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ORIGINAL ARTICLE

Introduction to cause-effect chain analysis plus with an application in solving manufacturing problems

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Abstract

Root-cause analysis (RCA) is useful in solving inventive problems in any area including manufacturing. It often plays the central role because the root causes revealed can directly imply directions for solutions. This study introduces a new RCA method called cause-effect chain analysis plus (CECA+), improved from the existing method, cause-effect chain analysis (CECA). CECA+ uses a single diagram built and updated in seven steps to manage all the main information of a problem solving process in a systematic and intuitive way. The seven steps are problem definition (1), building and verifying cause-effect chains (2, 3), building and verifying solving direction chains (4, 5), and building and verifying idea chains (6, 7). Based on the theory of solving inventive problems (TRIZ), it can help users to reveal hidden, overlapping or contradictory causes and to generate comprehensive solving directions semi-automatically. It also greatly improved the drawing convenience and readability by using a versatile free diagramming software and a set of intuitive and systematic drawing conventions. CECA+ has been used successfully in many problem solving projects. Application to solving a real problem in manufacturing process was described with tips for using.

Keywords Root cause analysis · Cause-effect chain analysis · Problem solving · Problem analysis · Idea generation · TRIZ · Innovation

1 Introduction

In this fast-changing world, full of competitions, there is a growing need for good methods and tools for innovation, particularly for analyzing and solving problems, generating ideas, and designing systems. Among the methods for inventive problem analysis, root cause analysis (RCA) often plays a central role because finding the right root causes can be critical in finding ideas for improvement.

As consultants in innovation area, the authors have been using many different RCA methods in various innovation projects and education since the end of the 1990s. Experiencing the pros and cons of different RCA methods, we combined the best features into a new version of RCA method and have been improving it further to get a more powerful and convenient RCA method for general problem solving for improving or inventing a system. This paper, which is the outcome of these long efforts, introduces a new RCA method to readers and articulate where and how it differs from others and describe how it is used in real problem solving projects.

In Section 2, we redefine the meaning and scope of RCA method in relation with the goal of our study. A few existing methods which are more suitable for our purpose are selected and briefly introduced. Then, they are analyzed by an RCA to find their deficiencies which lead us to requirements needed for a new method. Section 3 introduces how to use our new method and Section 4 explains a case

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study from our real consulting project to show how CECA+ is used in real context step by step.

2 Selected existing RCA methods and their deficiencies

RCA is a collective term that describes a wide range of approaches, tools, and techniques used to uncover causes of problems [1]. It has been applied in various fields with different purposes. In general, root cause analysis can be defined as a process of analysis to define the problem, to understand the causal mechanism underlying transition from desirable to undesirable condition, and to identify the root causes of problem in order to keep the problem from recurring by using a structured procedure [2]. Here,

- The SYSTEM can be a product, an equipment, a tool, a process, a service or a business which already exists or is to be developed.
- The PROBLEM of the system can mean any (future, current or past) undesirable state of useful functions (features, performance and quality etc.), cost (excessive use of money, material, energy or other resources) or harmful functions (harmful side effects and accidents etc.) of the system.
- The CAUSES can mean either the potential or real causes of a past problem or possible causes of a future problem

There are many methods for analyzing causes of a problem. This section restricts the discussion only to those methods which are more often used in innovation projects in industries, especially in manufacturing area. Such methods can be grouped into five categories.

1. Brainstorming-based methods: possibly using Post-It's (e.g., KJ Method) or Mind Maps
2. Category-based methods: in Fishbone (Ishikawa) Diagram or in Logic Tree format
3. Process variable-based methods: Process mapping with variables, Process FMEA
4. Causal relation mapping methods: 5 Whys [3] (e.g., in Cause Mapping [4] template), cause-effect chain analysis (CECA) [5, 6], problem formulator [7], root conflict analysis (RCA+) [8], fault tree analysis [9]
5. Supporting methods for finding hidden causes: function analysis [10], Anticipatory Failure Determination [11], and Harmful System Theory [12]

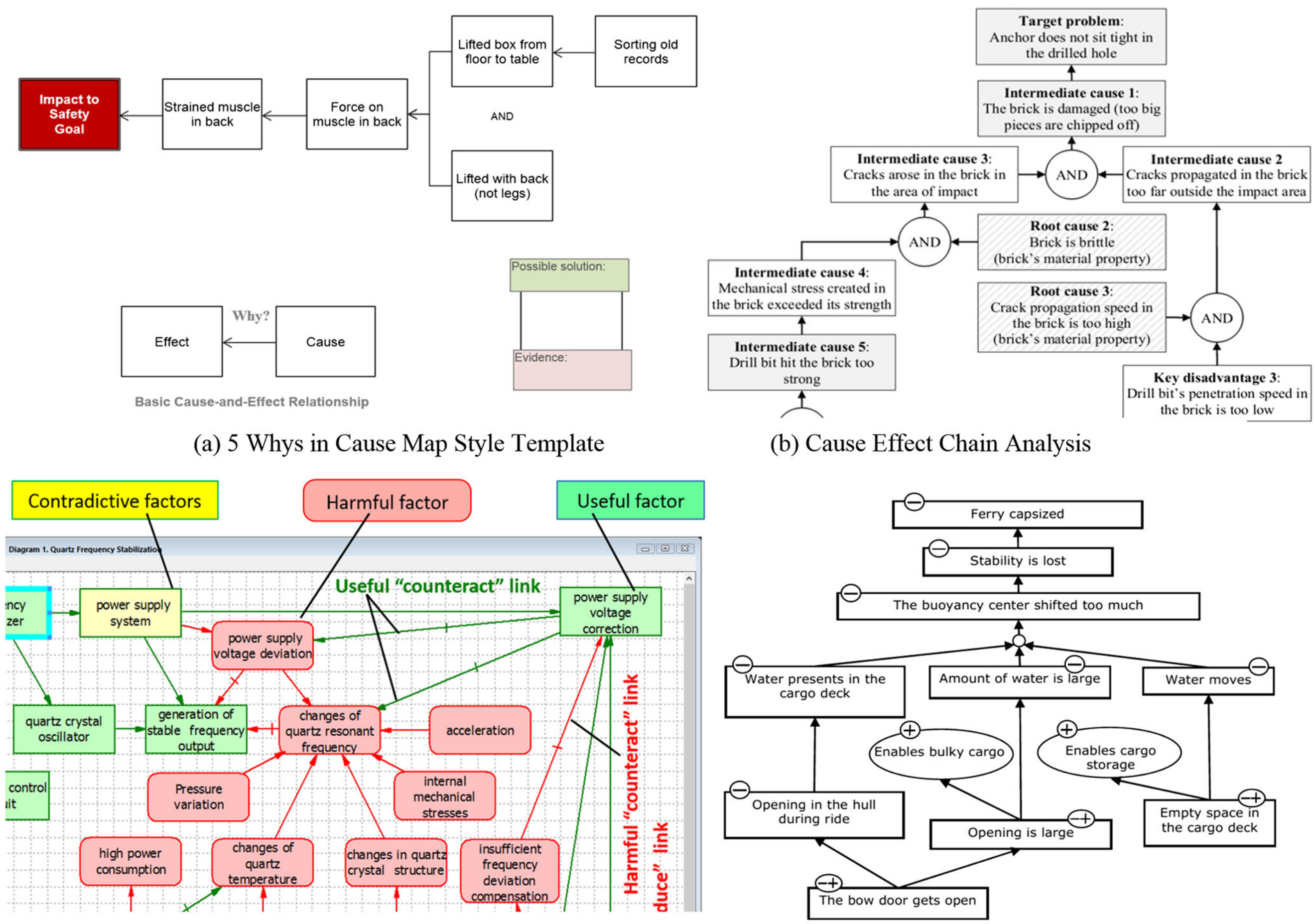
Generally speaking, the brainstorming-based methods are easy and flexible but provide not enough guide for searching initially unknown causes. The category-based methods guide the user to search the potential causes in a hierarchical tree structure of categories or search areas. The process variable-based methods guide the user to search the causes from input variables for each process step usually following the flow of time. Both category-based and process-based methods can guide the user to search or check causes from relatively unbiased set of search areas but their guide is limited because no tools except brain are provided to investigate the causal relation between the potential causes and the target problem. The causal relation mapping methods can guide the user to follow the chain of actions and states responsible for the target problem from end to the beginning step by step. Although a bit difficult to use, these methods have the basic capability to guide the user to investigate and reveal the hidden causes of a problem systematically. The other, supporting methods for finding hidden causes are sometimes very powerful but either more difficult or less often used than others. They require deeper knowledge and skills in value engineering or TRIZ.

Since the goal of this research is development of an RCA method that is powerful and convenient for general problem solving and conceptual design, the latter part of this section focuses on the causal relation mapping methods. Among the five methods in this category, fault tree analysis is excluded because this is mainly used in the fields of safety engineering and reliability engineering to identify comprehensively the ways how systems can fail, whereas the other methods can be used for more general problem solving, for example, improving an existing system or developing a new one in manufacturing. Examples of these four RCA methods are shown in Fig. 1.

1. 5 Whys [3], the classical RCA method which were developed in the 1950s in Toyota and then further developed into many variations including Cause Mapping [4] by Think Reliability,
2. Cause-effect chain analysis [5, 6], a standard RCA method used in TRIZ by GEN3 Partners Inc.,
3. Problem formulator [7], a module of a software for innovation of Ideation International Inc.,
4. Root conflict analysis (RCA+) [8], a TRIZ-based RCA method by ICG Training & Consulting.

To compare these methods and find their pros and cons, a set of evaluation criteria for RCA methods are needed. Reviews of requirements used for this purpose can be found in [13, 14]. However, since this study is more focused in RCA for general problem solving, a modified version of evaluation criteria is needed to suit better for our purpose. To do this, we conducted a simple RCA to find out the deficiencies of the existing RCA methods like 5 Whys, as shown in Fig. 2. The root causes found from this RCA shows directions for improving 5 Whys method.

5 Whys is known to be the first widely used RCA method [3]. Cause Mapping method developed it further into a convenient excel template and included evidence of the causes and possible solutions for each node [4].



(a) 5 Whys in Cause Map Style Template (b) Cause Effect Chain Analysis

(c) Problem Formulator (d) Root Conflict Analysis (RCA+)

Fig. 1 Diagrams of selected RCA methods for general problem solving

Although the appearance of cause-effect chain analysis is similar to 5 Whys, CECA has many advantages. It identifies the target problem and causes from other analysis methods systematically used together in a TRIZ project roadmap like benchmarking analysis, function analysis, flow analysis, or trends of engineering system evolution. And CECA's analysis is often deeper and more accurate due to many useful rules and conventions. When 5 Whys stops too early at superficial causes, CECA keeps revealing chains of hidden causes leading to more ideal solutions. It also informs the user where to terminate the search for causes. It can represent an overlapping (common) cause and helps identification of contradictions. With support from the TRIZ methods in solving stage, it helps the user to generate solving directions or preliminary ideas [5, 6].

Problem formulator is both a method and a module in a software called Innovation WorkBench (IWB) for doing RCA and generating solving directions. Problem formulator also uses a chain structure instead of the simple tree structure of 5 Whys. It uses three kinds of nodes (useful, harmful, and contradictory) and two kinds of arrows or "links" (produces and counteracts). So, it can represent contradictions more visually [7]. When the user builds an as-is model diagram correctly, the problem formulator can automatically generate dozens of solving directions to improve the system. But since the solving directions are generated as a text file, it is difficult to locate from which part of the diagram the solving directions is generated. Being a commercial software, it is not free of charge. Although problem formulator is more versatile and flexible than CECA, problem-solvers or readers without big experience can be lost in the complex freedom without additional guidelines for orientation.

Root conflict analysis or RCA+ combines some of good features of problem formulator and CECA, so it can represent both useful and harmful results and contradictions in the diagram. It focuses on contradictions and situations with interrelated multiple contradictions [8] but as with CECA, it does not clearly provide guide to generate all the type of way to generate solving directions from cause-effect chains. And all the tree RCA methods based on TRIZ do not emphasize or mention about the verification or evaluation

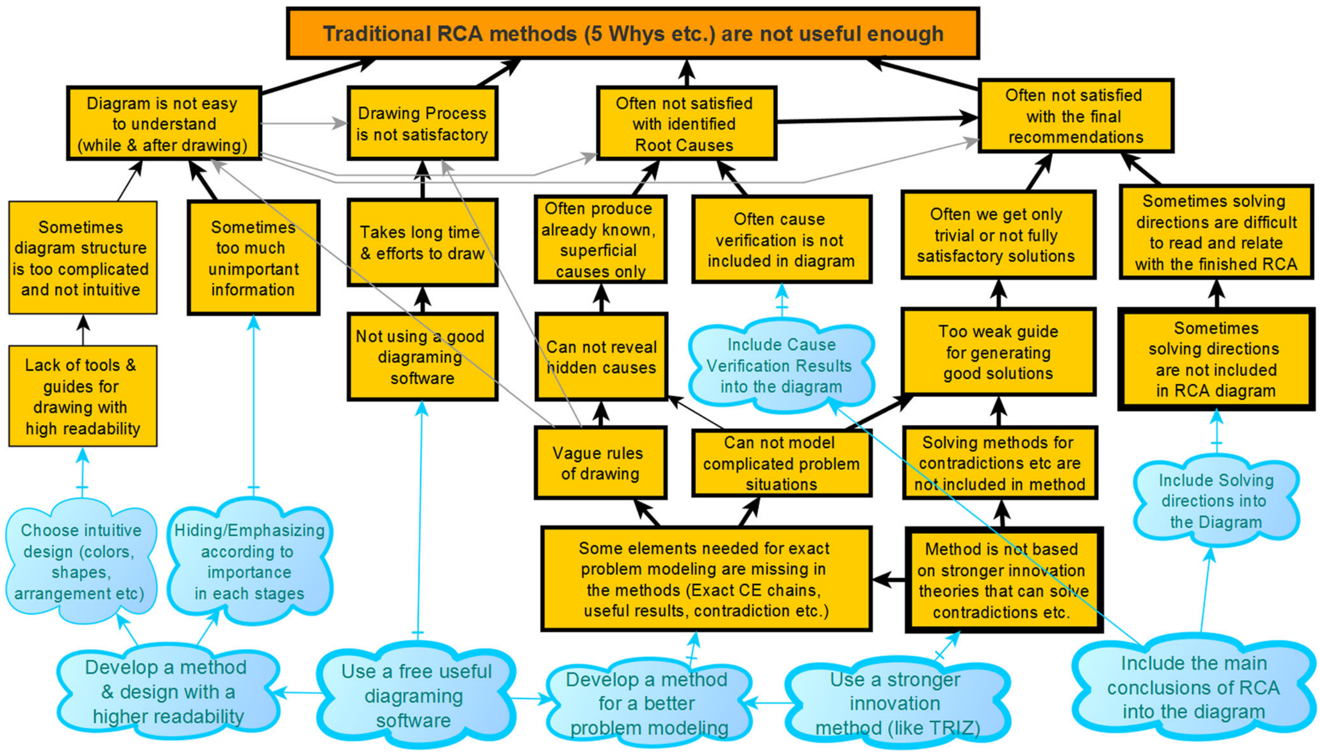


Fig. 2 RCA diagram on deficiencies of traditional RCA methods (simplified)

of the cause-effect chains. They do not incorporate solving part into the diagram. They neither provide convenient tools for drawing nor provide drawing conventions for templates for better readability.

Combining such information about 5 Whys and other methods and the existing evaluation criteria in the literature, a set of evaluation criteria was created against which the selected RCA methods were compared in Fig. 3. For

			RCA Methods					
			5 Whys	Cause Mapping	CECA	Problem Formulator	RCA+	CECA+
	Traditional Best Drawing Tool ->	weight	Any Drawing SW	Excel CM Template	Any Drawing SW	Innovation Work Bench	Any Drawing SW	yEd with templates
Evaluation Critera: Cause Analysing Method	Modeling common or contradictory causes	Weight depends on user, problem and situation	1	2	4	5	5	5
Evaluation Critera: Cause Analysing Method	Other Guide for finding hidden causes		2	2	4	4	4	4
Evaluation Critera: Cause Analysing Method	Clarity of Method (Definitions etc)		2	3	4	4	4	4
Evaluation Critera: Cause Analysing Method	Ease of Learning (Simplicity of logic)		5	4	3	2	3	3
Evaluation Critera: Solving Method	Guide to Generate Good Solving Directions		2	2	4	5	5	5
Evaluation Critera: Integrating Conclusions	Integration of Verification Results		2	3	2	2	2	3
Evaluation Critera: Integrating Conclusions	Integration of Solving Direction Results		3	3	3	4	3	5
Evaluation Critera: Intuitive Design	Readable & Intuitive Design		2	3	3	4	4	5
Evaluation Critera: Intuitive Design	Hiding/Emphasizing by Importance		3	3	3	3	3	4
Evaluation Critera: Convenient Drawing Tool	Cost Efficiency of the Best Software		5	5	5	2	5	5
Evaluation Critera: Convenient Drawing Tool	Drawing Convenience for Experienced user		3	4	3	4	3	5
Evaluation Critera: Convenient Drawing Tool	Drawing Convenience for Nonexperienced user		3	4	3	3	2	3

The above results of evaluation can depend on user, problem and situation

Evaluation Scale :	1	2	3	4	5
	Very Bad	Bad	Average	Good	Very Good

Fig. 3 Comparison of RCA methods for general problem solving

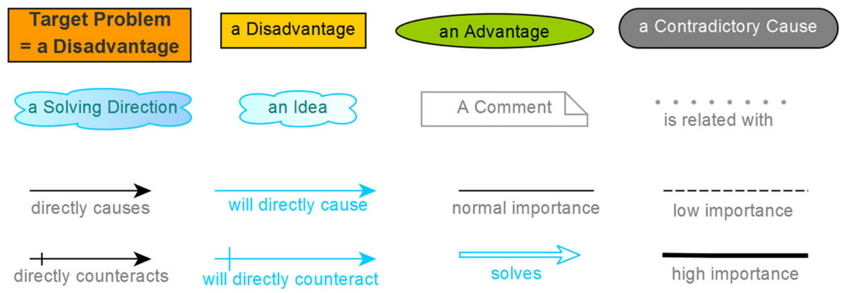


Fig. 4 Notations for CECA+ diagram

convenience, evaluation result of the new method CECA+ was also included in Fig. 3. Care was taken to base the evaluation on objective criteria like existence of certain functions or features but relatively subjective parts can still exist.

3 Introduction to the new method—cause effect chain analysis plus (CECA+)

This section introduces the basic rules and conventions to draw the diagram according to our new method. Although CECA+ can be drawn with any diagramming tools, it is strongly recommended to use yEd Graph Editor (https://www.yworks.com/products/yed) or Southbeach Modeller (http://www.southbeachinc.com/) to maximize drawing efficiency. Although the design conventions of the nodes and arrows in a CECA+ can be varied depending on the drawing tool or user preference, the following conventions are recommended for more readable and intuitive CECA+ diagrams. The new method is typically executed in seven steps—problem definition (1), building (2) and verifying (3) cause-effect chains, building (4) and verifying (5) solving direction chains, and building (6) and verifying (7) idea chains.

3.1 The notations of CECA+ diagram

A CECA+ diagram is built with the following types of entities which are shown graphically in Fig. 4:

- **A node** is a small object with area with different shapes representing the node types—a disadvantage, advantage, a contradictory cause, a solving direction, an idea, or a comment.
- **An arrow** can connect two nodes, starting from a node representing "direct controllable cause" and ending on a node representing direct "result" or "effect" of the cause.
- Two or more **arrow heads meeting exactly at a point** on the boundary of a node means that all the causes for the arrows are needed to get the result. A mark "&" could be added to clarify it for non-experienced users.
- In an as-is CECA+, if a node generates only harmful results, it is called **a disadvantage** (an orange rectangle). The target problem that a CECA+ wants to analyse is also a disadvantage. If a node generates only useful results, it is called **an advantage** (a green ellipse). If a node generates both a useful and a harmful result, it is called **a contradictory cause** (a gray stadium shape).
- **a comment** on plan or result of verification or evaluation can be added and connected with a dotted line to the related location in the diagram.
- A blue cloud can represent a **solving direction**. If an arrow with a short crossing bar is drawn from a solving direction to a disadvantage or an arrow, the solving direction is about counteracting (removing or mitigating) them. If a simple arrow is drawn from a solving direction to an advantage, the solving direction is about an alternative way of achieving the advantage. The hollow sky blue arrow represents solving the contradictory cause which it directs by using the separation principles in TRIZ. A sky blue cloud is an **idea** along the solving direction that it points with an sky blue arrow.

3.2 Procedure of conducting CECA+

This section explains the process of drawing and updating a CECA+ diagram through the seven steps with a series of sample diagrams in Fig. 5.

1. **Problem definition** CECA+ starts from the target disadvantage (Disadvantage 1) whose removal is the goal of the problem solving. It is better to check whether the first choice of target disadvantage is correct or not (as in Section 4.2.1).
2. **Building the cause-effect chains**
   (a) Identify and draw all direct controllable causes (like Disadvantages 11, 12) of the above disadvantage as nodes below it. Connect with an arrow each pair of cause and result. If there are other results of the causes, draw them also in the upper level and connect. If there are other causal relations between existing nodes, draw them also.

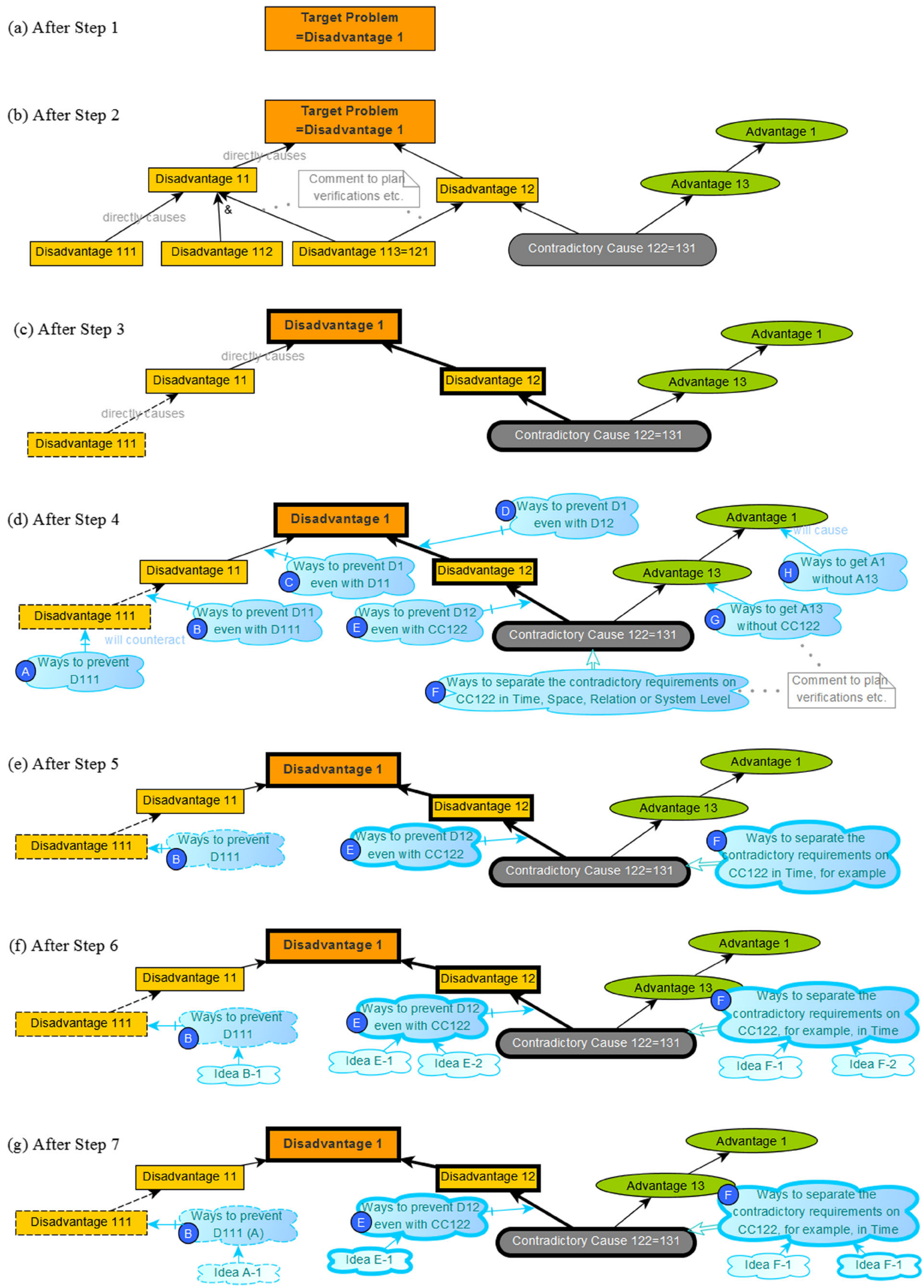


Fig. 5 A series of schematic diagrams showing the procedure of a CECA+ analysis

(b) For all the controllable direct causes just found, repeat step 2 (a) layer by layer until no more controllable direct cause is left. It is not needed to draw uncontrollable causes. The last direct controllable cause of a chain is called a key disadvantage.

3. **Verifying the cause-effect chains** Check validity and importance of each causal relations. Remove invalid causes and reduce visibility of invalid or less important causes by using dashed lines. Highlight more important causes by using thicker lines. Use comments for plans and results of verification.
4. **Building the solving direction chains** For each key disadvantage (the rectangle at the lower end of a chain, e.g., Disadvantage 111) remaining after cause validation step, identify and draw solving directions (like the cloud labelled "A") which can counteract (remove or mitigate) the key disadvantage. Draw a **counteraction arrow**. For a single-strand chain, removing the key (end) disadvantage will guarantee removal of all the disadvantages in the chain (results) if the cause-effect chain is perfectly drawn. But because of the complexity and difficulty of making a perfectly exhaustive cause-effect chains, it is often recommended to build it rather quickly at first. One can usually generate additional solving directions (like the clouds B, C, D, E) by trying to challenge each arrow (**"to cut the chain"**) from the end by asking "How can I make the above disadvantage not happen even if the cause below did happen?." Find at least **3 directions for each cause with contradicting results** (stadium)

(a) by cutting the cause-effect chain (as already did with the cloud E),
(b) by trying to find alternative ways (like the clouds G, H) to achieve the above advantage,
(c) and by solving the contradiction with **separation principles** of TRIZ (like the cloud F). This is one of the strong TRIZ methods for solving opposite and incompatible requirement on an object [15]. Brief explanation is as follows. There are opposite and incompatible requirement that the contradictory cause (122) should exist (to have the advantage 13) and its opposite (state or action) should exist (to prevent occurrence of the disadvantage 12). But if any of the exact times, spaces, conditions or system levels for these contradicting requirements differ with each other, the contradiction can be resolved by separating the opposite requirements into different times, spaces, conditions or system levels.

It is important to note that once the cause-effect chain is built, the words describing the solving directions can be automatically generated in the sense that they can be constructed from a simple excel function for concatenating words as in "ways to prevent" & (the above effect) & "even with" & (the below cause) for the case (a) of chain cutting. See other expressions that can be automatically generated in clouds in (d) of Fig. 5. Of course, these are only rough and big directions but they are quite complete and can prevent the solvers to miss other big directions for solutions.

5. **Verifying the solving direction chains** Check feasibility and importance of each solving directions. Remove or hide invalid or less important solving directions. Highlight and focus on the more important solving directions and generate ideas. Use comments for plans and results of substantiation and evaluation of the solving directions.
6. **Building the idea chains** Generate more detailed ideas for each solving direction. Add the ideas into the diagram as child clouds linked to the solving direction or write them elsewhere with trackable labels.
7. **Verifying the idea chains** Check feasibility and importance of each ideas. Update visibility of the ideas according to the result.

3.3 Characteristics of a CECA+ diagram

CECA+ was built on the merits of existing RCA methods and tools. To mention a few, the basic cause-effect chain structure is similar to all, but more similar with the TRIZ-based RCA methods. Use of "&" is similar to but simpler than fault tree analysis [9]. But CECA+ is improved from those existing methods in efforts to overcome most of the limits of the methods already mentioned in detail in Section 2. To summarize the change here, the process and result of generating solving directions are visually integrated into the diagram helping the user generate and interpret the solving directions easily. The process and result of verification of causes and solving directions are also incorporated into the diagram to help the user focus on important ones. The readability and ease of drawing were also much improved in CECA+ by using a convenient, versatile, and customizable diagramming software and a set of intuitive design conventions. In conclusion, as a one-diagram method for problem solving, CECA+ provides a convenient and intuitive way of visually thinking the causal relations of a problem and visually generating solving directions and ideas on the diagram systematically and semi-automatically.

4 Applying CECA+ to solve a real manufacturing problem and tips for using

The CECA+ method has been used in more than 100 projects, consulting or coaching. Because it can be used

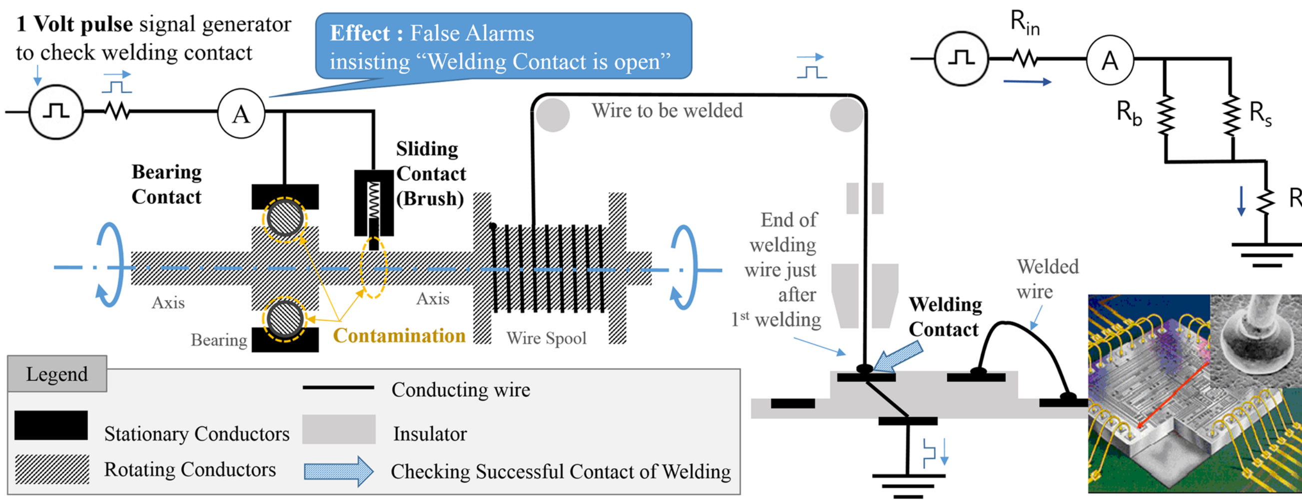


Fig. 6 Simplified view of the problem situation (while checking the bonding just after bonding a wire)

as a stand-alone method that can analyze and solve the whole problem in a single diagram updated in several steps, CECA+ has been the best choice for a short 2-h meeting or workshop for problem solving. In most of the cases, it helped the user, either the authors or customers who just learned it, discover a more comprehensive set of big directions for solving a problem.

The section introduces how CECA+ method is used in solving a real problem in a manufacturing line. Since the basic rule of conducting CECA+ was already introduced in Section 3, this section will focus more on the context, thinking process and related tips. Some details are omitted and simplified to keep the description understandable for most readers.

4.1 Initial situation

A large mass production line of wire bonding process had a problem that each bonding machine stopped 58 times a day due to false alarms. Wire bonding is a process of making electrical interconnections with very thin metal wires between an integrated circuit (IC) chip and substrate during semiconductor device fabrication. As illustrated in Fig. 6, what it does is basically arc welding the end of a

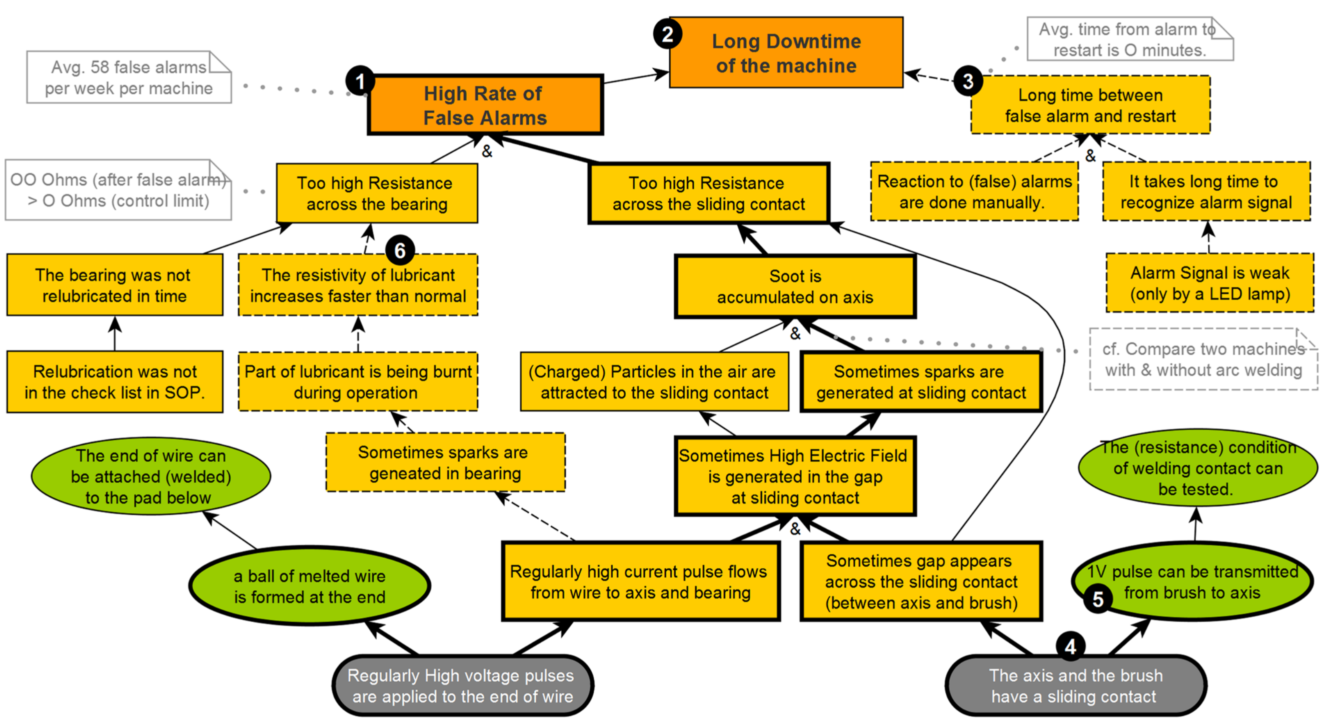


Fig. 7 A simplified version of the CECA+ diagram in step 3 (cause verification)

thin metal wire on a metal pad on an IC and then welding the other end on another pad on the substrate, cutting the wire and doing it over again for another pair of pads. After welding of the first end of wire, the machine checks the resistance across the first welding contact by flowing 1 Volt pulse through it. When the measured resistance is bigger than a certain value, the machine stops working and flash an alarm signal. But the reason of "false" alarms was not clear in the beginning of the project.

4.2 Using CECA+ to analyze and solve the problem

4.2.1 Defining and verifying the target problem (step 1)

The initial problem goal was to reduce the rate of false alarm occurrence. So the first node to start the CECA+ is ❶ "High Rate of False Alarms" as shown in Fig. 7. One could drill down the chains by asking the control question for RCA —"What causes the high rate of false alarms?" But when starting a new project, it is better to go up the chain structure to check the validity of given problem. The control question in RCA for going up is "What is the direct result caused by this?" The answer was ❷ "long downtime of the machine." If ❷ seems to be a better target problem to solve, we can select it as the new top node of cause-effect chain. Such verification of initial target problem by reverse (upstream) building of cause-effect chains can sometimes expand the scope of project, open new causes (❸ and below it) and new solving directions that were initially neglected as in this case. This verification of the initial target problem (target disadvantage) can help users to start with the correct or better problem to solve.

4.2.2 Building cause-effect chains (step 2)

After selecting the target disadvantage ❷ , we drill down the cause-effect chain as explained in Section 3. At the end of drilling down the chains, we meet the cause ❹ at the bottom right corner of the diagram in Fig. 9. When questioned "What are the direct cause of ❹ having a sliding contact?," one should not answer "to transmit 1 Volt pulse from brush to the axis" and put it below ❹ , because this is not a cause but a purpose or a desirable result of ❹ . Instead, the node ❺ has to be placed above ❹ as a desirable result. The resulting V shape with a partial solution, a desirable result, and an undesirable result defines a contradiction, an important concept of TRIZ.

4.2.3 Verifying the cause-effect chains (step 3)

The cause-effect chains just built is a draft guess of the real cause-effect chains, maybe a little bit bigger collection not to miss any important cause. To find areas to focus our efforts, we need to verify the reality and importance of each chain. The method of evaluation can be just a careful thinking, asking others, direct inspection of real situation, searching information, data analysis, experiment, simulation and survey, etc. One can add a comment into the diagram with a short text representing plans or result of the verification actions. These comments are connected to related node or arrows that it wanted to test. After cause verification, the visibility (thickness of lines etc.) of nodes and arrows can be changed according to the result as shown in Fig. 7. A part of the diagram can be even deleted (❻) or added. One of the main cause of the false alarms was the increase of the electrical resistance across the sliding contact due to deposition of soot particles which are generated from sparks in sliding contact as shown in Fig. 8.

4.2.4 Building and verifying solving directions and ideas (steps 4–7)

From the verified and evaluated cause-effect chains, possible solving directions were generated and added to

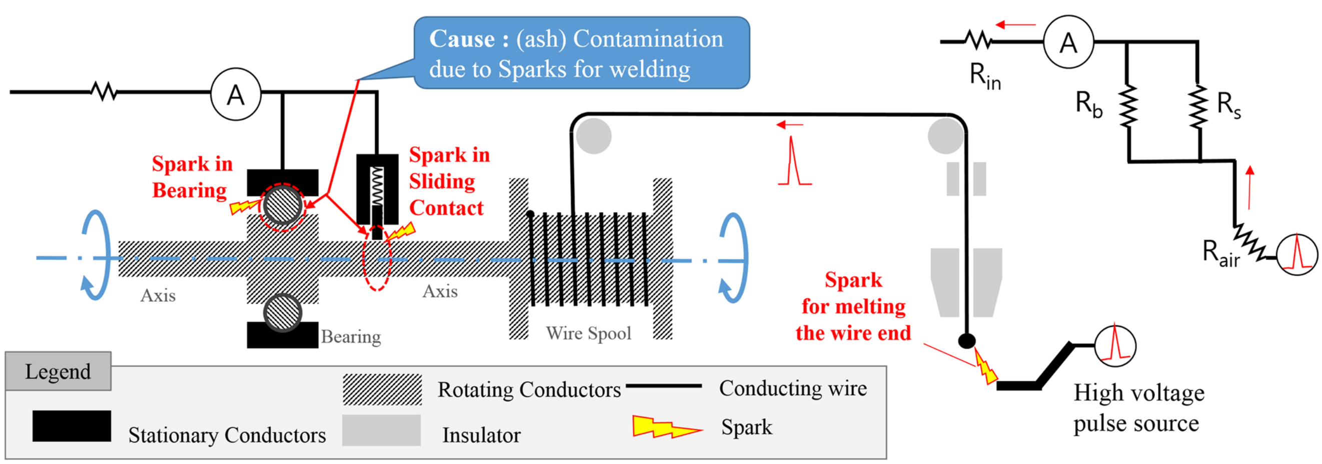


Fig. 8 Simplified view of main causes (while bonding a wire just before Fig. 6)

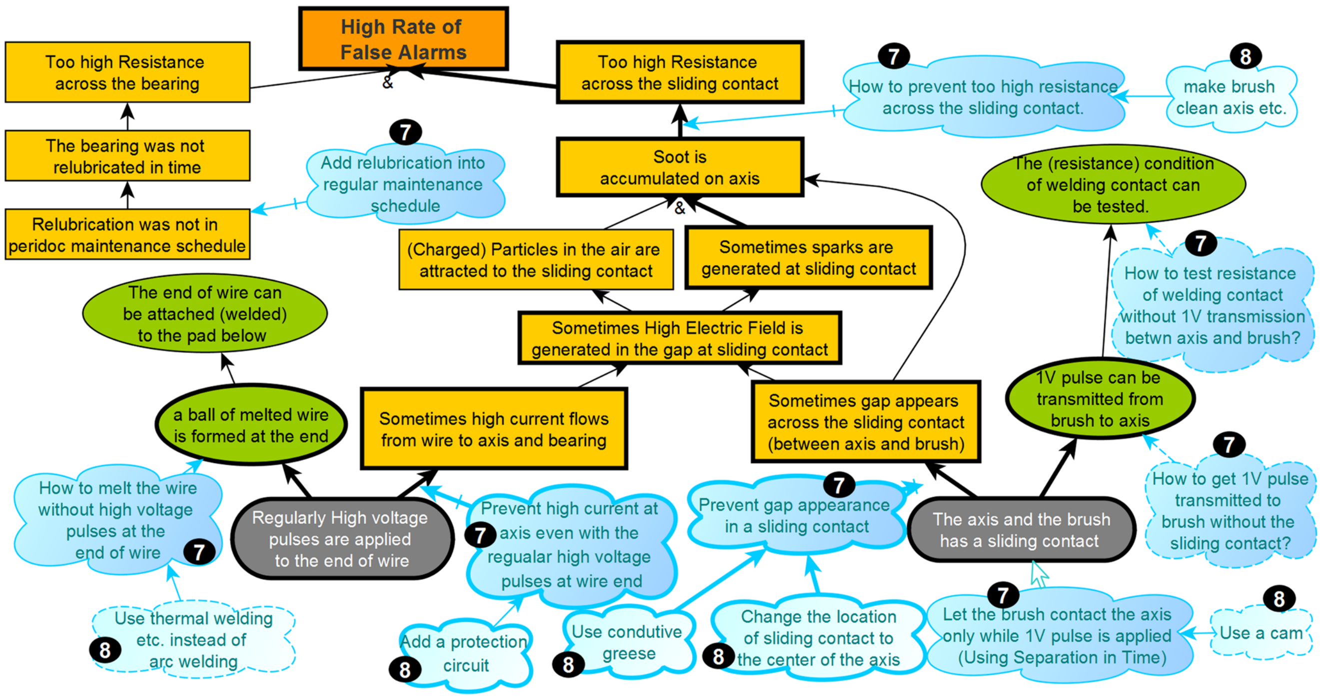


Fig. 9 A simplified version of the final CECA+ diagram after step 7 (idea verification)

the diagram as clouds with arrows according to the rules described in Fig. 5. Due to TRIZ, the theory of problem solving, many distinct directions for solutions could be semi-automatically generated. In Fig. 9, several feasible solving directions were added in the diagram as clouds 7. Then, after evaluating all the solving directions, some clouds were removed, made less or more visible according to their practical importance. Sometimes, below the clouds directly connected to cause-effect chains, one can add child clouds 8 representing more detailed ideas for solution.

4.3 Implementation of the solution and result

Some of the ideas including the use of conductive grease were selected and implemented by the problem owner (the details cannot be shown due to the confidentiality). Immediately after implementation, this kind of false alarms which used to be 58 times per day per machine suddenly dropped to zero and never appeared again.

5 Conclusion

This study introduces a new version of RCA method called cause-effect chain analysis plus (CECA+) that can be used for general problem solving. It is the outcome of the authors' long efforts to develop practical method and tool for innovation projects.

A comparison of several chosen RCA methods and an RCA on their deficiencies shows directions for improving the old methods.

CECA+ uses a single diagram updated in seven steps to visually capture all the main outcomes of the problem solving process in an efficient and intuitive way. The seven steps are problem definition (1), building (2) and verifying (3) cause-effect chains, building (4) and verifying (5) solving direction chains, and building (6) and verifying (7) idea chains.

Based on the theory of solving inventive problems (TRIZ), CECA+ can help users to reveal hidden, common, and contradictory causes and to generate innovative solving directions and ideas semi-automatically. It also greatly improved the convenience of drawing and readability by using a versatile free diagramming software and a set of intuitive and systematic drawing conventions.

CECA+ has been successfully used in more than 100 projects that the authors have consulted or coached. Because it can be used as a stand-alone one-diagram method, CECA+ has been successfully used even in in a short 2-h meeting for problem solving. Application in solving a manufacturing problem is described with tips for using.

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