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Examining the structural attributes of TRIZ contradiction Matrix using exploratory data analysis

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Abstract

While the efficacy of TRIZ Contradiction Matrix (CM) is still being disputed, CM has been widely used due to its relative ease of use compared to other TRIZ methodologies. However, research on CM has been dominated by case studies of its use, the fundamental structure and components of CM have not been thoroughly explored. This study aims to enhance our understanding on CM by analyzing the relationships between its structural elements and constituents. To do so, Exploratory Data Analysis (EDA) was utilized to explore the correlations between the parameters of improving and worsening features and inventive principles within the intersection boxes. Frequency analysis conjectured a considerable similarity between the same attribute parameters that possessed opposing features. Association rules analysis (ARA) was conducted to identify the structural features of CM. On average, 56.67% of similarity was observed in the inventive principles located within the symmetrical intersection boxes around the matrix's main diagonal. Remarkably, 93.62% of the intersection boxes shared at least one common inventive principle. Propositional logic was adopted as a conceptual tool to interpret and understand the observed probabilities of inventive principles within CM's symmetrical intersection boxes. The findings showed that both improving and worsening parameters tend to converge in function enhancement due to the inventive principles in the intersection boxes. Given that parameters symmetric with the CM's main diagonal represented physical contradiction relations, this study suggests that the intersection box's inventive principles could potentially offer solutions to these physical contradictions. By examining the correlations between 39 Parameters of CM and 40 inventive principles within the intersection boxes, this study provides meaningful insights to understand the complex mechanisms of CM.

Keywords: Exploratory Data Analysis, TRIZ Contradiction Matrix, 40 Inventive Principles

1. Introduction

Today, the significance of creativity is emphasized at personal, corporate, and even national levels (DiPietro, 2004; Puccio, 2017). In this regard, TRIZ (Theory of Inventive Problem Solving: Teoriya Resheniya Izobretatelskih Zadach) has gained substantial attention as a creative and systematic approach to problem-solving (Ogot & Okudan, 2006). Given that various methodologies of TRIZ have been widely applied and continuously evolved, Ilevbare etc. (2013) found that the 40 Inventive Principles (40IPs) has been most frequently utilized among various problem-solving methodologies within TRIZ, followed by Ideality and Ideal Final Result (IFR), Function Analysis (FA), and Contradiction Matrix (CM). Although 40IPs and CM are practical tools for addressing problems, the main objective of IFR focuses on problem-solving (Rantanen etc., 2017; Terninko etc., 1998) and FA is a tool that focuses on understanding the functions and interactions of system components (Rantanen etc., 2017). Among these four TRIZ methodologies, this study focuses on CM.

Altshuller (1984, 2002) suggested utilizing 40IPs with the assistance of CM due to its strength of resolving Technical Contradiction (TC). Later, however, CM's effectiveness had been a subject of debate and Altshuller declared the discontinuation of CM due to this controversial issue on effectiveness (Cascini, 2012). Nevertheless, owing to its intuitive and convenient application, CM continues to be widely used (Cempel, 2014; Ma etc., 2015; Pokhrel etc., 2015; Su & Lin, 2008). To apply CM for various study fields and domains, it has been continuously refined and persistently enhanced (Bogatyrev & Bogatyreva, 2009; Craig etc., 2008; Lim etc., 2018; Mann, 2002, 2004, 2009, 2021; Mann & Dewulf, 2003; Pokhrel etc., 2015). However, analytical studies on CM still remain relatively scarce.

The main purpose of this study is to deepen the fundamental understanding of CM through Exploratory Data Analysis (EDA). More specifically, this study aims to establish a basis for CM research and improvement for the effective utilization of CM by analyzing the relationship between CM and 40IPs. To do so, this study conducted a simultaneous literature review and EDA to facilitate structural understanding of CM. Initially, an in-depth analysis of CM was conducted by reviewing the relevant books and articles. This study then investigated the theoretical background of the reasons for selecting specific data and methodology for analysis. In this study, CM was analyzed by conducting Association Rule Analysis (ARA) using Python after frequency analysis using IBM SPSS version 21 and visualizing structural characteristics.

2. Literature Review

2.1 TRIZ and contradiction

Altshuller, who researched invention methodology since 1946, presented a problem-solving approach using TRIZ with CM, consisting of 39 engineering parameters and 40 IPs, in his 1969 book entitled The Innovation Algorithm (Altshuller, 1999). Contradiction is an essential concept within TRIZ, which refers to the conflict between objects or properties, or the clash between solutions (Rantanen etc., 2017). Resolving these contradictions is the core of innovative invention (Altshuller, 1984).

Contradictions are categorized into three types: Administrative Contradiction (AC), Technical Contradiction (TC), and Physical Contradiction (PC). AC refers to a situation in which the problem is recognized but no solution is available. It involves eliminating obstacles to obtain essential benefits (Orloff, 2017). TC arises when improving one aspect of a technical system leads to the deterioration of another aspect (Altshuller, 1984). To address this, 40IPs and CM are primarily used (Rousselot etc., 2012). PC occurs when two conditions must be satisfied simultaneously. To solve PC, Altshuller proposed the principles of separation (Altshuller, 1999).

2.2 40IPs and CM

Altshuller articulated 40 IPs by conducting patent analysis (Table 1). Since then, 40IPs have been considered the most representative invention tools within TRIZ. It is the most commonly used TRIZ tool for surveys, targeting TRIZ practitioners (Ilevbare etc., 2013).

Table 1. 40 Inventive Principles (40IPs)

1. Segmentation	2. Extraction	3. Local Quality	4. Asymmetry	5. Consolidation
6. Universality	7. Nesting	8. Counterweight	9. Prior Counteraction	10. Prior Action
11. Cushion in Advance	12. Equipotentiality	13. Do It in Reverse	14. Spheroidality	15. Dynamicity
16. Partial or Excessive Action	17. Transition into a New Dimension	18. Mechanical Vibration	19. Periodic Action	20. Continuity of Useful Action
21. Rushing Through	22. Convert Harm into Benefit	23. Feedback	24. Mediator	25. Self-service
26. Copying	27. Dispose	28. Replacement of Mechanical System	29. Pneumatic or Hydraulic Constructions	30. Flexible Membranes or Thin Films
31. Porous Material	32. Changing the Color	33. Homogeneity	34. Rejecting and Regenerating Parts	35. Transformation of Properties
36. Phase Transition	37. Thermal Expansion	38. Accelerated Oxidation	39. Inert Environment	40. Composite Materials

CM categorizes the characteristics of TC into improving and worsening features related to 39 parameters (Fig 1). It is structured as a grid with 39 rows and columns and serves as a tool for analyzing the interactions between these features (Altshuller, 1999; Hipple, 2012). Within the intersection boxes where the parameters of two features meet, IPs for solving the given problem are arranged in order of frequency (Haines-Gadd, 2016; Shin & Hyun, 2022; Terninko etc., 1998). Although CM has continuously

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improved since the early stages of TRIZ development, its fundamental structure has remained intact (Altshuller, 1984; Pala & Srikant, 2005).

CHARACTERISTICS			Characterristic that is getting Worse								
			1	2	3	4	5	6	7	8	9
Characterristics to be imporved	1	Weight of a mobile object			15, 8, 29,34		29, 17, 38, 34		29, 2, 40, 28		2, 8, 15, 38
	2	Weight of a stationary object				10, 1, 29, 35		35, 30, 13, 2		5, 35, 14, 2	
	3	Length of a mobile object	8, 15, 29, 34				15, 17, 4		7, 17, 4, 35		13, 4, 8
	4	Length of a stationary object		35, 28, 40, 29				17, 7, 10, 40		35, 8, 2,14	
	5	Area of a mobile object	2, 17, 29, 4		14, 15, 18, 4				7, 14, 17, 4		29, 30, 4, 34
	6	Area of a stationary object		30, 2, 14, 18		26, 7, 9, 39					
	7	Volume of a mobile object	2, 26, 29, 40		1, 7, 4, 35		1, 7, 4, 17				29, 4, 38, 34
	8	Volume of a stationary object		35, 10, 19, 14	19, 14	35, 8, 2, 14					
	9	Speed	2, 28, 13, 38		13, 14, 8		29, 30, 34		7, 29, 34		

Fig 1. Snapshot of CM

In order to select parameters for problem-solving, a precise understanding of these parameters is necessary (Domb, E., Miller, J., MacGran, E., & Slocum, 1998; Haines-Gadd, 2016). The following are the 39 parameters: 1) weight of moving object, 2) weight of stationary object, 3) length of moving object, 4) length of stationary object, 5) area of moving object, 6) area of stationary object, 7) volume of moving object, 8) volume of stationary object, 9) speed, 10) force, 11) stress or pressure, 12) shape, 13) stability of the object's composition, 14) strength, 15) duration of moving object, 16) duration of stationary object, 17) temperature, 18) illumination intensity, 19) use of energy by moving object, 20) use of energy by stationary object, 21) power, 22) loss of energy, 23) loss of substance, 24) loss of information, 25) loss of time, 26) quantity of substance/the matter, 27) reliability, 28) measurement accuracy, 29) manufacturing precision, 30) object-affected harmful factors, 31) object-generated harmful factors, 32) ease of manufacture, 33) ease of operation, 34) ease of repair, 35) adaptability or versatility, 36) complexity of device, 37) difficulty of detecting and measuring, 38) extent of automation, and 39) productivity.

The selection of a version of CM is crucial due to the potential discrepancies in IPs listed in the intersection boxes, which may vary based on the source. In this study, the materials from Tools of Classical TRIZ (Altshuller etc., 1999), 40 Principles (Altshuller, 2002), and The Innovation Algorithm (Altshuller, 1999) were reviewed. CM presented in Tools of Classical TRIZ includes some blank intersection boxes, differing from the other two books. In 40 Principles, some intersection boxes contain IPs, deviating from the principles where 0 to 4 IPs are typically listed. Considering these factors, the CM from The Innovation Algorithm, which provides the most stable and consistent presentation of IPs, was chosen as the research model. In particular, CM from The Innovation Algorithm consists of 1,521 intersection boxes. Among these, 234 intersection boxes are excluded because they are located around the main diagonal or have no IP. This leaves a total of 1,248 intersection boxes with 4,200 IPs listed in them.

2.3 Exploratory Data Analysis (EDA)

Exploratory Data Analysis (EDA) is an analytical approach that involves examining data from various angles without preconceived notions, aiming to understand the distribution, anomalies, patterns, etc. (Asian etc., 2016; Komorowski etc., 2016; Martinez etc., 2017; Morgenthaler, 2009). Through visualization and pattern discovery, EDA helps uncover insights, formulate hypotheses, identify patterns in complex phenomena, and gain insights necessary for decision-making in big data analysis (Karageorgiou, 2011; Martinez etc., 2017; Morgenthaler, 2009). EDA plays a significant role in understanding the structure and characteristics of the data.

In this study, EDA was conducted to examine the distribution of 40IPs within CM. This can be seen as an extension of the research related to the frequency or ranking of TRIZ principles. Previous studies have focused on analyzing the frequency order and comparative analysis of IPs (Dave, 2017; Hwang etc., 2018; Mann, 2004; Sen etc., 2021; Terninko etc., 1996). However, this study expands on this by analyzing the statistical characteristics of 40IPs for 39 parameters. Based on the insights obtained, visualization tasks and ARA were carried out.

Association Rule Analysis (ARA), commonly known as Market Basket Analysis, is a data mining technique used to identify relationships between items in large databases. In essence, it examines the associations between the purchase of specific items X and the purchase of item Y within customer buying patterns (Chen etc., 2005; Lu etc., 1998). In this analysis, measurement tools such as support, confidence, and lift are utilized (Agrawal etc., 1996; Hornik etc., 2005; Lu etc., 1998). It is used in conjunction with the Apriori algorithm to eliminate infrequent item sets. Support represents the proportion of cases in which items X and Y occur together, as shown in Equation (1).

$$\text{Support}(X \rightarrow Y) = P(X \cap Y) = \frac{P(X \cap Y)}{N(\text{total transactions})} \quad (1)$$

Confidence is a measure that indicates the proportion of cases where items containing X also include Y, as in Equation (2). It serves as a tool to evaluate the uncertainty of a rule and is based on the conditional probability.

$$\text{Confidence}(X \rightarrow Y) = P(Y|X) == \frac{P(X \cap Y)}{P(X)} \quad (2)$$

Lift is a measure that assesses the increase in the occurrence probability of Y given the presence of item X, as shown in Equation (3). It is used to validate the significance of the discovered rules by comparing them with randomly set rules. Lift serves as an essential tool for determining the accuracy of correlations

$$\text{Lift}(X \rightarrow Y) = \frac{P(Y|X)}{P(Y)} = \frac{P(X \cap Y)}{P(X)P(Y)} \quad (3)$$

By using an unsupervised learning approach without specific hypotheses or predictive models, ARA examines the co-occurrence frequency between items to uncover data sparsity and unique patterns. ARA confirms correlations but does not determine causality. In the field of TRIZ, ARA is employed for tasks such as text mining in patent information classification (He & Loh, 2010). In this study, the support calculation method was applied to analyze the similarity of IPs within the intersection boxes around the main diagonal. This approach was also extended to explore identical components between intersection boxes within CM. The analysis tools utilized included Pandas and NumPy, data analysis packages in Python, and Mlxtend, which provide an effective Apriori algorithm for ARA (Raschka, 2018).

3. Method and Results

3.1 Frequency analysis of 40IPs for CM

This study compared the results of the CM analysis from The Innovation Algorithm and the study by Dave (2017), which used the triz40.com dataset. In The Innovation Algorithm (N(Total number of IPs in CM)=4,200) and triz40.com (N=4,202), it was found that while there were frequency differences for certain IPs (10, 28, 18, 15, 19, 13, 3, 16, 40, 25, 23), the overall results were largely similar (Table 2). Due to space constraints, only a portion of the results is presented here.

Table 2. Frequency by IP (Due to space constraints, only a portion of the results is presented here)

R	Algorithm			triz40			R	Algorithm			triz40		
	IP	F	%	IP	F	%		IP	F	%	IP	F	%
1	35	413	9.8	35	413	9.8	4	28	231	5.5	28	229	4
2	10	272	6.5	10	274	6.5	5	2	222	5.3	2	222	5
3	1	232	5.5	1	232	5.5	6	18	162	3.9	18	163	6
……													
35	5	35	0.8	23	35	0.8	38	33	31	0.7	33	31	0.7
36	23	34	0.8	5	35	0.8	39	9	26	0.6	9	26	0.6
37	12	32	0.8	12	32	0.8	40	20	19	0.5	20	19	0.5
R=Frequency Ranking, IP=Inventive Principle, F=Frequency count							Sum	(N=4,200)		100	(N=4,202)		100

3.2 40IPs of 39 parameters

Previous research in the field of TRIZ primarily focused on the frequency of IPs, investigating 40 IPs within CM. However, since CM is structured based on 39 parameters to determine inventive principles within intersection boxes, analyzing the frequency of 40 IPs within these parameters allows us to grasp the correlations between each parameter and IPs, as well as their detailed rankings. In this study, this approach was adopted to analyze the frequency of IPs for each parameter. The improvement and worsening features of parameters with similar attributes were observed to note similarities in the frequency of IPs (See Table 3, due to space constraints, only a portion of the results are presented here.).

Table 3. 40 IPs Frequency by Parameter

Weight of moving object

R	Improving			Worsing		
	IP	**F (N=126)**	**%**	**IP**	**F (N=126)**	**%**
1	35	13	10.3	35	9	7.1
2	28	8	6.3	28	8	6.3
3	18	7	5.6	8	7	5.6
……						
34	27	6	4.8	23	1	.8
35				25	1	.8
36				30	1	.8
Total		126	100.0		126	100.0

Length of moving object

R	Improving			Worsing		
	IP	**F (N=104)**	**%**	**IP**	**F (N=120)**	**%**
1	1	11	10.6	1	11	9.2
2	29	11	10.6	15	8	6.7
3	15	9	8.7	29	8	6.7
……						
28				25	1	0.8
29				32	1	0.8
30				38	1	0.8
Total		104	100.0		120	100.0

Ease of repair

R	Improving			Worsing		
	IP	**Fy (N=111)**	**%**	**IP**	**F (N=103)**	**%**
1	1	16	14.4	1	16	15.5
2	10	12	10.8	10	12	11.7
3	2	11	9.9	2	11	10.7
……						
21	26	1	.9	19	1	1.0
22	29	1	.9	29	1	1.0
23	31	1	.9			1.0
Total		111	100.0	Total	103	100.0

Productivity

R	Improving			Worsing		
	IP	**F (N=136)**	**%**	**IP**	**F (N=132)**	**%**
1	35	18	13.2	35	20	15.2
2	10	17	12.5	10	14	10.6
3	28	12	8.8	28	13	9.8
……						
31	31	1	.7			
36	36	1	.7			
40	40	1	.7			
Total		136	100.0	Total	132	100.0

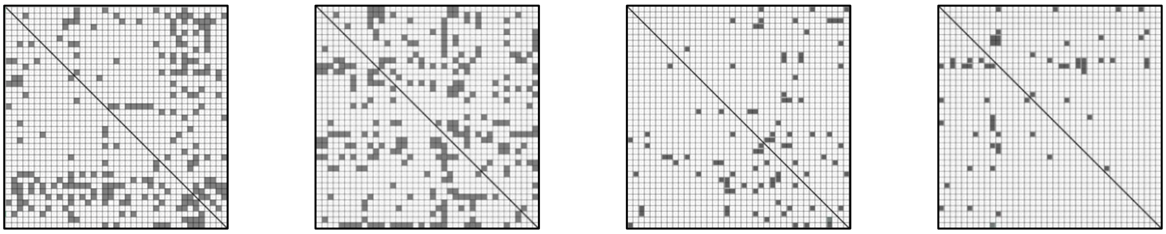
(R=Frequency Ranking, IP=Inventive Principle, F=Frequency count, N=Total number of IP)

Shulyak presented a method of utilizing CM to discover IPs or applying them sequentially (Altshuller, 2002). However, Dave (2017) proposed an approach that prioritizes the usage of the top 20 most frequent IPs, aiming for efficient problem-solving. In this study, it was suggested to apply frequency rankings for each parameter. The frequency order for each parameter allows for convenient application of IPs, even when focusing on only one parameter at a time.

3.3 Visualization of CM

TRIZ has undergone processes of learning, training, application, and continuous refinement and development. However, there remains a lack of structured and statistical analyses of TRIZ methodology. Just as John Tukey defined EDA as an attitude of seeking both what is believed to exist and what is believed not to exist, with flexibility and spontaneity (Martinez etc., 2017; O'Neil & Schutt, 2013), this study aims to advance the analysis of TRIZ.

For EDA, tasks such as pattern recognition and visualization are essential. In this study, the different characteristics of the 39 parameters (improvement features and worsening features) were used to confirm the similarity of IP frequencies. This formed the basis for graphing the distribution of IPs within the intersection boxes of CM. This approach is akin to TRIZ deriving patterns and laws of invention by analyzing numerous patents. Through this study, the aim was to gain a clear understanding of the structure of CM and the distribution of IPs within each intersection box. Throughout this process, the distribution of IPs from 1 (Segmentation) to 40 (Composite Materials) was comprehensively visualized as shown in Fig 2.



1. Segmentation 10. Prior Action 24. Mediator 36. Phase Transition

Fig 2. Visualization graphs of the distribution of IPs within CM

Interestingly, a symmetrical pattern was observed around the main diagonal. Therefore, the IPs within the intersection boxes symmetrically positioned across the diagonal were compared in Fig 3.

CHARACTERISTICS		Characterristic that is getting Worse 1	2	3	4	5	6	7	8	9
Characteristics to be improved 1	Weight of a mobile object		-	15, 8, 29,34	-	29, 17, 38, 34	-	29, 2, 40, 28	-	2, 8, 15, 38
2	Weight of a stationary object	-		-	10, 1, 29, 35	-	35, 30, 13, 2	-	5, 35, 14, 2	-
3	Length of a mobile object	8, 15, 29, 34	-		-	15, 17, 4	-	7, 17, 4, 35	-	13, 4, 8
4	Length of a stationary object		35, 28, 40, 29	-		-	17, 7, 10, 40	-	35, 8, 2,14	-
5	Area of a mobile object	2, 17, 29, 4	-	14, 15, 18, 4	-		-	7, 14, 17, 4		29, 30, 4, 34
6	Area of a stationary object	-	30, 2, 14, 18	-	26, 7, 9, 39	-		-		-
7	Volume of a mobile object	2, 26, 29, 40	-	1, 7, 4, 35	-	1, 7, 4, 17	-		-	29, 4, 38, 34
8	Volume of a stationary object	-	35, 10, 19, 14	19, 14	35, 8, 2, 14	-		-		-
9	Speed	2, 28, 13, 38	-	13, 14, 8	-	29, 30, 34	-	7, 29, 34	-	

Fig 3. Comparison between intersection boxes symmetrically positioned around the main diagonal of CM

The IPs within the intersection boxes showed symmetry around the main diagonal. For instance, in the intersection box between the improvement feature 1, Weight of a mobile object, and the worsening feature 3, Length of a mobile object, the IPs are 15, 8, 29, and 34. Similarly, in the symmetrically positioned intersection box around the main diagonal, between the improvement feature 3, Length of a mobile object, and the worsening feature 1, Weight of a mobile object, the IPs are 8, 15, 29, and 34. This symmetry allows for a more detailed comparison when arranging the parameters of the improvement and worsening features both vertically and horizontally (Table 4)

Table 4. Arrangement of identical parameters horizontally in CM

	1	2	3
[Improving] Weight of a mobile object		-	15, 8, 29,34
[Worsing] Weight of a mobile object		-	8, 15, 29, 34
[Improving] Weight of a stationary object	-		-
[Worsing] Weight of a stationary object	-		-
[Improving] Length of a mobile object	8, 15, 29, 34	-	
[Worsing] Length of a mobile object	15, 8, 29,34	-	

3.4 Association Rule Analysis (ARA)

(1) Analysis of similarity between symmetrical intersection boxes around the main diagonal

Out of the 3,042 intersection boxes generated by separating and rearranging the rows and columns of CM, 2,496 contain one or more IPs, while the remaining 546 are empty. Among these, 78 empty intersection boxes are located on the main diagonal, and there are 416 intersection boxes where both sides are symmetrically empty across the main diagonal. Additionally, there are 52 intersection boxes in which only one side is empty of IPs.

To measure the inferred similarities from the process so far, the support measure from set theory's tool, ARA, was utilized. Intersection boxes without IPs listed were excluded from the analysis. A total of 1,222 pairs of intersection boxes containing one or more IPs were analyzed using Python. To calculate the similarity between the improvement and worsening features, the number of common IPs was divided by the total number of distinct features. Here, the total number of distinct features refers to the union of the IPs corresponding to the 'improvement feature' and the 'worsening feature' within the set of intersection boxes under analysis, as in Equation (4).

$$Support \text{ (rate of similarity)} = \frac{\text{n}(\text{X} \cap \text{Y})}{\text{N(total transactions)}} \quad (4)$$

For the analysis, 2,444 intersection boxes were organized into a set data structure. In this process, 'i' was designated for the improving feature, and 'w' was used for the worsening feature. For instance, an intersection box with the characteristics of wanting to improve the weight of a moving object and worsening the length of a moving object was labeled as 'i1_w3' (Fig 4, left). Then, the following function was created (Fig 4, right).

```
i1_w3={15,8,29,34}
w1_i3={8,15,29,34}
i1_w5={29,17,38,34}
w1_i5={2,17,29,4}
i1_w7={29,2,40,28}
w1_i7={2,26,29,40}
...
i39_w36={12,17,28,24}
w39_i36={12,17,28}
i39_w37={35,18,27,2}
w39_i37={35,18}
i39_w38={5,12,35,26}
w39_i38={5,12,35,26}
```

```
total_prob = []

def two_prob(x, y):
    twointer = x.intersection(y)
    print(x, y,'twointer :', twointer)
    twounion = set.union(x, y)
    print(x, y,'twounion :', twounion)
    twoprob = (len(twointer)/len(twounion))
    print(x, y,'twoprob :', twoprob)
    total_prob.append(twoprob)
```

Fig 4. Treatment for similarity analysis
Note. Left: Set Data Structure; Right: Function for similarity verification

Subsequently, the arguments for executing the function were generated (Fig 5, left). The results of significance probability execution range from 1.0 to 0.0 are shown in Fig 5, right.

```
two_prob(i1_w3,w1_i3)
two_prob(i1_w5,w1_i5)
two_prob(i1_w7,w1_i7)
two_prob(i1_w9,w1_i9)
two_prob(i1_w10,w1_i10)
two_prob(i1_w11,w1_i11)
...
two_prob(i39_w33,w39_i33)
two_prob(i39_w34,w39_i34)
two_prob(i39_w35,w39_i35)
two_prob(i39_w36,w39_i36)
two_prob(i39_w37,w39_i37)
two_prob(i39_w38,w39_i38)
```

```
{8, 34, 29, 15} {8, 34, 29, 15} twointer : {8, 34, 29, 15}
{8, 34, 29, 15} {8, 34, 29, 15} twounion : {34, 8, 15, 29}
{8, 34, 29, 15} {8, 34, 29, 15} twoprob : 1.0
{17, 34, 29, 38} {17, 2, 4, 29} twointer : {17, 29}
{17, 34, 29, 38} {17, 2, 4, 29} twounion : {34, 2, 4, 38, 17, 29}
{17, 34, 29, 38} {17, 2, 4, 29} twoprob : 0.3333333333333333
...
{18, 35, 2, 27} {18, 35} twointer : {18, 35}
{18, 35, 2, 27} {18, 35} twounion : {18, 35, 2, 27}
{18, 35, 2, 27} {18, 35} twoprob : 0.5
{26, 35, 12, 5} {26, 35, 12, 5} twointer : {26, 35, 12, 5}
{26, 35, 12, 5} {26, 35, 12, 5} twounion : {35, 5, 12, 26}
{26, 35, 12, 5} {26, 35, 12, 5} twoprob : 1.0
```

Fig 5. Function argument generation and Execution result
Note. Left: Function argument generation; Right: Execution result

By analyzing a total of 2,444 intersection boxes (1,222 pairs), the average similarity was calculated to be 56.67%. For a specific case, in the instance of i2_w35 {19, 15, 29} and w2_i35 {19, 15, 29, 16}, where the common IPs were the same, the probability of agreement based on set theory was 75%. Considering this, the average similarity of 56.67% can be interpreted as a significant Fig representing the correlation between the improvement and worsening features (Fig 6).

```
len(total_prob)
```

```
1222
```

```
pecent_sum = sum(total_prob)
pecent_sum
```

```
692.4761904761921
```

```
total_mean_round = round(pecent_sum/len(total_prob) * 100, 2)

print(total_mean_round)
```

```
56.67
```

Fig 6. Average similarity

From the analysis, it was found that out of the 1,222 pairs of intersection boxes, approximately 94% had at least one common IP. Among them, 350 sets (28.64%) had the same IPs, and only 78 sets (6.38%) had no common IPs. This confirms that there is a meaningful relationship between the intersection boxes located around the main diagonal (Table 5)

Table 5. Calculation of significance group ratios

Equal ratio	Number of intersection box sets	Overall Ratio
100%	350	0.286416
75%	88	0.072013
	……	
14.29%	64	0.052373
0%	78	0.06383
Total	1222	1

As evident from Table 5, intersection boxes with 100% agreement account for approximately 29% (350 sets) of the total sets, whereas sets with no common IPs constitute around 6% (78 sets), making the former about 4.5 times more prevalent than the latter. This further confirms the significant relationship between the intersection boxes located around the main diagonal.

(2) Analysis of common components among intersection boxes of parameters

Intersection boxes contain IPs based on the improvement and worsening relationships between features, and identifying intersection boxes sharing the same IPs allows insights into the associations among parameters. To analyze such relationships, a set of 726 intersection boxes, each containing all IPs, was examined to investigate the distribution of the same IPs (Fig 7).

```
i1_w3={15,8,29,34}
i1_w5={29,17,38,34}
i1_w7={29,2,40,28}
• • •
i39_w36={12,17,28,24}
i39_w37={35,18,27,2}
i39_w38={5,12,35,26}
```

Fig 7. Set data structure for the analysis of common components

Through the analysis of common components, the similarities between each intersection box and the other 725 intersection boxes were compared. For instance, Fig 8 demonstrates that the verification of the similarity between i39_w2 and other intersection boxes was conFigd to output cases where the IPs of the intersection boxes were identical using Bool coding. As shown in Fig 8, it was observed that i39_w2 is identical to i37_w14.

```
if i39_w2==i1_w3:
    print("i39_w2==i1_w3:",i39_w2==i1_w3)
if i39_w2==i1_w5:
    print("i39_w2==i1_w5:",i39_w2==i1_w5)
if i39_w2==i1_w7:
    print("i39_w2==i1_w7:",i39_w2==i1_w7)
if i39_w2==i1_w9:
    print("i39_w2==i1_w9:",i39_w2==i1_w9)
• • •
if i39_w2==i39_w36:
    print("i39_w2==i39_w36:",i39_w2==i39_w36)
if i39_w2==i39_w37:
    print("i39_w2==i39_w37:",i39_w2==i39_w37)
if i39_w2==i39_w38:
    print("i39_w2==i39_w38:",i39_w2==i39_w38)

i39_w2==i37_w14: True
```

Fig 8. Bool coding for the analysis of common components

The analysis revealed that there were 107 cases in which 2 intersection boxes were identical, 10 cases which 3 intersection boxes were identical, and 3 cases which 4 intersection boxes were identical. While some instances showed the same IP in intersection boxes with different parameters, the similarity was mainly observed among intersection boxes symmetrically positioned around the diagonal. Among these symmetric intersection boxes, there were a total of 93 cases in which the same IPs were present (Table 6).

Table 6. Symmetric Intersection Boxes with the Same IPs

No.	cell_a	cell_b	No.	cell_a	cell_b	No.	cell_a	cell_b
1	i1_w3	i3_w1	32	i11_w31	i31_w11	63	i21_w25	i25_w21
2	i1_w11	i11_w1	33	i12_w17	i17_w12	64	i21_w30	i30_w21
3	i1_w36	i36_w1	34	i12_w23	i23_w12	65	i21_w36	i36_w21
……								
29	i9_w32	i32_w9	60	i19_w36	i36_w19	91	i35_w36	i36_w35
30	i11_w17	i17_w11	61	i20_w30	i30_w20	92	i36_w37	i37_w36
31	i11_w23	i23_w11	62	i21_w23	i23_w21	93	i38_w39	i39_w38

Furthermore, the results identified a total of 14 cases in which intersection boxes were diagonally asymmetric while still sharing the same IP (Table 4). In most cases, these were either identical or similar parameters (same parameters with different features). However, instances such as i5_w39 and i36_w28, i6_w16 and i15_w7, i14_w21 and i38_w2, and i39_w2 and i37_w14 did not overlap in terms of the 39 parameters (Table 7).

Table 7. Asymmetry intersection boxes with identical IPs

No.	cell_c	cell_d	IPs			
1	i1_w29	i38_w1	18	26	28	35
2	i1_w34	i2_w34	2	11	27	28
3	i3_w38	i37_w3	16	17	24	26
……						
6	i5_w39	i36_w28	2	10	26	34
7	i6_w16	i15_w7	2	10	19	30
8	i13_w34	i34_w30	2	10	16	35
9	i14_w21	i38_w2	10	26	28	35
……						
14	i39_w2	i37_w14	3	15	27	28

Among the 10 cases where 3 intersection boxes are identical, 9 of them exhibited a diagonal symmetry relationship between two of them. However, [i5_w33, i18_w34, i19_w35] did not display such symmetry (Table 8).

Table 8. Three intersection boxes with identical IPs

No.	cell_e	cell_f	cell_g	IPs			
1	i2_w27	i27_w2	i27_w10	3	8	10	28
2	i5_w11	i11_w5	i39_w10	10	15	28	36
3	i5_w33	i18_w34	i19_w35	13	15	16	17
……							
9	i25_w31	i31_w39	i39_w31	18	22	35	39
10	i30_w36	i30_w37	i36_w30	19	22	29	40

There were a total of 3 cases where 4 intersection boxes matched, and in all cases, the intersection boxes were symmetrically related across the main diagonal (Table 9)

Table 9. Four intersection boxes with identical IPs

No.	cell_h	cell_i	cell_j	cell_k	IPs			
1	i5_w28	i6_w28	i28_w5	i28_w6	3	26	28	32
2	i22_w30	i22_w31	i30_w22	i31_w22	2	21	22	35
3	i24_w25	i25_w24	i28_w37	i37_w28	24	26	28	32

Out of the 107 cases, 93 were part of the 350 intersection box sets identified in the previous similarity analysis. The remaining 14 cases shared the same IPs while having different parameters. Interestingly, some intersection boxes shared the same IPs despite being composed of entirely different parameters. These findings suggest the need for further research and investigation.

Choi (2015) and Hyun (2018) utilized propositions for clarity in contradiction resolution within TRIZ. Similarly, this study also employed propositional logic for inference to find evidence of the significance of the probabilities associated with the IPs listed in the intersection boxes around the main diagonal symmetry. A proposition refers to a declarative statement or expression that can be judged as true or false. The primary proposition is an indivisible basic unit. A compound proposition is formed by combining two or more primary propositions using logical connections. Among these, a conditional proposition takes the form if p, then q, is expressed as p→q. According to the contraposition law, if p→q is true, then ~q (the negation of q) →~p (the negation of p) is also true.

In this study, the parameters associated with the features to be improved and those associated with the features to be worsened are denoted as 'i' and 'w' respectively. According to this notation, CM can be explained as follows: If a certain parameter is to be improved (i), then another parameter will worsen (w). Altshuller described CM as follows: "(If) to resolve a parameter that requires improvement, (then) using conventional methods known for this purpose, (but) a parameter that worsens (is worsened) is written (in the matrix)." (Altshuller, 1984). For example, 'i1_w3' can be interpreted as follows: if (i1) the weight of a moving object is to be improved, then (w3) the length of the moving object will worsen (i1→w3). This problem can be solved using the IPs associated with the cross-point box {8, 15, 29, 34}. In other words, the IPs {8, 15, 29, 34} provide a solution where i1 (weight of a moving object) is improved, while w3 (length of a moving object) does not worsen (~w3). The contraposition of 'i1_w3' would be: if (~w3), the length of the moving object does not worsen, then (~i1) the weight of the moving object will not improve (~w3→~i1). Therefore, the IPs that can solve this contraposition problem are {8, 15, 29, 34}. In other words, {8, 15, 29, 34} are the IPs that can satisfy all conditions [i1, w3, ~w3, ~i1] of the problem.

The cross-point box i3_w1, located symmetrically around the diagonal, can be understood as follows. If (i3), the length of a moving object is to be improved, then (w1) the weight of the moving object will worsen (i3→w1). To resolve this, the IPs {8, 15, 29, 34} are used. In other words, the IPs {8, 15, 29, 34} offer a solution where i3 (length of a moving object) is improved, while w1 (weight of a moving object) does not worsen (~w1). The contraposition of 'i3_w1' would be: if (~w1), the weight of the moving object does not worsen, then (~i3) the length of the moving object will not improve (~w1→~i3). The IPs that can solve this contraposition problem are also {8, 15, 29, 34}. In other words, {8, 15, 29, 34} are the IPs that can address the conflicting conditions [i3, w1, ~w1, ~i3].

'Improving' signifies the intention to enhance the current situation, while 'not worsening' represents the desire to maintain or restore the present state without deterioration. Although improvement and worsening are opposing concepts, 'improving' and 'not worsening' both aim at enhancing performance in the current context. Thus, the relationships expressed in i1_w3 and i3_w1 may differ in the current state, but both are aimed at enhancing performance. Therefore, the associations between i1 and ~w1, as well as i3 and ~w3, in the context of CM's diagonal symmetry are closely related. In essence, the symmetry around the diagonal of the CM can often be seen as contraposition relationships. Hence, the similarity in IPs between cross-point boxes symmetrically located around the diagonal of the CM can be understood from this perspective.

The IPs {8, 15, 29, 34} for both i1_w3 and i3_w1 encompass solutions for the conditions [i1, ~i1, i3, ~i3, w1, ~w1, w3, ~w3]. Notably, i1 and ~i1, i3 and ~i3, w1 and ~w1, and w3 and ~w3 are opposing parameters that represent PC relationships. This illustrates the deep correlation between TC and PC and the cyclical solution pattern, as Altshuller suggested algorithms for eliminating TC: transposing it to PC, using S-Field transformations to remove the PC, and applying the system of operators such as CM at ARIZ 71 and the 76 Standard Solution at ARIZ 85-C ((Altshuller, 1984; 1999).

Some TRIZ researchers explain that when a box in the CM is empty, it represents a situation in which the occurrence of TC is unlikely. However, Altshuller and his colleagues acknowledge the presence of empty cells, but have not yet found solutions for them (Altshuller, 1984). Therefore, by utilizing the propositional logic as described above, it might become more feasible to fill in these empty cells within the CM.

(3) Analysis of the overall associative rules in CM

This study conducted an analysis of associative rules targeting 1,248 out of 1,521 intersections in the CM that included IPs. The setting for the analysis measurement tools generally included a minimum support of 1% and a minimum confidence of 50%. Additionally, associations were considered if the lift was greater than 1. However, since the required number of rules might not emerge or an excessive number of associative rules might be generated depending on the evaluation criteria, it was necessary to iteratively adjust the evaluation threshold to obtain an appropriate number of rules. In the analysis of associative rules, the observed values of transactions were not considered. Thus, in this research, only the IPs within the intersection boxes were used for analysis, excluding the names of the intersection boxes themselves. Initially, the analysis of associative rules was performed with a minimum support of 1%, without considering confidence and lift (Fig 9).

```
freq_itemsets = apriori(cont_df,
                        min_support=0.01,
                        use_colnames=True)
freq_itemsets
```

Fig 9. Minimum setting for support

Table 10 presents the results obtained when setting the minimum support to 1%, sorted in descending order, yielding 173 outcomes.

Table 10. Results of ARA with a minimum support set to 1%
(Due to space constraints, only a portion of the results is presented here.)

No.	support	item sets	No.	support	item sets
1	0.3309	IP35	88	0.0184	IP35, IP38
2	0.2179	IP10	89	0.0176	IP1, IP19
3	0.1859	IP1	90	0.0176	IP1, IP26
……					
85	0.0184	IP29, IP15	172	0.0104	IP39, IP19
86	0.0184	IP35, IP16	173	0.0104	IP22, IP39
87	0.0184	IP28, IP24			

In cases where a single IP is mentioned, the results align with previous frequency analysis findings. However, for instances where two IPs are mentioned together, some showed more significant results compared to a single IP. For example, the combination of '10. Preliminary Action' and '35. Change of Attribute' exhibited higher support than '24. Intermediary.'

In general, as the number of items increases, obtaining meaningful ARA results becomes more challenging. Therefore, judicious use of appropriate variables is recommended. However, in this study, all 40 variables were used to investigate the relationships among 40 IPs. Hence, when using standard measurement tool settings, it becomes difficult to derive suitable association rules. Due to this issue, this study set the confidence threshold to be lower than the typical setting. Setting the confidence threshold above 50% significantly narrowed down ARA results, resulting in only two rules being generated (Table 11).

Table 11. Result of ARA with a confidence level of 50% or higher

No.	Antecedents	Consequents	Support	Confidence	Lift
1	IP20	IP10	0.0104	0.6842	3.1393
2	IP21	IP35	0.0152	0.5135	1.5517

Accordingly, evaluation criteria were adjusted to obtain suitable results. The modified measurement tool settings were as follows: a minimum support of 1%, a minimum confidence of 30%, and a minimum lift of 1 (Fig 10).

```
rules[ (rules['antecedent_len'] >= 1) &
       (rules['support'] >= 0.01) &
       (rules['confidence'] >= 0.3) &
       (rules['lift'] >= 1) ]
```

Fig 10. Value amendment for support, confidence, and lift

Through these adjustments, 22 results were generated, and Table 12 below presents the results sorted in descending order based on lift.

Table 12. Analysis results with support ≥ 1%, confidence ≥ 30%, and lift ≥ 1

No.	Antecedents	Consequents	Support	Confidence	Lift
1	IP36	IP37	0.0160	0.3333	6.9333
2	IP37	IP36	0.0160	0.3333	6.9333
3	IP20	IP10	0.0104	0.6842	3.1393
……					
20	IP10	IP35	0.0745	0.3419	1.0332
21	IP2	IP35	0.0601	0.3378	1.0209
22	IP18	IP35	0.0433	0.3333	1.0073

'36. Transition' and '37. Thermal Expansion' have the highest lift value (6.9333), indicating a very strong relationship between these two IPs. Additionally, principles such as '35. Change of Attributes', '10. Preliminary Action', and '1. Segmentation', which showed high frequencies in the frequency analysis, are frequently appearing as Consequents. ARA results among IPs are in Table 13, and the sorting criterion in the table is based on decreasing lift values

Table 13. ARA results for 40 IPs

1. Segmentation

No	A	C	S	C	L
1	IP1	IP11	0.0136	0.0733	1.8663
2		IP13	0.0345	0.1853	1.6522
3		IP16	0.0168	0.0905	1.1527
4		IP17	0.0144	0.0776	1.1130
5		IP32	0.0240	0.1293	1.0978

13. Do It in Reverse

No	A	C	S	C	L
1	IP13	IP1	0.0345	0.3071	1.6522
2		IP17	0.0128	0.1143	1.6394
3		IP15	0.0184	0.1643	1.2814
4		IP32	0.0144	0.1286	1.0915
5		IP2	0.0208	0.1857	1.0440

26. Copying

No	A	C	S	C	L
1	IP26	IP24	0.0160	0.1418	1.9241
2		IP28	0.0296	0.2624	1.4177
3		IP17	0.0104	0.0922	1.3226
4		IP27	0.0120	0.1064	1.0882
5		IP32	0.0144	0.1277	1.0838

39. Inert Environment

No	A	C	S	C	L
1	IP39	IP22	0.0104	0.1688	2.5083
2		IP18	0.0128	0.2078	1.6008
3		IP19	0.0104	0.1688	1.3169
4		IP35	0.0264	0.4286	1.2951
5		IP2	0.0136	0.2208	1.2411

(A : Antecedents, C : Consequents, S : Support, C : Confidence, L : Lift)

In the ARA of 40 IPs, '7. Nesting', '9. Preliminary Anticipatory Action', '12. Equilibrium', '30. Thin Film', and '33. Homogeneity' had lift values of 1 or lower, indicating random relationships, and were therefore excluded from the analysis. Additionally, '5. Merge', '8. Floating in the Air', '11. Preliminary Prevention', '20. Continuity of Useful Action', '21. Hurry Through', '23. Feedback', '25. Self-Service', '31. Porous Materials', '38. Oxidizing Agents', and others had only one Consequent when they were antecedents and showed low associations with other IPs. This result could be understood in relation to the frequency analysis. In the frequency analysis, '35. Change of Attributes' was the most frequent with 413 occurrences, while '20. Continuity of Useful Action' was the lowest with 19 occurrences. Due to the dominance of these top 20 IPs, which accounted for

75% of all IPs, some principles were excluded from ARA.

Considering this, the study concluded that conducting separate association analyses for each of 40 IPs would be more meaningful than analyzing the overall associations across all 40 principles. This approach allowed for understanding how each IP is connected to others, and this information will serve as valuable data for building a network of relationships among the IPs in the future.

4.Discussion and Conclusion

Despite being declared discontinued by Altshuller, CM continues to maintain popularity as one of the essential tools in TRIZ. However, CM remains at a fundamental analysis level, which can be a significant hindrance to its development. For these reasons, this study aimed to gain a clear understanding of the underlying structure of CM and verify the relationships among its elements. To achieve this, frequency analysis and EDA were conducted. The findings of this study provide meaningful theoretical implications as follows:

(1) For users who find it challenging to generalize CM's parameters, a method was proposed that applies 40 IPs according to the frequency order of each parameter. In addition, it was discovered that parameters with contrasting characteristics often share similar IPs.

(2) Through EDA, the overall structure of CM and the similarity of IPs within cross-reference boxes were verified. This process revealed the potential for cluster analysis to be employed.

(3) ARA revealed that the relationships between parameters and cross-reference boxes were identified. This process led to a clearer understanding of the relationships between IPs and provided insights into comprehending the intricate mechanisms of CM.

(4) The findings suggest that further research is necessary concerning parameters that share the same components.

(5) The analysis of the overall associations among all IPs revealed that certain principles exhibit a high degree of correlation with other principles.

(6) The significance probability of IPs within diagonally symmetrical intersection boxes of CM was analyzed using propositional logic around the main diagonal.

These research findings will contribute to both the theoretical understanding and practical utilization of CM. They offer more efficient and objective problem-solving methods and provide valuable guidance to researchers and practitioners using CM. This study is anticipated to serve as a catalyst for expanding the depth and breadth of research and applications in the field of CM.

However, this study has certain limitations due to the intricate theoretical background of CM and the complexity of its exploration and validation processes. One limitation is that different versions of CM exist, which can lead to variations in the results depending on the version used for analysis. This could impose constraints on the universal application of CM, highlighting the need for a detailed analysis of these variations. Another limitation is that this study employed EDA methods, rather than traditional hypothesis testing, to extract insights from various perspectives. However, these findings need to be validated through subsequent research. This study utilized only a subset of various analytical methods. Therefore, it is anticipated that research employing a broader range of analytical methods could offer a deeper understanding of the CM.

For the full results of the analysis, see the Google Drive shared file: https://docs.google.com/spreadsheets/d/109pcZYn-roD9BA_naIdJ7Fsc3qhRBI1jl/edit?usp=drive_link&ouid=109092790199240646038&rtpof=true&sd=true

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