisions for new products. They still complain that they do not have enough information. Now you must find the root cause of this problem so you can get new products into the marketplace before your competitors.

Gizmo Division Expansion

You have recently been appointed the manager of a new division that will be housed in a building presently under construction. You have five new department heads who are hiring staff and purchasing office equipment.

DIVISION PROFILE

- Your management team is close and works well together.
- There are salary and seniority differences among your department heads.
- Each department head was recently promoted into his or her current job.
- People in the division feel strongly about things that reflect their status and position in the company.

SCENARIO

Yesterday, you received the final set of plans for the new building. For the first time, you examined the available parking facilities. There is a large lot across the street intended for clerical, blue-collar, and supervision. In addition, there are ten spaces immediately next to the building that are intended for reserved and visitor parking. Company policy requires a minimum of six spaces for visitor parking. This leaves you with only four spaces for you and the five department heads. There is no room to increase the size of the lot. You know that each department head expects to receive a reserved parking space. Now you must allocate four reserved parking spaces among yourself and your five managers. What root cause created this problem?

APPENDIX C: DETAILED STATISTICAL TABLES

Table C1.

RCAT-RI Individual Question Significance

#	Question	ε	p Univariate	p Multivariate
1.	Identified Root Cause	Huynh-Feldt	.494	.326
2.	Identified Causal Interdependencies	Assumed	.387	.445
3.	Identified Interrelationships	Assumed	.269	.272
4.	Displayed Intermediate Factors	Assumed	.062	.053
5.	Identified Cause Categories	Assumed	.001*	.001*
6.	Assesses Logic and Integrity	Assumed	.267	.288
7.	Facilitated Productive Activity	Assumed	.028*	.013*
8.	Difficulty or Ease of Use	Huynh-Feldt	.000*	.000*
9.	Overall Readability	Assumed	.033*	.027*
10.	Stimulated Discussion	Huynh-Feldt	.877	.844
11.	Promoted Productive Dialogue	Huynh-Feldt	.608	.517
12.	Actively Developed Participation	Assumed	.056	.069

*$p < 0.05$

Table C2.

RCAT-RI Significant Within-Group Differences for Individual Questions

Question/Contrast	*df*	*F*	*p*	*ES*
Identified Cause Categories	2, 74	7.839	.001	
CED vs. CRT	1, 71	15.754	.000	.59
CED vs. ID	1, 71	7.520	.008	.47
Facilitated Productive Activity	2, 71	3.650	.028	
CED vs. CRT	1, 71	9.161	.003	.38
Difficulty or Ease of Use	1.866, 71*	38.395	.000	
CED vs. CRT	1, 71	67.263	.000	1.15
ID vs. CRT	1, 71	45.020	.000	1.18
Overall Readability	2, 71	3.480	.033	
CED vs. CRT	1, 71	7.697	.007	.39

*Huynh-Feldt adjusted *df*

Table C3.

Overall Construct Descriptive Statistics

	Mean	*SD*
Causality	3.37	.575
Relationships	3.26	.520
Usability	3.24	.521
Participation	3.04	.613

Table C4.

Construct Covariance Matrix

	Causality	Relationships	Usability	Participation
Causality	.331			
Relationships	.212*	.270		
Usability	.199*	.205*	.271*	
Participation	.176	.177	.231*	.375

* $p < 0.05$

Table C5.

Construct Correlation Matrix

	Causality	Relationships	Usability	Participation
Causality	1.000			
Relationships	.709*	1.000		
Usability	.663*	.757*	1.000	
Participation	.499*	.555*	.723*	1.000

* $p < 0.001$

Table C6.

Coefficients for Model Variables of Constructs

Dependent Variable	Predictor Variable	β	t	Bivariate r	Partial r
Causality	Relationships	.537	4.70**	.709	.424
	Usability	.271	2.18*	.663	.212
	Participation	.033	.343	.499	.084
Relationships	Usability	.512	5.19**	.757	.459
	Causality	.370	4.70**	.709	.424
	Participation	.000	-.001	.555	.000
Usability	Participation	.413	6.41**	.723	.538
	Relationships	.411	5.19**	.757	.459
	Causality	.166	2.18*	.663	.212
Participation	Usability	.700	6.41**	.723	.538
	Causality	.035	.343	.499	.034
	Relationships	.000	-.001	.555	.000

* $p < 0.05$
** $p < 0.001$

Table C7.

Reliability for RCAT-RI

#	Specific Question	CED		ID		CRT	
		Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
1	Identified Root Cause	3.46	.69	3.35	1.13	3.29	1.00
2	Identified Causal Interdependencies	3.36	.86	3.47	.87	3.32	.77
3	Identified Interrelationships	3.22	.89	3.47	.86	3.31	.96
4	Displayed Intermediate Factors	3.43	.92	3.18	.88	3.33	.95
5	Identified Cause Categories	3.50	.87	3.06	.99	2.94	1.03
6	Assesses Logic and Integrity	2.97	.92	3.18	.91	3.10	.89
7	Facilitated Productive Activity	3.32	.80	3.17	.89	2.99	.91
8	Difficulty or Ease of Use	3.75	.82	3.78	.83	2.75	.92
9	Overall Readability	3.43	.95	3.26	1.01	3.07	.91
10	Stimulated Discussion	3.14	.83	3.08	.93	3.10	.98
11	Promoted Productive Dialogue	3.14	.70	3.04	.85	3.04	.83
12	Actively Developed Participation	3.07	.81	3.07	.97	2.82	.95

Cronbach $\alpha = .926$, $n = 72$, items = 36

Table C8.

Reliability for Constructs/Dependent Variables

	Mean	*SD*	Cronbach α	*n*
Causality	3.37	.575	.71	75
Relationships	3.26	.520	.68	75
Usability	3.24	.521	.80	72
Participation	3.04	.613	.86	72

Overall Cronbach $\alpha = .878$, $n = 105$, items = 4

Table C9.

Comparison of Calculated Significance (p) Values for Post Hoc Tests

Pairwise Comparison	Omibus F	Bonferonni t	Paired t
	p	p	p
Identified Cause Categories			
CED vs. CRT	.000	.000	.000
CED vs. ID	.008	.023	.006
Facilitate Productive Activity			
CED vs. CRT	.003	.010	.000
Difficulty or Ease of Use			
CED vs. CRT	.000	.000	.000
ID vs. CRT	.000	.000	.000
Readability			
CED vs. CRT	.007	.021	.001
Overall Usability			
CED vs. CRT	.000	.000	.000
ID vs. CRT	.003	.009	.020

APPENDIX D: PARTICIPANT COMMENTS, RESEARCH OBSERVATIONS, AND OUTPUT EVALUATIONS

Participant Responses and Comments

Comments About the Groups:

Obviously opinions vary and because of this, some of the close-mindedness affected the final outcome.

Did not work well as a team, mainly individual ideas.

Discussion occurred between a few “main players.”

Some members quiet.

The groups are too big. Too many different views on the same problem. There were about 3 or 4 people that didn’t give any input.

Some of the team was too quiet.

I think the group is too big to be effective.

Groups too big to have productive input from all members.

The size of the group was too big.

The groups seem to be so large; it lowers participation and productivity.

I think that the number of people in the group definitely affects the outcome. With a smaller group, I believe these tools would be more effective.

Can’t stand this team.

Comments About the Process:

I did not like how many times the person who was writing on the chart disregarded abstract ideas that I was throwing out. This happened several times.

Pretty boring.

Not enough information on company and situation.

I didn't like it.

The root cause of the problem was Bob.

I thought that all three tools were worthless.

Comments About the CED:

Good tool to use when problem solving, overall this is a good technique.

Overall good, but not exactly great for this tool.

Tough to find large category titles.

It was hard to determine the root cause—seemed like a lot of general causes but no specific set way to find root cause. Tool was cluttered.

We had a much better experience with this tool as opposed to the interrelationship diagram.

Best tool by far of the three.

Even though I did not participate much, I thought this tool was the most effective.

Comments About the ID:

The tool works as long as people are thinking of good causes. It seemed some of the causes were irrelevant.

I do not believe that the tool identifies the root cause of the problem, but does come up with some suggestions.

Seemed to list effects rather than causes. Broad range of causes—no single strong cause.

I thought this tool was better than the CRT.

Easiest to use of the three tools.

The best of the three.

Good tool!

Comments About the CRT:

This is much better than the CED.

We probably would have come to the same conclusion without any tools.

Very difficult to apply to our particular scenario.

Relatively confusing to get started.

This one was pretty bad. I think you can organize problems in better ways.

Hard tool!

This tool was confusing at first and it was hard to get everyone's input.

This one was difficult to understand. Whoever came up with this tool was trying too hard.

Explanation of tool/instructions was very confusing. A lot of information didn't seem needed to understand tool.

Questions, Observations, and Evaluations

(P) = Process

(C) = Construction

(R) = Root cause

(G) = Group dynamic

Cause-and Effect Diagram

Section 1: Group 1

Questions:

- What is the goal of the process? (P)
- Do we try to find a root cause or come up with a solution? (P)
- How do we put down the categories? (C)
- Can we select an entire category as the root cause? (R)

Observations:

- Slow to start. (P)
- Changed category titles once in the process. (C)
- Group determined that the whole chart was the root cause. (R)
- The group was unable to select a single root cause. (R)
- The women were more verbal in the process discussion. (G)

Output:

Technical Accuracy: Medium (cause categories not constructed correctly)

Root Cause Identification?: No

Integrity of Identified Cause: Low (root cause not identified)

Section 1: Group 2

Questions:

- None.

Observations:

- No main leader, but 5 or 6 people collectively accounted for the participation, other sat by silently. By the end of the session, one person emerged as the dominant leader. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: No

Integrity of Identified Cause: Low (root cause not identified)

Section 1: Group 3

Questions:

- Is this whole thing about causes or solutions to problems? (P)
- Does the main cause or the main problem go into the big box? (C)
- Does it matter which side the problem goes on? (C)
- Do we draw the main categories out from the main arrow? (C)
- Do the detail causes come off the main categories or are they branches? (C)
- Can we put more than one cause in more than one category? (C)
- Do we find the root cause by looking at the detailed causes?
- Can you have more than one root cause? (R)
- Do we need to find a root cause? (R)
- Can we make a main category the root cause? (R)

Observations:

- Group asked themselves why questions for each detailed cause. (P)
- Most questions came from 1 or 2 people. (G)

- One non-participant. (G)
- Activity was concentrated on one end of the table. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: Low (not specific, not reasonable)

Section 2: Group 1

Questions:

- Are we supposed to come up with a solution? (P)
- When do we stop? We could go on forever. (P)

Observations:

- The group seemed to be biased to one main factor even though it appeared to me another factor stood out more. (P)
- One male immediately acted as the leader of the group (G)

Output:

Technical Accuracy: High

Root Cause Identification?: No

Integrity of Identified Cause: Low (root cause not identified)

Section 2: Group 2

Questions:

- One question about the problem scenario (did not answer)
- How do we decide on the major category headings? (P)
- Do you want us to find more detailed causes off the main causes? (P)
- Do you want us to draw lines out from the main branches to the detailed causes? (C)

- Can we group the causes together? (C)
- Can causes be under more than one category? (C)
- How do we find the root cause? (R)
- How do we decide what the root cause is? (R)

Observations:

- Group found main issue to be addressed right away. (P)
- Fairly balanced participation. (G)
- 2 non-participants. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: No

Integrity of Identified Cause: Low (root cause not identified)

Section 2: Group 3

Questions:

- Can we have more than one root cause? (R)

Observations:

- Reminded the group that the first step was to identify the problem to be solved or controlled. (P)
- One participant read the newspaper the whole time. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: No

Integrity of Identified Cause: Low (root cause not identified)

Section 3: Group 1

Questions:

- Are we to solve the problem or just find the root cause? (P)
- Are we supposed to solve the problem? (P)
- Should we use the marker or a pencil? (P)
- Should we write our ideas on a separate piece of paper? (P)

Observations:

- Had to intervene because group was trying to come up with solutions. (P)
- Five people started working together at first. (G)
- As time progressed all worked together. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: No

Integrity of Identified Cause: Low (root cause not identified)

Section 3: Group 2

Questions:

- What are the four large boxes on the example diagram? (C)
- How do we know what is the root cause? (R)

Observations:

- Immediate group leader who sat on one end of the table. (G)
- Participation initially slow. (G)
- More people began to be involved progressively down the table from the group leader. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: No

Integrity of Identified Cause: Low (root cause not identified)

Section 3: Group 3

Questions:

- None.

Observations:

- Immediate group leader. (G)
- Participation dwindled as participants were further away from the group leader along the table. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: High

Interrelationship Diagram

Section 1: Group 1

Questions:

- How do we know when we have exhausted all possibilities of cause and effect on the diagram? (P)
- Are there subcategories used? (C)
- Which direction do the arrows point? (C)

Observations:

- Very organized, broke down a bit on arrow drawing. No real system. (P)
- Good collaboration among team, no real leader. (G)
- Some more quiet than others, but virtually everyone contributed. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: High

Section 1: Group 2

Questions:

- Does it matter which color of marker we use? (P)
- How does the arrow show cause and effect? (C)
- Can arrows go back and forth between the factors? (C)

Observations:

- A true group effort: no one personality dominated the discussion

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: Medium (not specific)

Section 1: Group 3

Questions:

- How many boxes needed? (C)
- Do we need to use complete sentences? (C)
- Do we draw the arrow from cause to effect? (C)
- Does the root cause come from the box with the most outgoing arrows? (R)

Observations:

- Group did not really focus on one effect/cause relationship. Jumped around a lot. (P)
- Had to tell group to go through each box systematically to hit all cause/effect. (P)
- Had to clarify to group to finish all cause/effect arrows and then discuss root causes. (P)

- Discussion resulted over main root cause/causes. (R)
- Communication broke down at times, splitting hairs over issues. (G)
- Three to four leaders, little, if any, participation from others. (G)
- As time passed, some frustration arose as they mapped cause and effect. (G)
- Comment overheard, "This tool sucks." (G)
- More participation from other group members as process continued. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: Medium (not reasonable)

Section 2: Group 1

Questions:

- Do we just throw the factors anywhere on the sheet? (C)
- Can we have one cause or multiple causes? (R)

Observations:

- Group had no initial questions. (P)
- Group began to blame tool for their frustration and difficulty in finding a root cause. (P)
- After group did arrow count, they immediately picked the factor with the most outgoing arrows as the root cause. (P)
- Group could not agree on a root cause. (R)
- Some group members did not want to discuss further whether they had truly found the root cause regardless of other group members' objections. (G)
- Primary group dynamics controlled by 2 or 3 people. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: No

Integrity of Identified Cause: Low (root cause not identified)

Section 2: Group 2

Questions:

- How do we determine how to solve this problem? (P)
- Is an effect a possible solution? (P)
- In the tool example, what problem did it represent? (C)
- Can arrows go both ways on the tool? (C)

Observations:

- Four to five main leaders. (G)
- One person "didn't understand" ignored project. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: Medium (not specific)

Section 2: Group 3

Questions:

- None.

Observations:

- No one person facilitated conversation for 3 minutes. (G)
- No dominant leader, predominantly 7 participants. The remaining members were not interested in what was going on. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: Medium (not reasonable)

Section 3: Group 1

Questions:

- Can the arrows go both ways? (C)

Observations:

- Group was concerned about the colors they used on the tool. (C)
- All group members worked together except for one who went outside to talk on the cell phone. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: Low (not specific/not reasonable)

Section 3: Group 2

Questions:

- Use the instruction example as a guide? (P)
- Use the self-adhesive notes to write the causes? (C)
- Do we use complete sentences? (C)
- Do we draw arrows out from the causes? (C)
- How many causes can we have? (R)

Observations:

- Group brainstormed causes on a separate sheet of paper, then started adding notes. (P)
- Group decided on a root cause before finishing the tool and doing the arrow counts. (P)
- Two to three non-participants. (G)

Output:

Technical Accuracy: Medium (factors not clearly stated)

Root Cause Identification?: Yes

Integrity of Identified Cause: Low (not specific/not reasonable)

Section 3: Group 3

Questions:

- What are factors? (P)

Observations:

- A few group members were not enthusiastic about doing the activity (e.g., "Can I just take the survey?"). (G)
- Only one person in the group really did not work together with the others. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: High

Current Reality Tree

Section 1: Group 1

Questions:

- Start with the effects? (P)
- Do we start at the top? (C)
- Do causes work downward from the top? (C)
- To make the connections between entities, do we start at the top? (C)
- Does the "and" connector circle the lines or the entities? (C)

Observations:

- Group wanted to solve the problem. (P)
- Group started to come up with solutions rather than causes. (P)

Output:

Technical Accuracy: Medium (one of the root causes was identified as an intermediate factor)

Root Cause Identification?: Yes

Integrity of Identified Cause: High

Section 1: Group 2

Questions:

- What does the ellipse mean? (C)
- Without the ellipse, can one be the cause by itself? (C)
- Can we use more than 5 UDEs? (C)

Observations:

- Group made UDEs with lines around them. (C)
- Two people immediately evolved as the group's leaders. (G)
- Group dynamics was good. (G)
- Interaction was good. People listened to ideas—participation involved about 50% of group members. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: High

Section 1: Group 3

Questions:

- What is the difference between a problem and a UDE? (P)
- How to determine cause and effect relationships? (P)
- Are we to solve the problem or just find the root cause? (P)
- What are the CLRS? (P)
- How do we build the tree? (C)
- Where do we start writing? (C)
- Can we build the tree below the original root cause? (C)

Observations:

- First attempt was to try to solve the problem instead of looking at UDEs. (P)
- A small minority of people appeared to take control of the process. (G)
- Some clash of personalities over whether to solve the problem or build the CRT downward to find the root cause. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: High

Section 2: Group 1

Questions:

- Can the arrow go both ways? (C)

Observations:

- Suggested to group they use a marker so everyone could see. (P)
- Suggested the use of the "and" connector. (C)
- One person took charge and then asked group if they agreed. (G)

- Group did not really work together at first. (G)
- Initial leader lost position due to group involvement. Got book out and started reading. (G)

Output:

Technical Accuracy: Low (direction of arrows incorrect, unclear factors, format incorrect, incorrect use of conventions)

Root Cause Identification?: No

Integrity of Identified Cause: Low (root cause not identified)

Section 2: Group 2

Questions:

- Do we start with intermediate effects first? (P)
- What are the factors called that are neither intermediate nor UDEs? (P)

Observations:

- Group was only 7 persons, several participants absent. (G)
- High participation in the group. (G)
- One group leader immediately emerged. (G)

Output:

Technical Accuracy: Low (arrow directionality not consistent, factors not specific or clear, unrecognizable as CRT, improper use of conventions)

Root Cause Identification?: Yes

Integrity of Identified Cause: Low (not specific/not accurate)

Section 2: Group 3

Questions:

- Are we to solve the problem or just find the root cause? (P)
- What are UDEs? (P)

Observations:

- Extensive facilitator intervention required. (P)
- Lack of group questions held progress back. (P)
- One person built the chart as an individual and shared with group who accepted. (G)

Output:

Technical Accuracy: Low (direction of arrows backwards, factors not clearly stated, unrecognizable as CRT, conventions not used correctly)

Root Cause Identification?: Yes

Integrity of Identified Cause: Medium (not specific)

Section 3: Group 1

Questions:

- What are the CLRs used for? (P)
- Do we use all of the CLRs? (P)
- Do we start with effects or causes? (P)
- Do we pick more than one effect? (P)
- Do we need one main effect? (P)
- When do we use the "and" connector? (P)
- Do we work backwards from the UDEs to causes? (C)
- Do we connect the UDEs together? (C)

Observations:

- One person tried to dominate the group right away. (G)
- Later in the process, 3 or 4 people were heavily engaged in the discussion with more balanced participation. (G)
- Two non-participants engaged in an unrelated sidebar conversation. (G)
- At the end of the process, one person was leading the group's effort. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: High

Section 3: Group 2

Questions:

- Do we start with effects or causes? (P)
- Do we start from the top or the bottom? (C)
- How do we connect the factors together? (C)
- How do we know what the root cause is? (R)

Observations:

- The group initially drew the arrows the wrong way. (C)
- Group changed process halfway through from construction of tool from top-down to bottom-up. (C)
- Reminded group to use if-then statements, reminded group about top-down construction, reminded the group about putting the effects on top. Suggested the use of the "and connector and the CLRs. (C)
- One half of the group took charge of the activity and ignored the other half. Had to encourage the group to include all members. (G)
- 1 to 2 non-participants. (G)
- Group began to get frustrated after about 30 minutes. (G)

Output:

Technical Accuracy: High

Root Cause Identification?: Yes

Integrity of Identified Cause: High

Section 3: Group 3

Questions:

- What is the difference between a UDE and an intermediate factor? (P)

Observations:

- Equal group participation. (G)
- No one particular leader. (G)

Output:

Technical Accuracy: Medium (some arrows not directionally accurate, conventions not used)

Root Cause Identification?: Yes

Integrity of Identified Cause: Medium (not specific)

Table D1.

Factors and Connections Counts for the Tool Outputs

Measure/ Tool	ID		CRT		CED	
	Causes/ Factors	Arrows	Entities/ Factors	Connections	Major Categories	Detailed Causes
Section 1						
M_1						
CED					5	15
ID	10	16				
CRT			8	8		
M_2						
CRT			10	12		
CED					4	20
ID	8	21				
M_3						
ID	9	16				
CRT			14	15		
CED					4	25
Section 2						
M_1						
CED					4	16
ID	10	16				
CRT			7	6		
M_2						
CRT			7	7		
CED					4	17
ID	9	16				
M_3						
ID	8	17				
CRT			11	15		
CED					3	12
Section 3						
M_1						
CED					4	20
ID	8	15				
CRT			10	13		
M_2						
CRT			11	11		
CED					4	16
ID	8	11				
M_3						
ID	11	15				
CRT			8	9		
CED					4	13
Means	9	16	10	11	4	17

Table D2.

Cause-and-Effect Diagram (CED) Output Evaluations, Questions, and Observations

Section/ Group	Technical Accuracy	Root Cause?	Integrity of Root Cause	Process Questions	Process Observations	Root Cause Questions	Root Cause Observations	Construction Questions	Construction Observations	Group Dynamics Observations
1/1	M	N	L	2	1	1	2	1	1	1
1/2	H	N	L	0	0	0	0	0	0	1
1/3	H	Y	L	1	1	4	0	5	0	3
2/1	H	N	L	2	1	0	0	0	0	1
2/2	H	N	L	2	1	2	0	3	0	2
2/3	H	N	L	0	1	1	0	0	0	1
3/1	H	N	L	4	1	0	0	0	0	2
3/2	H	N	L	0	0	1	0	1	0	4
3/3	H	Y	H	0	0	0	0	0	0	2
TOTAL CED	1M, 8H	2Y, 7N	8L, 1H	11	6	9	2	10	1	17
TOTAL COMPOSITE OF CED QUESTIONS AND OBSERVATIONS				Total Process	17	Total Root Cause	11	Total Construction	11	

Typical Questions and Observations: (1) use categories, (2) use of multiple root causes.
H = High, M = Medium, L = Low
Y = Yes, N = No

Table D3.

Interrelationship Diagram (ID) Output Evaluations, Questions, and Observations

Section/ Group	Technical Accuracy	Root Cause?	Integrity of Root Cause	Process Questions	Process Observations	Root Cause Questions	Root Cause Observations	Construction Questions	Construction Observations	Group Dynamics Observations
1/1	H	Y	H	1	1	0	0	2	0	2
1/2	H	Y	M	1	0	0	0	2	0	1
1/3	H	Y	M	0	3	1	1	3	0	5
2/1	H	N	L	0	3	1	1	1	0	0
2/2	H	Y	M	2	0	0	0	2	0	2
2/3	H	Y	M	0	0	0	0	0	0	2
3/1	H	Y	L	0	0	0	0	1	1	1
3/2	M	Y	L	1	1	1	0	3	1	1
3/3	H	Y	H	1	0	0	0	0	0	2
TOTAL ID	1M, 8H	8Y, 1N	3L, 4M, 2H	6	8	3	2	14	2	16
TOTAL COMPOSITE OF ID QUESTIONS AND OBSERVATIONS				Total Process	14	Total Root Cause	5	Total Construction	16	

Typical Questions and Observations:: direction of arrows
H = High, M = Medium, L = Low
Y = Yes, N = No

Table D4.

Current Reality Tree (CRT) Output Evaluations, Questions, and Observations

Section/ Group	Technical Accuracy	Root Cause?	Integrity of Root Cause	Process Questions	Process Observations	Root Cause Questions	Root Cause Observations	Construction Questions	Construction Observations	Group Dynamics Observations
1/1	M	Y	H	1	2	0	0	4	0	0
1/2	H	Y	H	0	0	0	0	3	1	3
1/3	H	Y	H	4	1	0	0	3	0	2
2/1	L	N	L	0	1	0	0	1	1	4
2/2	L	Y	L	2	0	0	0	0	0	3
2/3	L	Y	M	2	2	0	0	0	0	1
3/1	H	Y	H	6	0	0	0	1	0	4
3/2	H	Y	H	1	0	1	0	2	3	3
3/3	M	Y	M	1	0	0	0	0	0	2
TOTAL CRT	3L, 2M, 4H	8Y, 1N	2L, 2M, 5H	17	6	1	0	14	5	22
TOTAL COMPOSITE OF CRT QUESTIONS AND OBSERVATIONS				Total Process	23	Total Root Cause	1	Total Construction	19	

Typical Questions and Observations: (1) start at the top or bottom, (2) use of conventions such as: "and" connector, ellipse, UDEs, CLRs, and intermediate effects.
H = High, M = Medium, L = Low
Y = Yes, N = No

Table D5.

Grand Summary of Output Evaluations, Questions, and Observations

Section/ Group	Technical Accuracy	Root Cause?	Integrity of Root Cause	Process Questions	Process Observations	Root Cause Questions	Root Cause Observations	Construction Questions	Construction Observations	Group Dynamics Observations
TOTAL ALL	3L, 4M, 20H	18Y, 9N	13L, 6M, 8H	34	20	13	4	38	8	55
TOTAL COMPOSITE OF ALL QUESTIONS AND OBSERVATIONS				Total Process 54		Total Root Cause 17		Total Construction 46		Total Group Dynamics 55

H = High, M = Medium, L = Low
Y = Yes, N = No