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Indicating and assessing quality criteria for cause-effect models

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Abstract. It seems to be a common understanding in the TRIZ community that cause-effect models built for the same problems by different analysts may differ a lot and also that it requires some practice to build "good" cause-effect models. This paper aims at identifying reasonable quality criteria and feasible ways of applying them to models developed using Cause-Effect Chains Analysis (CECA) and Root Conflict Analysis (RCA+). The paper starts with considerations about human factors in causal modeling and a review of the relevant TRIZ literature. Then various approaches to quality are briefly presented, and the proposed assessment method is described. Although the most important semantic level has not been addressed, the rules of syntactical correctness have been formulated, which may be used for automated model validation in software applications.

Keywords: TRIZ, Cause-Effect Chains Analysis, Root Conflict Analysis, CECA, RCA+, quality criteria, formal language.

1 Cause-effect analysis – craft or art?

People performing cause-effect analysis use their specific capabilities, perception, and life experience to build a causal model. Therefore the model is more like a painting inspired by the problem situation rather than a photograph of this situation. And even for a photograph, the results strongly depend on light conditions as well as the intent and perspective taken by the photographer, which is expressed by using a particular view, lens, and filters. Expecting two paintings of the same object to look the same sounds pretty unrealistic, but in the case of a portrait, each of the paintings should be adequately similar to the original object, i.e. sufficiently *correct* and *complete*.

We may also perceive a cause-effect model as a map of the analyzed problem, which reflects its selected characteristics and ignores the others. And so, the cartographers use different projections for maps properly showing either the distances or the angles or the areas, as the perspective of the *correctness* of a model depends on its purpose. To address the aspect of *completeness*, let us point out that to retain all the details, a map of a city should be probably nearly as big as the city itself, which would make it usability next to none. Hence, a useful map – as well as a useful model – should reduce the complexity of the original, preserving its characteristics necessary for the intended use.

So when is the cause-effect model creation like craft, and when is it more like art? The analysts apparently use two main resources, namely their education building the knowledge and their personal experience building professional wisdom or mastership. The former is standardized – for instance, everybody is taught at school that the kinetic energy of a moving object depends on the mass of the object and its velocity. Consequently, when the analyzed problem pertains to kinetic energy, the influence of mass and velocity should be reflected in the cause-effect model. This is a craft level of the analysis, which is reasonably expected by default.

We try to identify which causes are primarily responsible for the appearance of the initial problems, and we are expected to solve these problems. Therefore the analysis may also be perceived as a medical diagnosis stated by a doctor from observed symptoms and an interview with the patient. Suppose the situation fully matches a typical pattern. In that case, the chances to correctly diagnose a well-known disease or health disorder are high even for an inexperienced physician because this falls into the scope of standard education. However, when the symptoms are incomplete or ambiguous, a correct diagnosis requires additional expertise that comes from experience. Likewise, an experienced analyst would presumably indicate more effective directions to explore than a newcomer, bringing more finesse to the cause-effect analysis and approaching it to the art level.

2 Right problem vs. right model

A lot was written in TRIZ literature about the selection of "the right problem", but what about "the right model"? How can we tell if a given cause-effect model is right or not? Does right mean appropriate? Of high quality? What constitutes the quality of a cause-effect model? What can we measure or evaluate to assess the model quality?

The creators of each method defined rules and guidelines stating how the cause-effect diagrams should be built and analyzed, which are generic in nature and refer mostly to structure rather than the contents, which is unknown a priori. Therefore the correctness of a model may be assessed by judging if its structure complies with these rules. The problem is that with time the original rules have been changed by different researchers in different directions (see the next section). Consequently, the correctness of a model evaluated against one set of rules cannot be easily related to the results of assessment referring to another set of rules unless one of them is contained in another.

We might try to generalize this approach and consider a model to be correct if and only if it correctly reflects cause-effect relations of the problem situation. Regrettably, indicating that X causes Y (or Y is triggered by X) seems to be just the beginning of an investigation. Does this mean that X *must* always trigger Y or that X *may* trigger Y? How soon and to what extent will Y appear when X appears? What parameters are used to decide if X or Y has occurred? Moreover, the time axis may be perceived in different ways depending on the situation – consider e.g. blowing fuse vs. corroding metal.

It should also be emphasized that cause-effect analysis is not being done for itself, as we don't need just a neat model. We need to provide, or at least propose, a solution to a particular problem.

It is similar to using a drilling machine for making a hole in the wall – what we need is just the hole and using a drilling machine is solely a way of achieving this goal. Therefore the usability or effectiveness of the model seems to be a better candidate for a quality perspective than its formal correctness. On the other hand, a drilling machine will not make a hole without an operator. An experienced operator can achieve acceptable results using inadequate tools, while even the highest-quality tool in the hands of a newcomer does not guarantee success. And this also holds for cause-effect models, as their contribution to the project success greatly depends on the analysts' skills.

3 Cause-effect analysis in TRIZ

The chronology of the selected TRIZ-related attempts to develop cause-effect analysis is briefly described below, with a focus on the quality aspects. Among the numerous approaches, Cause-Effect Chains Analysis (CECA) and Root Conflict Analysis (RCA+) methods have been selected for further consideration due to their popularity.

- 1995 – Ponomarenko [1] – a systematic approach to formulating candidate problems derived subsequently by traversing a cause-effect chain.
- 1996 – Litvin and Akselrod [2] – methodical theses on building diagrams and identifying key problems; this is probably the oldest set of CECA rules.
- 2001 – Abramov and Kislov [3] – practical guidelines for building and analyzing cause-effect diagrams developed for in-company purposes.
- 2001 – Pavlov [4] – a systematic approach to transforming key disadvantages into a map of key problems connected with logical operators.
- 2001 – Apte, Sha, and Mann [5] – considerations about using the 5W+H approach (who-what-when-why-how) to enhance cause-effect analysis and other TRIZ tools.
- 2005 – Souchkov [6] – introducing Root Conflict Analysis (RCA+) method, modeling both negative and positive effects to support identification of contradictions.
- 2007 – Pinyayev [7] – combining cause-effect analysis with identification of typical problems and recommendations on solving these problems (Functional Clues).
- 2007 – Axelrod [8] – Interactions Causality Scheme as a hybrid modeling concept merging cause-effect analysis with function analysis and flow analysis.
- 2007 – Khomenko and De Guio [9] – introducing Network of Problems for analyzing a problem situation from causes to effects and indicating goals and partial solutions.
- 2011 – Efimov [10] – considerations regarding proper selection of key disadvantages in CECA models and transforming them into key problems.
- 2011 – Howladar and Cavallucci [11] – introducing Problem Graph for modeling problems and partial solutions with strict rules of creating text descriptions of nodes.
- 2013 – Falkov and Misyuchenko [12] – analysis of typical errors made during selecting logical operators combining causes in cause-effect models.
- 2013 – Falkov and Misyuchenko [13] – considerations regarding possible errors in building linear cause-effect chains and identification of such errors.
- 2013 – Medvedev [14] – categorization of repeatable cause-effect patterns based on statistical analysis distinguishing parameter- and interaction-related disadvantages.

- 2014 – Yoon [15] – introducing rules for building cause-effect models using parameter-related disadvantages interleaved with interaction-related disadvantages.
- 2014 – Kisela [16] – approach to support RCA+ method with quantitative data and fuzzy logic calculations.
- 2015 – Dobrusskin [17] – considerations regarding the identification of contradictions within CECA and RCA+ models as well as IST/SOLL approach.
- 2016 – Kislov [18] – methodical guidelines for creating and analyzing CECA models using outcomes from Function Analysis.
- 2016 – Chrzęszcz and Salata [19] – partitioning a CECA model into contents and structure layers and analyzing the structure described as a set of Boolean functions.
- 2017 – Chrzęszcz [20] – complementing combinational approach to CECA with rules supporting the selection of key disadvantages using quantitative attributes.
- 2017 – Chrzęszcz [21] – TRIZ literature review focused on selecting the problems for solving and interactions between TRIZ and Neuro-Linguistic Programming.
- 2017 – Lok [22] – approach to support the quality of cause-effect models using MECE criteria (Mutually Exclusive and Collectively Exhaustive).
- 2017 – Sun [23] – considerations regarding proper selection of target disadvantages in a CECA model, including the effects of initial target disadvantages.
- 2018 – Abramov and Savelli [24] – considerations regarding combining key problems derived from CECA and other TRIZ tools into Conceptual Directions.
- 2018 – Chrzęszcz [25] – indicating contradiction in the classic CECA approach and introducing hazard-vulnerability perspective with model completeness criteria.
- 2018 – Chrzęszcz [26] – transforming a CECA diagram following condition-action style into a state machine model with synchronization on equivalent conditions.
- 2018 – Lok [27] – an attempt to describe CECA as an algorithm and procedure for validating candidate key disadvantages.
- 2018 – Lee, Chechurin, and Lenyashin [28] – introducing the CECA+ approach for indicating advantages, contradictions, solution directions, and ideas in one model.
- 2019 – Chrzęszcz [29] – an algorithmic approach to deriving quantitative characteristics from a CECA model using its structure and logical operators solely.
- 2019 – Chrzęszcz [30] – considerations regarding the applicability of logical negation in CECA models and differences between negation, conflict, and contradiction.
- 2019 – Chrzęszcz [31] – transforming a state machine CECA model into a regular expression using formal grammar.
- 2020 – Chrzęszcz [32] – an algorithmic approach to describing cause-effect models and conditions for eliminating key disadvantages using nested logical expressions.
- 2020 – Sun [33] – introducing a new operator to be used in CECA diagrams with quantitative extensions for alternative causes combining to 100% of the impact.
- 2020 – Chrzęszcz [34] – introducing computer-friendly representation for building and processing cause-effect models.
- 2020 – Chrzęszcz [35] – using inspirations from RCA+ and Standard Inventive Solutions to extend state machine CECA models with patterns of candidate solutions.
- 2020 – Hanifi et al. [36] – introducing Inverse Problem Graph, inspired by Problem Graph, RCA+, CECA+, and Lean approach, which uses 8 types of objects.

The methods proposed in the mentioned works seem to aggregate into a few main areas indicated below, although some concepts cannot be categorized unequivocally.

- introducing additional constraints without changing the procedure [3, 15, 18],
- introducing patterns or statistics coming from practical experience [7, 14],
- introducing additional object types into the model [6, 8, 17, 28, 33, 36],
- introducing additional rules or criteria [4, 6, 10, 12, 13, 17, 20, 21, 23, 24, 27],
- introducing elements of quantitative analysis [16, 17, 20, 28, 29, 33],
- supporting selection of key disadvantages [4, 10, 24, 27, 29, 32],
- changing modeling paradigm [6, 8, 9, 11, 19, 20, 25, 26, 30, 31, 32, 35, 36].

The aspects of model correctness or completeness appear in several works, but they are usually described as examples, remarks, or guidelines rather than explicit criteria which could be assessed in a systematic way.

4 Different approaches to quality

There are five different approaches to quality indicated in [37]: *transcendent*, *product-based*, *user-based*, *manufacturing-based*, and *value-based*. As the first one has mainly philosophical meaning, we will focus on the remaining four used in business and management. A few well-known quality definitions derived from these approaches are given below.

Table 1. Selected definitions of quality [37, 38].

author	perspective	description
Crosby	manufacturing-based	conformance to requirements
Lvov	product-based	all product's properties which determine its usefulness
Deming	user-based	how well a good or service meets consumers' needs
Juran	user-based	fitness for use
Drucker	value-based	what the customer is willing to pay for
Taguchi	value-based	intended operation of the product without variability

The conformance to requirements is equivalent to the formal approach to quality mentioned before, which is also expressed in ISO 9000, where quality is defined as the *degree to which a set of inherent characteristics fulfills requirements*. The advantage of this attitude is that the characteristics of a product may be objectively verified before it is supplied to the consumer, while a known drawback is that the requirements may not fully represent the consumer's needs. The opposite approach is to perceive quality as entirely subjective and user-dependent.

These four quality perspectives fall into two broader categories oriented towards the supply side (manufacturing-based, product-based) and the demand side (user-based, value-based), which seem to correspond with the *voice of the product* and the *voice of the customer* perspectives used in TRIZ. Additionally, Drucker's definition combining the notion of quality with consumer's willingness to pay comes close to the concept of Main Parameters of Value (MPVs).

A correct and complete model is expected to support the development of strong solutions properly. Yet, an incorrect or incomplete model may still inspire such solutions – so what is the purpose of assessing the quality of models? For the masters working at the art level and capable, like Paganini, to play a violin concert with only one string, this is probably not important, but the rest of the TRIZ community would presumably benefit from practical criteria for evaluating the quality of models during their creation. The valuable outcome of such a quality check, preferably automated, would be the early detection of errors. The main questions appearing in this context are listed below, and we will address them in the following sections of the paper.

- Which of the mentioned approaches may be used for cause-effect models?
- What and how should we measure to assess the quality of such models?
- To what extent are such measures objective, repeatable, and comparable?
- What shall we do with the results of the quality evaluation?

5 Causality model as a formal expression

A causality model consists of chains of causes that may connect on inputs (with common causes) or outputs (with logical operators) just like a story is built upon a plot being a system of interconnected threads. One part of the story described by a cause-effect model is embedded into the structure of branched chains constituting the plot, while the other part is written into the text labels of boxes. A good story requires good structure and good content, and in cause-effect models, the content is problem-specific so that it may be (and usually it is) highly specialized and thus difficult to examine, especially in an automated way. As the Artificial Intelligence methods necessary to understand the meaning and assess the quality of box descriptions remain beyond the scope of this work, we will focus on evaluating the correctness of the structure of the model. Such a challenge looks not only much easier than assessing the quality of the whole model but – being domain-neutral – also more universal.

To take an ordered approach, let us point out that a formal language is defined by an alphabet, vocabulary, syntax, and semantics [39]. Alphabet is a set of all allowable symbols used in a given language, vocabulary is a set of allowable words built over the alphabet, syntax defines allowable patterns of expressions built over the vocabulary, and semantics determines the meaning of expressions. An expression is considered correct if it obeys the syntax of a given language. The completeness will not be further considered, as its assessment requires understanding the box descriptions. On top of that, one cannot usually be sure if a given effect may not be triggered by another cause or a combination of causes that have not been indicated in the model [29].

Although the linguistic approach to analyzing the correctness of causality models seems reasonable, the formal notations used in this area are oriented to linear sequences of symbols. They cannot be directly applied to branched structures typical for cause-effect diagrams (not to mention feedback connections). Therefore we will use the concept of syntactical correctness merely as an inspiration and apply a different approach to assess the quality of models based on the allowable patterns of interconnections.

The CECA models following the guidelines stated in [2] contain boxes with text labels reflecting disadvantages, unlabeled arrows indicating causality flow from causes to effects, AND operators reflected with explicit objects, and OR operators shown as explicit objects or implied by converging arrows. An arrow may connect two boxes, two operators, a box with an operator, and an operator with a box.

Possible interconnection variants are described in the following tables; "2+" stands for "2 or more" and "X" stands for "any number", which is equivalent to "don't care".

Table 2. CECA box type and correctness as a function of the number of inputs and outputs if AND and OR operators are explicit objects.

in	out	status	description
0	0	incorrect	error: an isolated object
0	1	correct	a root cause
0	2+	correct	a common root cause
1	0	correct	a target disadvantage
1	1	correct	an intermediate disadvantage – possibly a linear chain segment
1	2+	correct	a common intermediate cause
2+	X	incorrect	error: no more than one input is allowed

Table 3. CECA box type and correctness as a function of the number of inputs and outputs if AND operators are explicit objects and OR operators are implied by convergent arrows.

in	out	status	description
0	0	incorrect	error: an isolated object
0	1	correct	a root cause
0	2+	correct	a common root cause
1	0	correct	a target disadvantage with a single direct cause or AND on input
1	1	correct	an intermediate disadvantage – possibly a linear chain segment
1	2+	correct	a common intermediate cause
2+	0	correct	a target disadvantage with an implied OR operator on input
2+	1	correct	an intermediate disadvantage with an implied OR operator
2+	2+	correct	a common intermediate cause with an implied OR operator

Table 4. CECA operator type and correctness as a function of the number of inputs and outputs if only AND and OR operators are allowed.

in	out	status	description
X	0	incorrect	error: at least one output is required
0	X	incorrect	error: at least two inputs are required
1	X	incorrect	error: at least two inputs are required
2+	1	correct	a multi-input operator sourcing a single cause
2+	2+	correct	a multi-input operator sourcing a common cause

One of the most important extensions to the classic CECA method is the condition-action approach [15]. This postulate normalizes the content of a model, but it does not affect the structure, and thus it cannot be evaluated using the proposed approach unless we introduce two distinct types of boxes [26]. Similarly, the recommendations regarding the correctness and completeness of a model, considered by several authors [10, 12, 13, 17, 19, 20, 22] cannot be verified by analyzing the structure solely, as they depend on the meaning (semantics) of the model contents.

The RCA+ models consist of boxes with text labels, unlabeled arrows connecting causes with effects, explicit AND operators with 2 or more inputs, and implied OR operators depicted by converging arrows. Contrary to the CECA, where all the boxes reflect disadvantages, the RCA+ models use boxes of several categories. This results in a more complicated representation, which appears in the literature in two versions. The original notation [6] uses different shapes and plus/minus markers, while the simplified notation differentiates boxes by shape and color, as described below.

- negative effect (cause) – a rectangle with a "-" marker (orange),
- non-changeable cause – a rectangle with a "--" marker (red),
- positive effect – an oval with a "+" marker (green),
- contradiction cause – a rectangle with a "+-" marker (yellow).

Table 5. RCA+ non-changeable cause ("--" / red box) – correctness as a function of the number of inputs and outputs.

in	out	status	description
X	0	incorrect	error: at least one output is required
0	1	correct	a root cause (correct if the successor is not green)
0	2+	correct	a common root cause (correct if none of the successors is green)
1	X	incorrect	error: a red box must not have predecessors
2+	X	incorrect	error: a red box must not have predecessors

Table 6. RCA+ negative effect ("-"/ orange box) – correctness as a function of the number of inputs and outputs.

in	out	status	description
0	0	incorrect	error: an isolated object
0	1	correct	a root cause (correct if the successor is not green)
0	2+	correct	a common root cause (correct if none of the successors is green)
1	0	correct	a target disadvantage
1	1	correct	an intermediate cause (correct if the successor is not green)
1	2+	correct	a common intermediate cause (correct if none of the successors is green)
2+	0	correct	a target disadvantage with an implied OR operator
2+	1	correct	an intermediate cause with an implied OR operator (correct if the successor is not green)
2+	2+	correct	a common intermediate cause with an implied OR operator (correct if none of the successors is green)

Table 7. RCA+ contradiction cause ("+-"/ yellow box) – correctness as a function of the number of inputs and outputs.

in	out	status	description
X	0	incorrect	error: at least two inputs are required
X	1	incorrect	error: at least two inputs are required
0	2+	correct	a common root cause (correct if exactly one successor is green)
1	2+	correct	a common intermediate cause (correct if exactly one successor is green)
2+	2+	correct	a common intermediate cause with an implied OR operator (correct if exactly one successor is green)

Table 8. RCA+ positive effect ("+" / green oval) – correctness as a function of the number of inputs and outputs.

in	out	status	description
0	0	incorrect	error: isolated object
X	1	incorrect	error: a green box must not have successors
X	2+	incorrect	error: a green box must not have successors
1	0	correct	correct if the predecessor is yellow
2+	0	incorrect	error: green box must have exactly one predecessor

Table 9. RCA+ AND operator – correctness as a function of the number of inputs and outputs.

in	out	status	description
X	0	incorrect	error: at least one output is required
0	X	incorrect	error: at least two inputs are required
1	X	incorrect	error: at least two inputs are required
2+	1	correct	a multi-input operator sourcing a single cause (correct if none of the neighbors is green)
2+	2+	correct	a multi-input operator sourcing common cause (correct if none of the neighbors is green)

The rules presented above for RCA+ models may be rephrased as follows:

- a target disadvantage is, by definition, a negative effect (an orange box),
- a legitimate root cause should be indicated as non-changeable (a red box),
- a red box must have no predecessors and one or more orange or yellow successors,
- an orange box may have any number of red, orange, or yellow predecessors and any number of orange or yellow successors, excluding zero-zero combination,
- a green box must have exactly one yellow predecessor and no successors (if several causes bring the same positive effect, then the respective green box is replicated),
- yellow box may have any number of red, orange, or yellow predecessors, one or more orange or yellow successors, and exactly one green successor (if the same cause brings several positive effects, then they are indicated in one green box),
- an AND operator must have two or more red, orange or yellow predecessors and one or more orange or yellow successors.

During the formulation of the correctness criteria for RCA+ models, a possibility of improvement has been identified: upon finding a positive effect of a cause that also has negative effects, we should change its color to yellow (contradiction cause), while on the other hand, the root causes may also have positive effects. In other words, seeing a yellow box, we don't know if it was originally orange or red, as by changing a red box into yellow, we would lose "this is a non-changeable cause" information previously recorded in the model. This remark also applies to the original notation using plus/minus markers, as it exhibits the same deficiency.

A workaround to avoid this ambiguity is not to look for positive effects of non-changeable causes, which seems to serve well the purpose of identifying only solvable contradictions [40]. However, suppose a cause is labeled as non-changeable by mistake. In that case, such an approach turns counterproductive since by skipping the search for positive effects, we give up the chance to verify the categorization and fix the error.

6 Summary and further work

Let us summarize the above considerations by answering the questions asked before.

Which of the mentioned approaches to quality may be used for cause-effect models? We have only explored a manufacturing-based perspective relying on assessing the conformance of a model structure to predetermined requirements. This is expected to support the usefulness of a model as well, which defines the product-based approach. User-based and value-based perspectives have been rejected as being subjective while analyzing textual box descriptions has been considered beyond the scope of this work.

What and how should we measure to assess the quality of cause-effect models? Using inspiration from the formal languages, we have devised quality criteria for all categories of objects appearing in CECA and RCA+ models, which use the numbers of incoming and outgoing connections to assess structural correctness.

To what extent are such measures objective, repeatable, and comparable? A benefit of selecting easily recognizable structural characteristics is that they are objective, and therefore each object may be unequivocally judged as correct or incorrect, and quality check results obtained by different people using the same model should be identical.

What shall we do with the results of the quality evaluation? The proposed approach reduces quality assurance to assessing the correctness of object connections within the model, which obviously does not touch the merit reflected by the contents of the model. Despite this crudeness, it allows for checking if the connection patterns of all objects in the model obey the respective rules, which appears close to the syntactical level of correctness. Due to its simplicity and algorithmic nature, this approach may be easily transformed into a software application, but its inherent drawback remains the inability to verify the completeness of models.

As declared in the abstract, we have proposed reasonable quality criteria (although limited to assessing structural correctness) and feasible ways of applying them to CECA and RCA+ models. We have also suggested an improvement in the RCA+ method, resulting from the analysis of correct and incorrect configurations.

Further research may address expanding the scope of verification beyond a single object and its direct neighbors as well as merging it with the concept of the causality matrix [29, 32] to support the creation and automated analysis of cause-effect models.

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