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A NEW METHOD FOR FORMULATING A STRONG HYPOTHESIS IN RCA

Abstract: *This paper assesses how well quality tools identify the correct root cause with a modified usage compared to more traditional usage. The purpose of this research is to empirically evaluate the use of a modified Ishikawa diagram and variation of another quality tool for identifying testable hypotheses in root cause analysis.*
Two experiments were performed using engineers to evaluate the proposed methods for hypothesis selection and evaluation. One study evaluated the use of an Ishikawa diagram with a hypothesis related action item tracking list versus teams with just an Ishikawa diagram. The second study determined if the correct hypothesis was selected more often than chance when multiple hypotheses and observations are presented in a list. Use of the proposed method including a modified Ishikawa diagram leads to more testable hypotheses and listing the available evidence can lead to the identification of the correct hypothesis.

Keywords: *Quality tools, Ishikawa diagram, Root cause analysis*

1. Introduction

There is a wide variety of quality tools available and they have a wide range of uses in both manufacturing and service companies. Quality tools are often used when looking for the cause of a failure during root cause analysis (RCA), as tools for quality improvement projects, and as tools for assisting in decision making (Starzyńska et al., 2018).

However, previous research on quality tools has been mainly oriented towards studying the level of employee knowledge about the tools and determining the degree of their application in practice or case studies documenting the use of quality tools. Few works deal with assessing their efficacy when they are used. The universality of the quality tools is often the dominant reason for their selection. As a result, many have remained unchanged over the years and they are applied in a routine manner.

This paper proposes a new method for a more effective selection of the strongest hypotheses during an RCA and comments in this paper will have an emphases on use of quality tools for RCA. Specifically, this paper asses how well quality tools identify the correct root cause with a modified usage compared to more traditional usage. Forming incorrect (weak) hypotheses leads to a waste of time and incurs unnecessary additional costs such as when additional scrap is produced as the RCA investigation continues.

The proposed method for formulating a strong hypothesis in RCA is based on Ishikawa diagram with a tracking list and variation of another quality tool.

One of the first steps in both problem solving (RCA) and continuous process improvement (CPI) is to recognize the problem,

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hypothesize potential problem causes, and identify which of the potential reasons are relevant. Forming and evaluating the correct hypothesis allows you to identify the root cause of the problem.

There are many tools used in this area (Hagemeyer et al., 2006), one of the most useful and popular is the Ishikawa diagram (Lam 1996). The rich literature on the subject shows that it is used in a routine manner, following one scheme. The authors of this paper believe that by introducing additional ways of presenting and analyzing data, their potential can be used even better.

The goal of this paper is to show that combining an Ishikawa diagram with a tracking list together with an L-shaped matrix (Tague, 2005) as a prioritization tool is a method for forming strong hypotheses during a RCA.

This paper explores new ways of using these quality tools; especially the Ishikawa diagram and the L-shaped matrix. Both are simple to use, but they can both be used in new ways.

The need to expand an Ishikawa diagram using an action item tracker is explained. There is limited mention in the literature of using an action item tracker together with an Ishikawa diagram, although the addition of an action item tracker can potentially make an Ishikawa diagram more efficient than one that does not use an action item tracker.

The one article that explains this method is descriptive and does not determine if the method is indeed superior (Barsalou, 2016b). This research attempts to determine if the use of an Ishikawa diagram together with an action item tracker is more efficient than an Ishikawa diagram without a method for tracking action items related to the investigation. An action item tracker is a spreadsheet used to track actions and includes details such as what the action is, who will perform it, and a deadline for the results. In this case, efficiency consists of hypotheses which could be evaluated by checking the pin and plate. Two groups of engineers from industry will be used; one with an action item tracker and one without. The engineers will be randomly selected for each group. This study assesses which group identifies a higher percentage of hypotheses that could be evaluated by checking the failed parts. This is intended to demonstrate that use of an action item taker during a failure investigation in industry would lead to the identification of more testable hypotheses than not using an action item tracker.

This paper also proposes that a need exists for a new method of comparing observations to hypotheses when performing a failure analysis. The literature was reviewed to determine what, if any, methods are currently available. There was one by Barsalou (2017), which had not been evaluated empirically to assess efficiency. The method was explained in detail and then a study was performed.

The authors of this paper suggest in this article a method based on Ishikawa diagram and a variation of the L-shaped matrix (Tague 2005) for prioritization for quickly evaluating hypotheses in a way that leads to the quickest identification of the root cause. In the paper, this method is assessed using a simulated product failure and a list of observations.

2. Literature Review

Much of the literature on RCA is in the form of case studies such as Mooren et al. who describe an investigation into the premature wear of a drill bit used in a manufacturing process (2012). The failure of protective gloves used in a hazardous environment were investigated in a case study that used an Ishikawa diagram to generate potential failure causes (Cournoyer et al., 2012). Pan and Kolarik presented a case study into the cause or relay failures; this case study also illustrated the use of an Ishikawa diagram during an RCA (1992)

There are many types of quality tools available such as check sheets, Pareto diagrams, and scatter plots (Tari & Sabater,

2003) and the use of an Ishikawa diagram for solving problem is well documented in the literature (Mahanti, 2014; Przdek & Maciulla, 1995; Sharma et al., 2010).

An Ishikawa diagram, also known as fishbone diagram or cause and effect diagram, (Tague, 2005) is a graphical depiction of potential causes of a problem or situation (Munro et al., 2008) where "a cause is a proven reason for the existence of a defect" (Gryna, 2001) or failure under investigation. It is useful method for hypothesis generation (de Mast, 2011) and it is also an easy method to use (Wilson et al., 1993). It is used both in industry (Starzyńska, 2014; Chapman et al., 2011) and the use of Ishikawa diagrams is also taught in university classes (Immel, 2013).

The Ishikawa diagram was developed in the 1940s (Skrabec, 1991) and remains relatively unchanged over time; it seems that the full potential of this simple tool has not been fully utilized. For example, a team analyzing drill bit wear out brainstormed 38 potential causes. This was too many to simultaneously investigate, so the team voted on which causes to prioritize; unfortunately, this resulted in 15 potential causes with an approximately equal number of votes. This was still too many to investigate simultaneously (Mooren et al., 2012) and a method for prioritization and tracking the investigation actions is needed (Barsalou, 2016b).

In spite of the Ishikawa diagram's long history, there is close to no scientific assessments of the use of Ishikawa diagrams in the literature. Research on Ishikawa diagrams have been done; for example, Starzyńska studied the use of quality tools in organizations (2014). Other research has covered knowledge of quality tools in organizations (Starzyńska & Hamrol, 2012). But the effectiveness of Ishikawa diagrams has not been studied in detail. The only evaluation is by Hagemeyer et al. who passed the usefulness of Ishikawa diagrams on a scale of low, medium, and high and only found the effectiveness to be medium (2006) and, it has been the experience of the authors of this paper that the Ishikawa diagram is limited to classifying causes in logical groupings.

Ishikawa diagrams are often used together with brainstorming (Dorsch et al., 1997) and are often used for organizing potential failure causes after a brainstorming session (Hillmer 1996). It is also one of the most popular quality tools (Sousa, Aspinwall, Sampaio, & Rodrigues, 2005); however, an Ishikawa diagram alone does not provide an option for hypotheses prioritization (Bamford & Greatbanks, 2005).

Ishikawa himself named his namesake diagram a cause and effect diagram because "it shows the relationship between characteristics and cause factors" (1991) and the Ishikawa diagram is often used for addressing quality problems. Ishikawa diagrams are also used for listing potential influence factors during Six Sigma quality improvement projects based on DMAIC (Define Measure Analyze Improve Control), with Ishikawa diagrams used during the Analyze phase (Breyfogle, 2003.) Behrooz and Latifi describe using an Ishikawa diagram for improving a grinding process (2018) and Anderson and Kovach provide an example of using one to investigate the causes of a high number of butt welds needing repairs (2014).

One of the advantage of an Ishikawa diagram is that it presents potential causes graphically, which makes them easier for people to grasp (Burrill & Ledolter, 1999); another advantage is that it provides structure to brainstorming (Sarazen, 1990). An Ishikawa diagram is also easy to create (Smith, 1998). An Ishikawa diagram consists of an arrow pointing to the problem under investigation; branches on the arrow list potential causes.

There are three types of Ishikawa diagrams; cause-enumerative, dispersion-analysis, and process-analysis. The cause-enumerative Ishikawa is the more common type which is used for identifying the cause of a problem. Dispersion-analysis Ishikawa diagrams are used for analyzing variability and process-analysis Ishikawa diagrams are intended for looking for causes within a process by listing the branches coming off of the process step under consideration (Besterfield, 1998). This paper describes the use of a cause-enumerative Ishikawa diagram.

The literature shows that there are many possible methods for creating an Ishikawa diagram. For example, Tague recommends agreeing on a problem statement that is listed as the effect and then determine categories for the branches when creating an Ishikawa diagram. A team should them brainstorm potential causes of the problem with an additional cause listed for each cause until the team runs out of ideas (2005).

Burrill and Ledolter suggest first listing all plausible causes of the effect being considered and then placing the causes in the Ishikawa diagram (1999). Sarazen tells readers to determine what should be improved and then determine potential causes to use as main branches before brainstorming all possible causes to list on the breaches as sub-causes. The causes of the sub-causes are then to be listed (1990).

Besterfield tells us to have team members take turns naming causes with those who can't think of one being skipped. He recommends quantity over quality and states that all ideas should be included without criticism. Ideas should then sit overnight with the team taking a fresh look the next day (1998). Alternatively, potential causes can be first identified and written down prior to organizing them within the Ishikawa diagram (Anderson & Fagerhaug, 2000).

Pyzdek and Berger recommend brainstorming together with those who have process knowledge and ensuring every idea is captured (1992). Brainstorming together with process and subject matter expertise is also recommended by Kubiak and Benbow, who also recommend using 7Ms as top branches; these are Mother Nature, materials, methods, manpower, measurement, machines, and management (2009.) In contrast, Robitaille suggests 5 Ms and one E consisting of material, manpower, machinery, method, measurement, and environment (2004).

Breyfogle states that materials, machine, method, personnel, measurement and environment are appropriate top categories although he also depicts an example in which purchasing data, other, people, process, purchasing methods, and suppliers is used (2003). ReVelle suggests using men/women, machine, measurement, material, method, and environment as top branch labels in an Ishikawa diagram (2004). Other authors suggest 5Ms consisting of machinery, manpower, method, material, and measurement (Jirasukprasert, 2014) or a comparable 5Ms consisting of men, materials, machines, methods and measurements (Smith, 1998).

Some authors (Berstene, 2018; George, et al. 2005) recommend applying five whys when creating an Ishikawa diagram. Five whys is a method of discovering the underlying cause of a problem by asking "why?" five times (ReVelle, 2004). Five whys is to determine the actual cause of the problem when investigating a failure (Ohno, 1988) and has been found to be used in 3% of organizations surveyed on the use of quality tools (Starzyńska, 2014). This approach risks building multiple unsupported hypotheses upon other unsupported hypotheses; instead hypotheses should be based on what could explain the failure and investigated instead of creating an Ishikawa diagram cluttered with unsubstantiated ideas. Any confirmed hypothesis could then be expanded upon based on evidence.

Sharma et al. (2010) state that every possible cause should be listed in an Ishikawa diagram and Smith tells readers that a weakness of an Ishikawa is that it is limited to brainstormed ideas (Smith, 1998); however, needlessly adding every brainstormed idea can be partially countered by observing the available evidence and to determine what should be listed. As an alternative to simply brainstorming every potential cause, the problem solving team should consider both "Given the structured and functional model, the symptoms would be a logical consequence of X, so X may be the case" as well as "X may be the cause, since the symptoms are known to have been caused by X before" (de Mast, 2011) when generating ideas for the Ishikawa diagram. Here, the potential causes would be driven by both subject matter knowledge and the available evidence.

There are no rules prohibiting those using an Ishikawa diagram from modifying or adapting the way in which they use an Ishikawa diagram. (Wilson et al., 1993) and although various words beginning with an M are often used as branch labels (Kubiak and Benbow, 2009; Robitaille, 2004; Breyfogle, 2003), Ishikawa himself did not always use the six Ms and he has stated "A good cause-and-effect diagram is one that fits the purpose, and there is no one definite form" (1991). Table 1 shows other variations that both Ishikawa and others have used as main branches.

Table 1. Table of Ishikawa diagram main branches according to various authors

Ishikawa 1991	**Pan & Lolarik 1992**	**Dorsch et al. 1997**	**Sharma & Sharma 2010**	**Krishnan & Gitlow 1997**
Inspection	Environment	Failre to return calls	Forming	Material
G resistor	Material	System used for call screening	Incoming stock	Manpower
Tools	Measurement	Greeting not regularly updated	Dryer unit	Machine (Lectro treat)
F resistor	Man		Press unit	Tools and fixtures
Machine/ Equipment	Machine/ Equipment			Environment
	Management			
	Method			

Table 1 (continued). Table of Ishikawa diagram main branches according to various authors

Pyzdek & Maciulla 1995	**Jirasukpraser et al. 2014**	**Mahanti 2014**	**Ophir et al. 1988**
Assembly	Measurement	Performance issues	Machine
Process	Machine	Design issues	Man
Design	Man	Requirement error	Method
Fabrication	Materials	Database issues	Material
	Methods	Technical issues	
	Environment	Human issues	
		Data issues	
		Environmental errors	

Information is collected during the RCA and hypotheses are formed and then evaluated (Smith, 1998). In RCA, a hypothesis is a tentative explanation that explains the failure being investigated (Rooney & Hopen, 2004). There will often be multiple hypotheses to investigate; often, these hypotheses will be listed in an Ishikawa diagram (Ishikawa, 1991).

As previously stated, an Ishikawa diagram does not provide a means for the prioritization of hypotheses (Bamford & Greatbanks, 2005).

The use of a spreadsheet for assigning priorities and actions to Ishikawa items has been explained by Barsalou who used a hypothetical example where the Ishikawa item was listed as a hypothesis as shown in Table 2. The worksheet was referred to as a "Perkin Tracker" to give credit to the person who had introduced the concept to the author. Hypotheses from an Ishikawa diagram were copied into the tracking sheet and then each hypothesis received one of three prioritization ratings. Prioritizing prevents wasting resources by investigating hypotheses that probably don't lead to the root cause. High priority hypotheses are those that are either strongly believed to be linked to the failure or those that are quick and easy to check. Actions were identified for each of the high and medium priority hypotheses and a person was then assigned responsibility for carrying out the actions and a deadline was given. The results of each action were then explained (2016a). Smith recommends selecting three to five hypotheses for active investigation (1998).

Table 2. Example of a Perkin tracker © Barsalou 2016. Used with permission

Perkin Tracker
Issue Name:
Created by:
Status Date:

Ishikawa Item	Priority	Action to Evaluate Hypothesis	Responsible	Target	Root Cause?	Conclusion
Material: Wring material used (Incorrect material was not sufficient for the usage)	High	Ensure material is per drawing 75646e	B. Gadison	18 March 2016	Yes	The material used was not the type of material specified on the drawing
Material: Wrong turning speed (High turning High speed damaged surface)	Medium	Check material specification to ensure material meets requirements	A. Ethridge	22 March 2016	No	Material on the drawing is robust to operating conditions
Machine: Wrong turning speed (High turning speed damaged surface)	High	Check parts for signs of wrong turning speed	D. Fulton	31 March 2016	No	No sign of wrong turning speed
Machine: Clamping damage (Clamping damage pre-weakened part)	Low					

A matrix diagram is another common quality tool and groups of data can be compared using a matrix diagram. A matrix diagram is a method to "….present and analyze various types of data in a visual format that provides greater understanding than a table of data" (ReVelle, 2004 p. 98). A matrix diagram can come in many forms. An L-shaped matrix diagram is used for comparing two groups of data. Three groups of data can be compared using T-shaped, Y-shaped, and C-shaped matrix diagrams. An X-shaped matrix diagram is used for comparing four groups of data (Tague, 2005). Specifically, a matrix diagram "…shows the connection (or correlation) between each idea/issue in one or more other groups of data" (Anjard, 1995 p. 36).

The matrix diagram is a versatile tool and can be slightly modified for use. For example, Liu recommends using a matrix diagram when planning a new organization. Here, strategies would be in the left-side column and core strengths would be listed in the top row. The objective would be to determine which strategy best fits the organization's core strengths (2013).

The simple L-shaped matrix diagram also serves as the basis for more complex tools such as the prioritization matrix. Whereas a matrix diagram is used for identifying relationships between two sets of data, a prioritization matrix is a version of the matrix diagram that is used for quantifying and prioritizing options (Breyfogle 2003). The prioritization matrix was introduced to the world as part of the seven new management and planning tools, which were based on operations research performed in Japan in the 1960s and published in the 1970s (Brassard, 1996). A prioritization matrix is used to compare between options by assigning weighted values to the options under consideration (Westcott, 2013). A prioritization matrix can also be modified to consider the risks of various options (Barsalou, 2016b).

The top row of the prioritization matrix is labeled with alternatives and the column on the left is labeled with the criteria or requirements that must be fulfilled. The importance of each criterion is then rated. A team determines how well each option fulfills the criteria and a value is given. The degree of fulfillment is then multiplied by the importance of the criteria to determine an overall score (McCain 2011). The overall score can then be converted into a percent of all possible points.

Prioritization matrixes are used during RCA; however, they are used as a method for identifying solutions (Lubell & Smith 2016) and not causes. The Pugh matrix is another useful matrix that can be used for planning solution after a root cause is identified. The Pugh matrix lists required features in the vertical column and potential concepts in the horizontal column. Each concept is then assessed on how well it fulfills the requirements (George et al., 2005). Criteria versus concepts can be assed using comparisons where new concepts are rated as better than the current design, the same as the current design, or not as good as the current design. The ratings are then totaled and the concept with the highest rating is selected (Bailey & Lee, 2016).

Robitaille suggests first investigating potential causes believed to be most likely to be the root cause (2004) without offering a method for doing so. There are currently methods available for determining which hypothesis is best in regards to correctly identifying the root cause. For example, Berstene recommends the use of tools to determine which potential cause should be investigated first (2018); unfortunately, no mention is made regarding which tools to use. There are tools available for prioritization; for example, a prioritization matrix (Borror 2009) could be used. Unfortunately, such a prioritization does not directly compare the hypotheses to the evidence and results could vary wildly based on the level of experience of the problem solving team.

The use of a table for evaluating hypotheses is suggested by Rooney and Hopen. The table consists of four columns. The first column is for listing the source and type of data and the second column is for rating how well the data can be trusted on a scale of low, medium, and high. The third column is where inferences are made based on the data; conclusions are drawn and explained. The final column is where the hypotheses best supported by the data is listed (2005).

Wilson et al. suggest using intuition, asking others who have experienced the same problem, and using experience (1993). Although all three may be needed during an RCA; they are not methodological approach finding which hypothesis best explains the root cause.

Latino and Latino propose using what they call a logic tree; higher levels causes are listed above lower level causes, which are investigated (2002); this approach is illustrated in a case study by Hallen and Latino where n-butyl alcohol was transferred into a tank intended for ethyl acetate. In this case, the operator got two trucks mixed up resulting in filling the wrong tank. This cause had 24 lower-level causes listed under it with no way to compare the hypotheses against the available evidence (2003); the root cause could be found quicker by first testing hypotheses that best fits the available evidence. This method sounds much like a fault tree analysis, which Kubiak and Benbow recommend using a fault tree for RCA (2009). A fault tree analysis lists the failure on top and lower level causes below with lower level causes often having their own causes (Gryna 2001). Probabilities can be added to a fault tree analysis, but to add probabilities, the probability of a failure occurring must be known and such data may not be available for a new type of failure. Paradies proposes using what he calls a Root Cause Tree® (2000); which looks much like a fault tree analysis. Here, investigators must investigate and eliminate each cause individually.

Ammerman recommends asking "If (blank) is the root cause, how does it explain the problem situation as well as comparable situations?" (1998 p. 68). No method is offered for answering Ammerman's question and this paper attempts to provide and evaluate a method suitable for answering Ammerman's question.

Robitaille (2004) offers no method and Berstene (2018) simply says to use tool without specifying which ones. Wilson, Fell, and Anderson suggest intuition and asking others who have experienced the failure, yet there may not be people available to ask (1993). The logic tree (Latino & Latino 2002), fault tree (Kubiak & Benbow 2009), and Root Cause Tree® (Paradies 2000) methods are all essentially fault trees; they list hypotheses for investigation, but do nothing for prioritization. Rooney and Hopen's evidence table (2005) comes closest to offering a method for hypothesis prioritization, but it is intended generating hypotheses based on collected data and not used for prioritization.

The concept of lines of evidence is well illustrated by Nusz et al., who assessed the risk to organisms in water due to the presence of octamethylcyclotetrasiloxane, a substance used in the production of polymer based products. They used the results of a survey of octamethylcyclotetrasiloxane and compared it to the evidence of harm in four different sets of data (2018).

Another example of lines of evidence in science is a study in which multiple lines of evidence are used to determine the origin of the domesticated chili pepper. Here, the evidence consisted of archeological evidence in the form of the location of old chili pepper remains. The ecological conditions necessary for wild chili peppers to grow were determined and using estimates for the necessary temperature and rainfall, the areas most suitable for chili peppers 6,000 years ago were located. A survey of 30 protolanguages in Mesoamerica was assessed for the terms relating to 41 crops including chili peppers; they then identified the earliest use of the word and the region in which the language was spoken. Expeditions were also conducted to collect genetic samples from wild chili peppers and the results were compared to genetic data from cultivated chili peppers to determine the location of wild verities that best matched domesticated varieties. An analysis of the four lines of evidence showed several regions in which chili peppers may have been independently cultivated, which was believed to be consistent with patterns of cultivation in other parts of the world (Kraft et al. 2014).

Another study used multiple lines of evidence to determine that a high level of arsenic in central Massachusetts ground water is the result of naturally occurring process resulting from the dissolution of minerals containing arsenic. Historical information was reviewed and the information indicated arsenic was not used in the area, geologic mapping, field observations from well drilling, concentrations of arsenic in local minerals, and the chemical composition of local groundwater (Nelson et al. 2010).

There is one occurrence of an L-shaped matrix as a hypothesis evaluation tool in the literature. Barsalou explains that observations are listed in the vertical column on the left and competing hypotheses are listed at the top of the matrix; an "X" is placed in the cell where an observation fits a hypothesis. This method can be used when following lines of evidence to a cause (2017). Unfortunately, this was a practical "how-to" type article with no scientific evaluation of the method.

Other methods for RCA in the literature include Kepner-Tregoe Problem Analysis (Kepner & Tregoe, 2006) and the is/is-not analysis (Schnoll, 2011). There is also the A3 report (Chakravorty, 2019) and 8D report (Vissir, 2017) as well as Plan, Do, Check, Act (PDCA) (Bushell, 1992). The Six Sigma approach to quality improvement can also be used for RCA (Barsalou & Perkin, 2018). Proprietary methods include Taproot (Paradies, 2000) and Shainin methods (Bhote & Bhote, 1991).

3. Methodology

3.1 The Essence of the Method for Formulating a Strong Hypothesis in RCA

An Ishikawa diagram should be expanded by copying the hypotheses from the Ishikawa diagram to a spreadsheet that can be used for prioritization and tracking the assigned investigation actions. New insights from the investigation, such as the unexpected discovery of a new potential cause, should then be entered into both an updated Ishikawa diagram and the spreadsheet itself. This approach has only been addressed once in the literature and it was a hypothetical example in a non-peer reviewed online publication (Barsalou, 2016a).

The goal of this paper is to show that combining an Ishikawa diagram with a tracking list together with an L-shaped matrix as a prioritization tool is a method for forming strong hypotheses during a RCA. To do so, the authors of this paper propose the use of an Ishikawa diagram with an action item tracking sheet and an L-shaped matrix for identifying the better hypothesis, where the better hypothesis is defined as one that would be testable.

Ishikawa diagrams are often presented in books and journal articles as a simple brainstorming tool; however, the inputs in the Ishikawa diagram should be transferred to a spreadsheet to help prioritizing, assigning investigation actions, and tracking the root cause analysis actions. This tool has existed for over 50 years (Sarazen, 1990) and remains relatively unchanged since it was first introduced to the wider world in the 1971 English translation of Ishikawa's classic work *Guide to Quality Control* (Ishikawa, 1991). There is has been little innovation in such a commonly used method and transferring the items from the diagram to a spreadsheet makes it easier to ensure items are investigated.

An Ishikawa diagram is not a static tool; it needs to be updated as the investigation continues and new information is unearthed. Mizuno warns against assuming the all causes are listed in the Ishikawa diagram advises updating the Ishikawa diagram as new potential causes are discovered during the investigation (1989).

According to the proposed method, the hypotheses from an Ishikawa diagram are to be copied into an action item tracker and compared to the results of a traditional an Ishikawa diagram without an action item tracker. The research hypothesis is that that teams using the modified Ishikawa and action item tracker will identify the correct root cause more often than those who use an Ishikawa without an action item tracker.

In addition, the authors of this paper propose that more-specific product relevant branch category names should be used in place of the traditional 6Ms. For a manufactured product, the cause will often be due to a quality failure such as a dimension out of specification or an error during assembly, a design that was not adequate for the indeed use, or misuse on the end user's side.

Specifically, an Ishikawa diagram with three branches is proposed. These branches would cover quality failures, design failures, and failures due to the end user. The hypotheses from the Ishikawa diagram would then be transferred to an action item tracker. Identifying the actions to take to investigate is believed by the authors to help ensure the hypotheses are ones that can actually be investigated. Available evidence should also be listed in a hypotheses prioritization matrix together with the hypotheses. This is thought by the authors to help in identifying the strongest hypotheses.

An action plan for items in an Ishikawa diagram has been described in the literature, but this one requires simply stating the corrective action for each item in the Ishikawa diagram. There is no assigned responsibility or deadline and corrective actions are assigned to all items without investigation to determine if the item is indeed the root cause (Mengesha et al. 2013). A method is needed for quickly evaluating hypotheses in a way that leads to the quickest identification of the root cause.

The concept of following lines of evidence is combined with an L-shaped matrix to create an evidence matrix, a tool for identifying the hypothesis that is best supported by the evidence (Barsalou 2015a).

In addition to evaluating the use of a tracking list of Ishikawa diagrams, a new method for prioritizing multiple competing hypotheses is worth looking for and this paper proposes using a variation on the L-shaped matrix. The proposed method uses the form of a matrix diagram for assessing lines of evidence so these two topics will be reviewed. This methodology will then be evaluated to determine if using it is more efficient than not using it when comparing hypotheses against observations.

A variation of the L-shaped matrix diagram can be used for following lines of evidence (Barsalou 2017). Following lines of evidence is a concept from science that can be applied to RCA. There may be multiple indications or observations that individually support a hypothesis. Following lines of evidence is especially helpful when there are multiple, potentially contradictory, pieces of evidence (Barsalou, 2015b). The point at which hypotheses converge is called consilience (Whewell, 1840).

An example of an evidence matrix is shown in Table 3, where no observation supports hypothesis number four. This hypothesis can be rejected. On the other hand, most of the evidence supports hypothesis two, so hypothesis two should be the highest priority for continued investigation. Ideally, an attempt should be made to run the problem on and off to confirm that it is the cause of the problem (Barsalou 2015a).

Table 3. Example of an evidence matrix

Observation	Hypothesis 1	Hypothesis 2	Hypothesis 3	Hypothesis 4
Observation 1		X	X	
Observation 2	X			
Observation 3			X	
Observation 4		X		
Observation 5		X		
Observation 6		X		
Observation 7	X			

3.2 Testing the Effectiveness of the Proposed Method with an Ishikawa Diagram

Two experiments were performed using engineers to evaluate the proposed methods for hypothesis selection and evaluation. One study evaluated the use of an Ishikawa diagram with a hypothesis related action item tracking list versus teams with just an Ishikawa diagram. The second study was performed to determine if the correct hypothesis was selected more often than would be expected by chance if hypotheses are compared to evidence in a list.

The particular set up was planned to determine if using the proposed methodology generated more testable hypotheses than not using the proposed methodology as represented by a simple list. The study participants were young engineers employed in manufacturing companies; each participant graduated from the university that performed the study and held at a minimum a bachelor degree, which included courses on basic quality tools. The participants returned to the university for graduate studies or additional coursework and volunteered to participate in the study when offered the opportunity.

Thirty teams consisting of three members each were presented a technical drawing of a pin and plate as shown in Figure 1, which was intended to represent a simple manufactured product. The team members came from various positions including quality and production engineers from manufacturing enterprises. They were informed that the pin would not fit into the block, which was intended to represent a manufacturing failure. Then each group was tasked with completing a cause-enumerative type Ishikawa diagram listing potential causes.

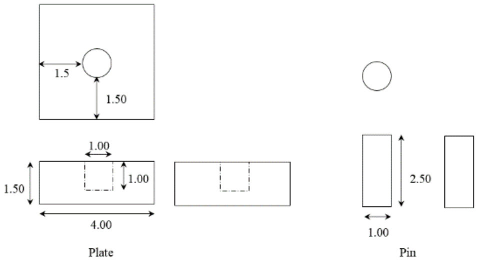


Figure 1. Pin and plate

Both groups of teams were each given the Ishikawa diagram with branches labeled quality failure, design failure, and end user failure as shown in Figure 2. Both groups of teams were instructed to identify 10 hypotheses explain the failure as well as how they would investigate the hypotheses. However, the first group (fifteen of thirty teams) was also given the tracking list shown in Table 4 and the second group was simply given a blank sheet of paper.

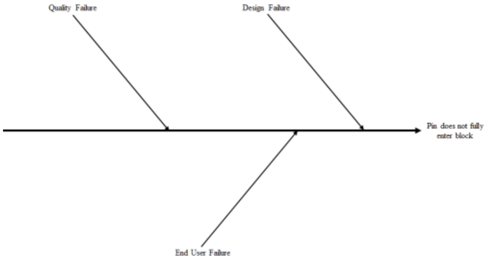


Figure 2. Modified Ishikawa diagram

Table 4. Action item tracker for a modified Ishikawa diagram

Main Branch	**Lower Branch Hypothesis**	**Action to Investigate**

The teams with the action item tracker were given the following instructions: "Observe the pin and plate drawing. The pin only partially enters the plate; it goes to a depth of approximately 0.5 mm and stops, but should enter and stop when it reaches the bottom of the 1.0 mm deep bored hole. Identify potential causes in the Ishikawa diagram that you were given and then transfer these potential causes to the worksheet that you were given. List the top branch, (quality failure, design failure, end user failure) in the top branch column and then list the potential causes under in lower branch hypothesis column. Once the potential causes are listed in the worksheet, identify actions to investigate the causes."

In place of an action item tracker, the second group of teams was only given a blank sheet of paper for listing any actions that they would take to investigate hypotheses. The second group of teams were given the following instructions: "Observe the pin and plate drawing. The pin only partially enters the plate; it goes to a depth of approximately 0.5 mm and stops, but should enter and stop when it reaches the bottom of the 1.0 mm deep bored hole. Identify potential causes in the Ishikawa diagram that you were given and then transfer these potential causes to the blank sheet of paper you were given. Once the potential causes are listed in the blank sheet of paper, identify actions to investigate the causes."

3.3 Testing the Effectiveness of the Proposed Method with a List

Authors such as Latino and Latino (2002), Paradies (2000), and Kubiak and Benbow (2009) offer methods for listing hypotheses, but these methods fail to explain how to prioritize among competing hypotheses. Instead, they simply recommend evaluating the hypotheses, but such an approach fails to consider the time and resources lost in evaluating incorrect hypotheses.

The goal of this next part of the study is the development and assessment of a method for comparing hypotheses to evidence or observations. The hypotheses here is the use of a list of evidence increases the possibility of identifying the correct hypothesis.

A scenario for a failing assembly was created based upon the drawing shown in Figure 3. In this hypothetical situation, a rotating assembly is failing with multiple damaged parts after each failure. The test subjects are to identify the component that fails first, leading to the follow-on failures.

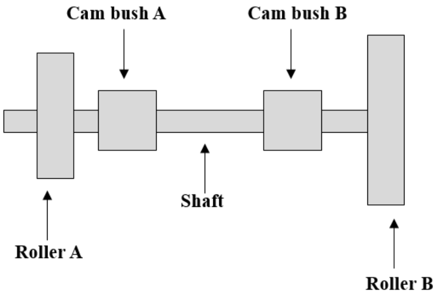
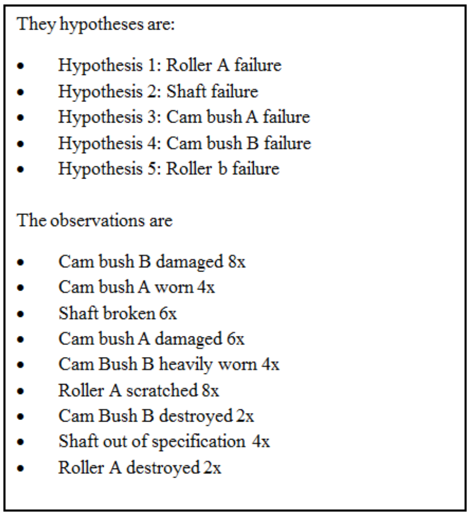


Figure 3. Failed assembly

Twenty-five engineers were presented with the following scenario: "An assembly is failing during use and multiple components are damaged during the failure making it difficult to identify the component that fails first leading to the subsequent failures. Your task is to use the given information to identify the component that fails first. All five hypotheses are that one part failed first leading to the damage on the others as the assembly continued to rotate after the initial failure; the part that failed first is different between the hypotheses. After the evaluator says 'start,' identify the responsible component."

All twenty-five engineers were given the list of hypotheses and observations shown in Figure 4. These respondents were be told to "Look at the list of hypotheses and observations. Use the information available to determine which component failed and led to the additional failures."



They hypotheses are:

- Hypothesis 1: Roller A failure
- Hypothesis 2: Shaft failure
- Hypothesis 3: Cam bush A failure
- Hypothesis 4: Cam bush B failure
- Hypothesis 5: Roller b failure

The observations are

- Cam bush B damaged 8x
- Cam bush A worn 4x
- Shaft broken 6x
- Cam bush A damaged 6x
- Cam Bush B heavily worn 4x
- Roller A scratched 8x
- Cam Bush B destroyed 2x
- Shaft out of specification 4x
- Roller A destroyed 2x

Figure 4. List of observations and hypotheses

4. Results

4.1 The Ishikawa Diagram Study Results

There are multiple potential causes of the failure. For example, the drilled hole may be too small or the pin diameter may be two large. If one of these is the case, it could be due to a part being out of specification or due to the tolerances of the two parts resulting in a contact situation even when the parts are in specification. Alternatively, the hole may simply be blocked by debris such as metal chips from a machining operation.

The resulting actions lists were evaluated to determine which hypotheses can be investigated empirically. Investigating testable hypotheses is more likely to lead to the correct cause and use of the Ishikawa diagram with a list for investigation actions required the study participants to think about how causes would be tested. For example, a measurement deviation can be checked by measuring the part. However, measurement deviation due to inadequate operator training can't be checked on the parts. The total number of hypotheses that could be investigated empirically was then divided by the total number of hypotheses listed by the team. To determine if there was a statistically significant difference, a hypothesis test two proportions was performed. A test of proportions is used to determine if there is a statistically significant difference between proportions (Silver 1997). Here, it was performed to compare the totals for both groups to determine if the difference in results was due to random chance or due to different methodology. A test of proportions was ideal for this study as the study results were well suited for converting not a portion by dividing each groups number of testable hypotheses by the total number of hypotheses generated.

The results for the groups with an action item tracker are shown in Table 5 and the results for those without an action item tracker are shown in Table 6.

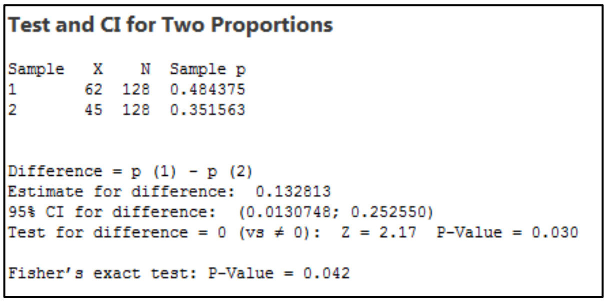
Table 5. Results using Ishikawa diagram with action item tracker

Team number	Total number of hypotheses	Number of testable hypotheses
1	9	5
2	4	4
3	9	6
4	10	7
5	9	3
6	13	9
7	10	3
8	8	2
9	11	1
10	8	5
11	10	2
12	9	0
13	5	5
14	8	5
15	5	5

Table 6. Results using an Ishikawa diagram without an action item tracker

Team number	Total number of hypotheses	Number of testable hypotheses
1	10	4
2	3	0
3	8	2
4	3	2
5	12	1
6	9	1
7	10	9
8	5	4
9	10	3
10	10	6
11	12	1
12	14	3
13	7	1
14	6	6
15	9	2

The proportions of testable to non-testable hypotheses for each group were analyzed with a two tailed test of two proportions with an alpha of 0.05 and the results are shown in Figure 5. This was done to determine if the difference in results was statistically significant. There is a statistically significant difference in proportions between the groups with a modified Ishikawa diagram and an action item tracker an Ishikawa diagram with a blank sheet of paper. A two tailed hypothesis test only determines if there is a statistically significant difference so (Barsalou and Smith 2019) a one tailed lower tail test of two proportions with an alpha of 0.05 was performed and there is still statistically significant difference between the two groups as shown in Figure 6.



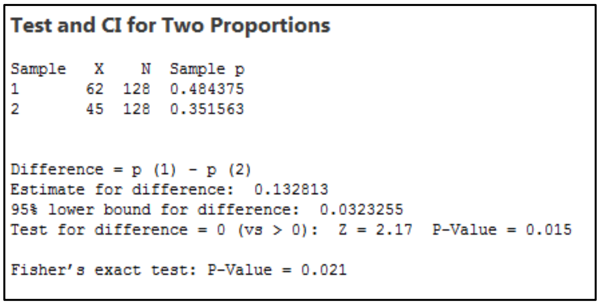
```
Test and CI for Two Proportions

Sample   X    N  Sample p
1       62  128  0.484375
2       45  128  0.351563


Difference = p (1) - p (2)
Estimate for difference:  0.132813
95% CI for difference:  (0.0130748; 0.252550)
Test for difference = 0 (vs ≠ 0):  Z = 2.17  P-Value = 0.030

Fisher’s exact test: P-Value = 0.042
```

Figure 5. Two tailed test of two proportions



```
Test and CI for Two Proportions

Sample   X    N  Sample p
1       62  128  0.484375
2       45  128  0.351563


Difference = p (1) - p (2)
Estimate for difference:  0.132813
95% lower bound for difference:  0.0323255
Test for difference = 0 (vs > 0):  Z = 2.17  P-Value = 0.015

Fisher’s exact test: P-Value = 0.021
```

Figure 6. One tailed test of two proportions

The teams using a modified Ishikawa diagram and action item tracker identified more testable hypotheses than those using a blank sheet of paper. Providing structure in the form of a tracking list seems to have increased the quality, in terms of empirical testability, of the hypotheses as a hypothesis that can be tested is more likely to lead to the root cause than one that is untestable.

4.2 The List Study Results

The most supported hypothesis is cam bush B failure with three observations that support it. Furthermore, the total number of cam bush B occurrences exactly matches the total number of failures; cam bush B was either damaged, heavily worn, or destroyed in one hundred percent of the failures.

Hypothesis four, cam shaft B, was selected sixteen times. Hypothesis two was selected five times, hypothesis one was selected three times, and hypothesis five was selected twice. Hypothesis three was not selected by any of the respondents. The results are shown in Figure 7.

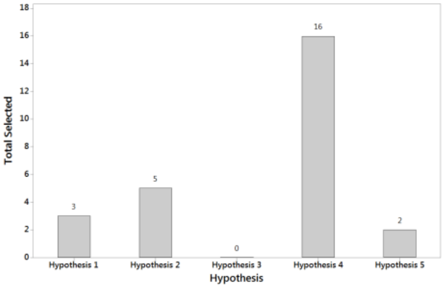


Figure 7. Results of failed shaft study

The results were statistically analyzed using a Chi-Square Goodness of fit test, which compares the number of occurrences to the expected number of occurrences (Box et al. 2005). Figure 8 shows a comparison of observations to the expected values and Figure 9 shows a comparison of the contribution to the results by category.

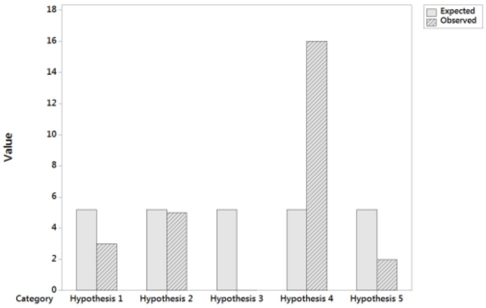


Figure 8. Comparison of observed and expected values

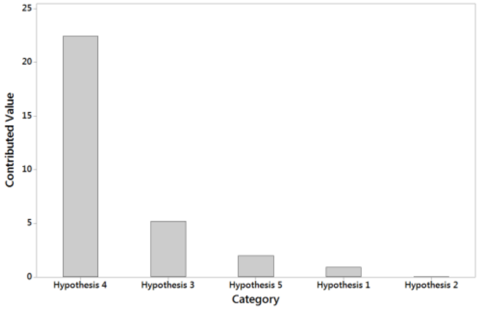


Figure 9. Contribution to the Chi-Square value by category

Hypothesis four was selected more often than the other hypotheses and the difference is greater than random chance. Listing available evidence lead to the selection of the correct hypothesis in the majority of trials.

5. Discussion and Conclusions

The authors of this paper believe that by applying the methods described and evaluated in this paper it is possible to better formulate hypotheses during root cause analysis than in the case of traditional (and more intuitive) approaches. The first study demonstrated a method of turning Ishikawa diagram inputs into hypotheses in a spreadsheet that could be used for prioritization and tracking investigation actions. New insights gained from the investigation would then be feedback into the Ishikawa diagram as a hypothesis and the new hypothesis would then be entered into the tracking spreadsheet so that actions could be assigned. The Ishikawa diagram is a time-tested tool; that does not mean it is not time to update it as shown in this case study.

In addition, the use of the Ishikawa diagram is expensively covered in the literature, both in case studies and "how-to" type articles. However, empirical support for such a basic quality is lacking in the literature. Although a comparison of use of an Ishikawa diagram versions not using an Ishikawa diagram was outside the scope of this research, there is now evidence available to support the effectiveness of an Ishikawa diagram with an action item tracker versions and Ishikawa diagram without an action item tracker.

The second study showed the value of having an overview of all available evidence when selecting a hypothesis as a strong candidate for the root cause; this would save resources as the hypothesis that is more likely to be correct would be evaluated before less well supported hypotheses. The L-shaped matrix is a quality tool that already exists that can be used in place of a simple list. The observations can be listed in the column on the left and the hypothesis can be listed in the top row; an X can be placed in the appropriate cells when an observation fits a hypothesis.

Research on the effectiveness of quality tools is lacking. Much of what can be found in the literature pertains to the use of quality tools in organizations (Starzyńska 2014) and not the effectiveness of quality tools. In addition, much of what is written on quality tools is a of a descriptive nature; either describing how to use the tools or describing how the tools were used in an actual case.

There is empirical research on the use of quality tools such as a study to determine if company size relates to quality tool usage or to identify the most company used quality tools (Fonseca & Silva, 2015). In spite of common usage in industry and many published articles on quality tools, there is scant empirical evaluation of the effectiveness of quality tools. This paper set out to fill the gap in the literature; however, there are still many quality tools that have yet to be assessed for effectiveness. There is much room in the literature for additional empirical investigations into the effectiveness of quality tools.

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