LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
Faculty of Technology
Degree Program in Chemical and Process Engineering

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ADAPTATION OF TRIZ METHOD FOR PROBLEM SOLVING IN PROCESS ENGINEERING

Examiners: Professor Andrzej Kraslawski
Dr.Sc. (Chem) Yuri Avramenko

ABSTRACT

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Adaptation of TRIZ Method for Problem Solving in Process Engineering

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TRIZ is one of the well-known tools, based on analytical methods for creative problem solving. This thesis suggests adapted version of contradiction matrix, a powerful tool of TRIZ and few *principles* based on concept of original TRIZ. It is believed that the proposed version would aid in problem solving, especially those encountered in chemical process industries with unit operations. In addition, this thesis would help fresh process engineers to recognize importance of various available methods for creative problem solving and learn TRIZ method of creative problem solving. This thesis work mainly provides idea on how to modify TRIZ based method according to ones requirements to fit in particular niche area and solve problems efficiently in creative way. Here in this case, the contradiction matrix developed is based on review of common problems encountered in chemical process industry, particularly in unit operations and resolutions are based on approaches used in past to handle those issues.

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October 2013, Lappeenranta, Finland

Chhabin Pokhrel

CONTENTS

ABBREVIATIONS

ARIZ	-	Algorithm of Inventive Problem Solving
BAT	-	Best Available Technologies
CBR	-	Case Based Reasoning
CIP	-	Clean in Place Systems
CP	-	Concentration Polarisation
CPI	-	Chemical Process Industry
CPS	-	Creative Problem Solving
DC	-	Direct Current
FBC	-	Fluidised Bed Combustion
HAZOP	-	Hazard and Operability Study
IFR	-	Ideal Final Result
MF	-	Microfiltration
MUF	-	Main Useful Function
NF	-	Nano filtration
PAT	-	Process Analytical Technology
PEI	-	Potential Environmental Impact
QRA	-	Quantitative Risk Analysis
RO	-	Reverse Osmosis
TFC	-	Thin Film Composite
TIPS	-	Theory of Inventive Problem Solving
TRIZ	-	Teoriya Resheniya Izobreatatelskikh Zadatch (in Russian)
UF	-	Ultrafiltration
WAR	-	Waste Reduction

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1. INTRODUCTION

In past decades, chemical process industry (CPI) has experienced a rapid change. Challenges to develop new industrial processes or to modify existing ones seems essential to meet various environmental legislation criteria, to reduce production cost and increasing requirements for enhancement of innovative design activities to succeed in market are few of endless list of obstacles that these industries are currently facing.

To cope with above mentioned challenges, traditional problem solving methods do not seem to provide much help for these industries, in order to survive in today's cutting edge market. So, being creative and innovative is the only possible way for these industries to keep up with shifting benchmarks. A process engineer plays vital role in any process industry to cope with increasing demands and standards of product, tightening legislation and other requirements. Process engineers today has to handle not only technical problems but also issues concerning design, economic, sustainability and so forth prevailing in modern chemical process industries. For example, while performing complicated task, such as design of new process or modification of old existing ones; creative problem solving skills could prove a handy tool for any process engineer which would aid in problem solving or decision making.

This thesis sheds some light on few popular creative problem solving (CPS) techniques which could aid a process engineer in systematic problem solving and better decision making. This study mainly focuses to develop an adapted version of contradiction matrix, a powerful tool of TRIZ (theory of inventive problem solving) which follows CPS model and could be used in process industry for problem solving in creative way. This adapted version of contradiction matrix would aid a process engineer in various tasks, such as; in design of new process, to improve older processes, to troubleshoot technical problems, to improve overall safety of chemical process, and so forth. Classical TRIZ which is an inventive problem solving theory was developed to solve technical problems and deals with mechanical problems. This makes original TRIZ usability less applicable in very unlike domain such as chemical process industry. Due to inapplicability and ambiguity of terminology in classification of parameters used in original contradiction matrix of TRIZ, this thesis presents adapted version of contradiction matrix, which is especially intended for CPI with terms and terminology found in this field. This would increase usability of contradiction matrix in CPI for problem solving. In addition, this study demonstrations how to modify TRIZ based method to meet requirement of specific area.

In chapter 2, creative problem solving (CPS) method is introduced, and its application and benefits are presented. Importance of creative problem solving in today’s process industry and its advantages over ordinary problem solving process are explained in details. Chapter 3 gives background knowledge on various possible methods that uses CPS model to tackle problems and also describes their advantages and disadvantages and usability in CPI. Application of TRIZ methodology for creative problem solving in process industry is illustrated and provided with plenty of examples related to various types of process industries in chapter 4. Chapter 5 points out the details and necessity of adapted contradiction matrix for CPI, the methodology implemented in development of contradiction matrix is explained and two different case studies are presented. In chapter 6, adapted contradiction matrix for CPI is presented, and along with it, various *characteristics* and *principles* are proposed and explained in detail which would act as backbone for revised version. Chapter also highlights the benefits of modified version of contradiction matrix which is proposed and discusses its applicability in field of CPI. Final chapter 7 concludes by illustrating importance of TRIZ compared to other intuitive and analytical methods and how adapted contradiction matrix for CPI would aid in problem solving.

The aim of this work is to develop a new contradiction matrix based on the concept of contradiction matrix presented in original TRIZ which would be readily usable in domain of CPI. Set of new *characteristics* and few *principles* had to be suggested that would well represent the concepts and terminology found in CPI field. Upon completion, this tailored tool would aid process engineers to solve numerous problems found in process industry and also equips with a method to tackle problems in creative style.

2. CREATIVE PROBLEM SOLVING

A problem is a gap between an initial (existing) situation and the desirable situation [1, 2]. In order to solve any problem, understanding of problem is necessary. Basically, from review of various problem solving literature, it was found that any problem falls into one of the following category of problems as being well-structured, ill-structured, or semi-structured [3, 4]. This categorization helps problem resolver to understand problem better and to choose possible problem solving technique intelligently rather than making likely guesses. In general, well-structured problems or routine problems are relatively clear-cut and can be resolved using ready-made or routine solutions. These ready-made solutions almost always will guarantee success for well-structured problems. On the other hand, an ill-structured problem, in contrast, must be dealt with using custom made or non-routine solutions. Semi-structured problems those fall between well-structured and ill-structured problems possess elements of both and could be resolved using either custom-made solutions or ready-made solutions. Among these three problem types, ill-structured problems usually seems be the most difficult to resolve. [5]

2.1. Traditional Problem Solving Approaches

The ability to deal with above mentioned recurring problem varies depending on solver's personal experience. Typically, for structured problems, a person would analyse any given problem based on his knowledge and expertise, and also the problem is solved step by step. Many surveys have shown that the oldest and still most prevalent method for problem solving, regardless of class of problem, is trial and error [6-8]. No insight seems to be involved in solving a routine problem as ready-made routine solutions are used. This is seen as ordinary thinking process (figure 1) which consists of remembering of past events (memory), formulating schemes in order to accomplish the task (planning) and evaluating the outcomes (judgment) and finally choosing method to solve the problem (decision). [9] Similar concept was pointed out in a book '*Lateral thinking: a textbook of creativity',* as term 'vertical thinking' which is believed to be traditional type of thinking where one moves forward by sequential steps, each of those must be justified and problems are solved on stepwise manner linking one fact to another to reach conclusion. [2]

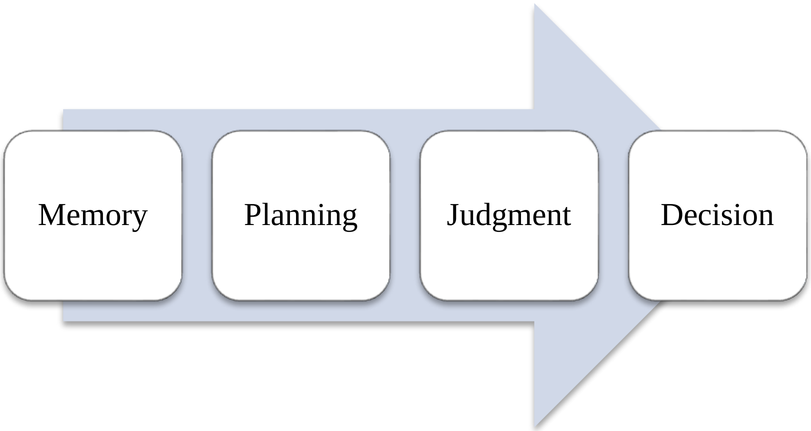

Figure 1 Ordinary Thinking Process [9]

The ordinary thinking process works efficiently for structured problems, which is encountered on day to day basis, whereas applying same process to solve ill structured problems makes it harder to solve. It is often experienced in case of ill-structured and semi-structured problems that huge extent of time is spend to find custom solutions, with greater improbability to grasp solution. So, different approaches are required to solve these problems more efficiently. In such cases, use of creative problem solving (CPS) model comes in handy. CPS had proven to be most appropriate for ambiguous and ill-structured types of problems. [5]

2.2. Creative Problem Solving (CPS) Model

Today's '*CPS model*', also known as the Osborn-Parrnes CPS model, arose directly out of Alex F. Osborn's work which later was extended by Psychologist Sidney J. Parnes. CPS had proven to be the most efficient and effective method, as with CPS, problem solver could use time economically, and in addition increases the odds of achieving a workable solution. The main reason behind effectiveness of CPS is that it increases problem familiarity. It helps to question the assumptions of problem solver, hence making the problem solver aware of perceptions of their situations, which are subjective. Understanding this basic concept is very important because another problem solver may see the same problem with an entirely different light, as what may be someone's semi-structured problem might be as ill-structured or well-structured for someone else. So, as problem solver acquires more information about the problem, the situation eventually evolves and workable solution emerges. [5]

Increasing problem familiarity is the basic process involved in using CPS model [10]. Acquiring more information about any problem and changing perceptions towards problem increases problem solvers' understanding. CPS model utilises similar concept for problem solving as Bloom's taxonomy uses in learning (figure 2). Bloom's taxonomy is a classification of levels of intellectual behaviour that are important in learning. [11] According to Bloom's taxonomy, by improving learning, one will be moving up in hierarchy and would be able to understand and apply information in efficient manner. In similar manner, problem familiarity maximizes possibility to solve the problem in CPS model.

Figure 2 Bloom's Taxonomy [11]

Creative problem solving (CPS) is Osborn-Parnes process of how to solve problems creatively [5, 12]. In some ways, changing of perceptions and concepts is the basis of creativity that involves new idea. [8] Though exact definition of creativity is difficult, as concept has many dimensions, basically creativity could be thought as 'the production of novel and useful ideas in any domain' [13]. Creativity involves an ability to come up with new and different viewpoints on a subject by breaking down and restructuring problem solvers knowledge about the subject in order to gain new insights into its nature. [14]

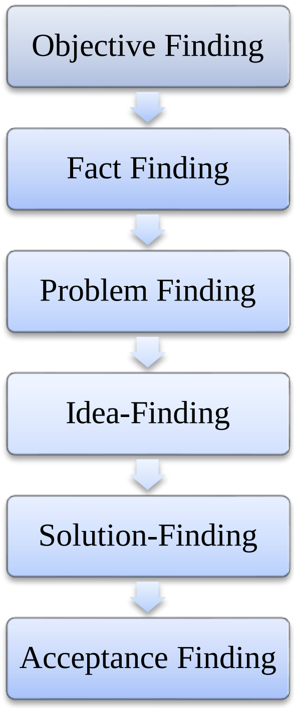

Figure 3 CPS Model [4]

In CPS model (figure 3), creative thinking involves six basic stages: objective-finding, fact-finding, problem-finding, idea-finding, solution finding, and acceptance-finding. Each stage of CPS process is designed to fulfil certain task. First three stages are concerned primarily with understanding and choosing a challenge. The first stage is objective finding stage, which will help to clarify several potential starting points and select one primary objective to focus solvers' efforts. The primary purpose of fact-finding stage is to increase understanding of the target area which was selected, by gathering as much as relevant data. By analysing this information and sorting relevant from irrelevant, an initial problem definition might be materialized. One can then use this definition and relevant information as starting point for third stage. The third stage which is problem-finding, where numbers of different problem statements are developed, and one problem statement is chosen which has potential for stimulating a variety of potential solutions that best captures the problem is formulated. In idea-finding stage, as many as potential solutions (ideas) for the problem stated in earlier stage are generated by use of several techniques. At the end of this stage, list of ideas will be narrowed and only those ideas with the highest potential for resolving problem are selected. In Solution-finding stage, potential solutions are systematically analysed and best ones are selected for possible implementation. First, a list of criteria would be generated which would be used in evaluation of idea. Then, using the most important criteria to judge ideas, one or more solutions that might have the highest potential to resolve the problem are chosen. Acceptance-finding, the last stage of CPS model involves considering ways to overcome all the obstacles that might prevent application of solution and also development of an action plan to guide implementation. [5, 15]

Each stage in CPS involves divergent and convergent activities [12]. The concept of divergent and convergent principles was first illustrated by Isaksen in earlier work [16]. The CPS model involves basic cycles of diverging-converging, diverging-converging, and so forth until the problem is resolved. These cycles keeps problem solver on course during problem solving. In a divergent search of data (facts, problems, ideas, criteria, obstacles) open mind nature is adopted, whereas on convergent phase, only narrowing down of whatever data already collected is emphasized. [5] Claims and cited evidence to support the view that divergent thinking processes, as opposed to convergent thinking processes, are related to creativity could be found [17]. Divergent thinking involves a broad search for decision options with respect to a problem for which there is no unique answer. The diverging-converging might feel quite impractical and difficult at beginning but experience gradually makes solver proficient with the model. Even though not all six stages would be required to solve each and every problem, it is important to understand that all these six stages always begins with a divergent phase and ends with a convergent phase. [5, 15]

2.3. Application and Benefits of CPS Approach

CPS model works as a tool for solver that enhances capacity to identify problems and opportunities, which is one of the most vital stages in creative process. [12, 18] Problems which require creative thinking are ‘open-ended’ problems, problems for which there is more than one solution, such as design or improvement of process, to improve product quality, to reduce harmful effects, to reduce operation cost and so on. Use of CPS was found to be quoted in various studies [19-24].

Applications of CPS model in process industry could mainly be: [25]

- For new process and plant design.
- For processes improvement (troubleshooting, de-bottlenecking, synthesis, and design).
- For products improvement (identification of new products and their formulation).
- To cut costs through more efficient or effective production methods.
- To identify new and profitable product-market opportunities.
- To reduce various operational problems.

Through creative problem solving, new ideas could be generated and innovative solutions for problem could be found. These ideas will be more efficient and often of much higher quality. [14] CPS model could prove effective in order to design and improve process or to troubleshoot problems in process, as currently process industry mainly uses experience-based techniques (techniques that had worked in past) from designing to problem solving which does not guarantee any solution. Example of such techniques could be a hierarchical heuristic procedure for chemical process design proposed by Douglas. Various use of heuristic approach could be found, such as; the synthesis of separation systems [26, 27], in process flowsheets [28], in waste minimization [29] and in design of metallurgical process [30]. The hierarchical heuristic method consists of five steps as shown in figure 4. [25]

CPS will prove useful in case where an individual has discovered a strategy (hierarchical heuristic as mentioned above) that initially functions well in solving certain tasks but later blocks realisation of new and simpler solutions to similar problems. In such instances, CPS would enhance possibility to achieve solution. [31] Creative problem solving is required to make up for the limitations in basic education where there has been an emphasis on the use of mind for storing information instead of developing its power for fabricating new concepts and turning these into reality [14]. Such ideas would really prove helpful for improvement of safety, troubleshooting and de-bottlenecking which is faced commonly in CPI. Existing processes or products could be improved with minimal production cost by exploring opportunity more efficiently and effectively using CPS techniques. Not only will a systematic approach to problem solving makes problem solver more efficient, but also could result in higher-quality solutions. [5]

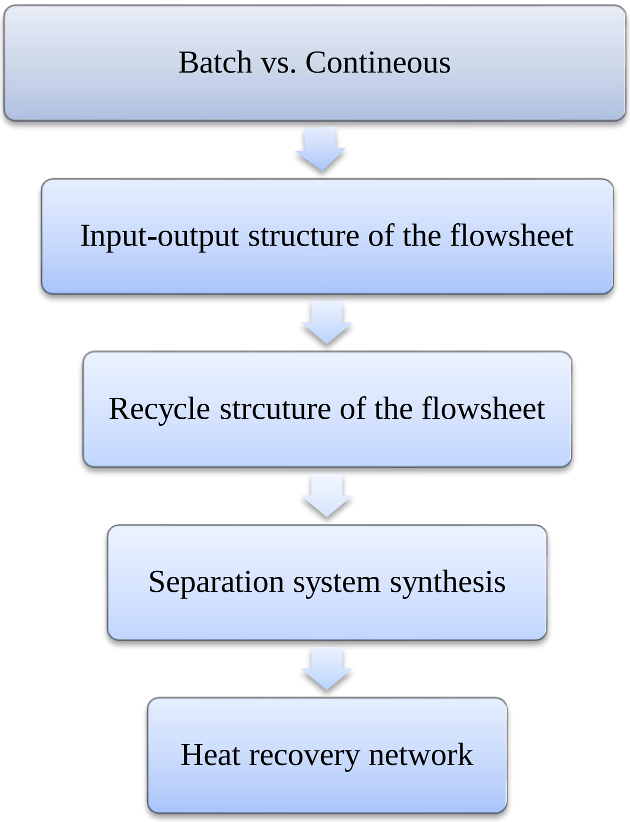

Figure 4 Hierarchical Heuristic Method [25]

On the other hand, not all problems involve use of a creative problem solving process. In some cases, CPS process would not be as useful as ready-made solutions are readily available. These kinds of solutions generally exist for recurring problems, and when it is possible to use readily available solutions, it is often much quicker and more practical than to follow CPS model. [14]

None the less, by use of CPS, solution from old problems could also be utilised and adapted to fit current problem on hand. Open-ended problem: for example, trouble-shooting problems (how to reduce downtime on the production line) could be solved in many ways. [14] For example, use of brain storming process (which follows CPS model) is recognized to be very useful in identification of process hazards in process industry. [32] In another example, when a pharmaceutical industry needed a way to deal with excess foam forming in a pharmaceutical process; by use of TRIZ method, solution was found in beverage industry which tackles similar problems on regular basis. [33]

3. METHODS OF CREATIVE PROBLEM SOLVING

Certain attributes that can affect person’s ability to deal with problems differs on individual basis, some are good at it whereas others are not. Intuitive thinking is important to problem solving, but so is analytical thought [5]. In this chapter, few very popular intuitive and analytical techniques to solve creative problems have been discussed. Even though everybody does not possess intuition and intuitive methods may seem difficult to learn, analytical methods are those problems solving skills that one could acquire and gain benefits throughout life.

3.1. Intuitive Methods

Intuitive thinking is a feeling or sense that never uses any rational process like data or facts. Good intuition comes from several years of experience and knowledge that allows a person to understand how other people in the world work. Many circumstances tend to be intuitive. This very reason makes these types of techniques hard to develop. Few well known intuitive methods such as: brainstorming, synectics and lateral thinking are explained below.

3.1.1. Brainstorming

Brainstorming is probably one of the most well-known tools of creative problem solving [21, 34]. It is a paradigm-preserving approach to creative problem solving that enables us to gain insights into problems that otherwise problem solver might overlook. It also enables problem solver mind to catch those eccentric solutions that somehow always seem to evade solver’s mind when solver utmost needs those solution. [14] This technique, designed especially for use in groups, encourages participants to express ideas, no matter how strange they may seem and forbids criticism during brainstorming session. [35]

Originally developed by Alex Osborn, currently known as classical brainstorming is the most widely known creative problem solving technique. [5] According to Osborn, brainstorming was only one of a variety of tools for generating ideas, and idea generation was outlined as only one aspect of the entire creative problem solving process. [36] With time various brainstorming techniques were developed, and among them, few very popular forms of brainstorming are listed. These include [14]

- Classical brainstorming
- Wildest-idea variant
- Round-robin brainstorming
- Gordon–Little variant
- Trigger method
- Brainwriting
- Brainlining (brainstorming on the internet)

Most brainstorming techniques fall into two categories: unstructured and structured. Unlike structured brainstorming, unstructured brainstorming is not led by any agreed-upon set of procedures and result is often an unproductive session. A good example of structured brainstorming is classical brainstorming which was based upon a few major principles and was originally recognized and used from the early 1950s. [14]

On the other hand, brainstorming being a popular creative problem solving tool has its limitations. While it is useful for acquiring large numbers of ideas, it is better-suited to conceptually simple problems, as opposed to the more complex development of those ideas. Brainstorming also relies on random association and therefore does not always produce original solutions. Brainstorming is not a suitable technique for a number of situations, including those with a high technical content, people motivation and problems requiring the consideration of written material. [37] In addition, it is important that members follow 4 basic principles of brain storming. Brainstorming disadvantages include disruptive interpersonal conflicts and unequal participation. On contrary, to perform brainstorming successfully, either brainstorming group should be led by skilled leader or group must be experienced. Brainstorming is a process that works best with a group of people when they follow agreed rules. [5] Group brainstorming was suggested as a supplement to individual ideation, not a replacement. [36] Groups have the potential advantage of being able to generate more ideas in same time period than one individual working alone. As a result, the final solution should be of higher quality. [38]

Use of brainstorming techniques in CPI to perform quantitative risk analysis (QRA) could be found. In additional, for HAZOP analysis (hazard and operability study), brainstorming techniques are used to methodically determine causes and consequences of deviations from normal operating conditions. [39] Brainstorming can be used to help in finding solutions to many different kinds of open-ended problem: for example, trouble-shooting problems (how to reduce downtime on production line [14]. Brain storming process is used for identifying process hazards in CPI. [32] For detail steps on how to brainstorm, refer to [14, 15].

3.1.2. Synectics

Synectics is the most highly refined and universally applicable among all the creative problem solving techniques. Synectics was developed by William J.Gordon. With slogan – '*stay loose till rigour counts'* – which expresses a basic feature of the process. [40] It is similar to brainstorming, but uses analogical thinking where a group of participants tries to work jointly en route for a particular solution, rather than producing a large number of ideas [41]. Not unlike brainstorming, it is a complete problem solving process and is particularly useful for problem identification and idea development. Synectics aims to open up a problem to new insights. It is the process of combining unrelated factors to allow problem solvers to view a problem from a different perspective. [14]

Synectics encourages use of analogies such as; personal, direct, symbolic and fantasy analogies to make the familiar strange. The main aim is to use two operational mechanisms. To make the strange seem familiar and to make the familiar strange in order to produce various psychological states which are necessary to achieve creative responses. [14, 40] Devised and termed as 'defamililarization' by Willam Fordon, synectics is a technique in which creative thinking is developed through using similes and metaphors: a) comparing different thoughts, b) connecting irrelevant matters, and c) developing creative thinking. [42] Results show that, compared to traditional teaching method, synectics and brainstorming promote more creativity development, while the former has more significant effect. [43]

On contrary, Synectics is perhaps the most difficult to perform of all ideation techniques. Skill and experience need to be acquired before attempting to perform synectics. In addition, use of synectics in CPI is very difficult due to its intuitive nature, and also the synectic process in itself is difficult to master by everyone. None the less, synectics could be used in idea generation for possible new product but seems inappropriate for solving technical problem. For details on exact ways to perform synectics, several writings could be referred. [40, 44]

3.1.3. Lateral Thinking

Lateral thinking is about moving sideways when working on a problem to try different perceptions, different concepts and different points of entry [14]. In general, lateral thinking means exploring multiple possibilities and approaches instead of pursuing a single approach. Bono envisages lateral thinking as a description of a mental process leading to new insights. [45]

Lateral thinking has very much to do with perception. In lateral thinking, problem solver seeks to put forward different views. All are correct and can coexist. The different views are not derived from each other but are independently produced. In this sense, lateral thinking has to do with exploration just as perception has to do with exploration. This is the specific purpose of lateral thinking. Normal logic is very much concerned with 'truth' and 'what is'. Lateral thinking, like perception, is very much concerned with 'possibilities' and 'what might be'. Problem solver builds up layers of what might be and eventually arrives at a useful picture. Lateral thinking is concerned with the changing concepts and perceptions, and based on behaviour of self-organizing information systems. [8] De Bono stated normal or vertical thinking as to dig the same hole deeper, whereas lateral thinking is concerned with digging a hole in another place. Seemingly, if that hole is in the wrong place, no extent of logic is going to put it in the right place. [46] Again, Lateral thinking is not an attack on vertical thinking, but a method of making it more effective by adding creativity. Lateral thinking is useful for generating ideas and approaches; then vertical thinking is responsible for developing them. [2] Although, creative problem solving method (CPS) requires these dual thought processes, the model will not be constructive unless the ‘digger’ is on the right track. [46]

In process industry, lateral thinking seems very much difficult to implement, due to its unique perspective requirement. However, if someone would learn the process, it would certainly prove helpful to start the search in right direction but there is no guarantee to find solution as most of the problems faced in CPI are technical and interwoven. For supplementary aspect about lateral thinking, refer to following resources [2, 8, 45, 47]

3.2. Analytical Methods

There are certain problems solving skills those could be acquired. Techniques that could be learned and improved throughout one’s life. Thinking analytically is a skill like any other skill. It could be taught, it could be learned, and it could be improved with appropriate practice. [48] Contrary to intuitive methods, analytical methods makes problem solving process progress from random to systematic, while keeping and exploring all possibilities of good solutions [49]. Out of various available techniques, a few commonly known analytical methods such as; morphological analysis, analogies and TRIZ are explained below.

3.2.1. Morphological Analysis

Morphological analysis is a tool which could help to generate a vast number of ideas. It seems ideal for generating a large number of ideas of an opportunity-seeking or exploratory nature in a logical way. Moreover, it is a powerful tool for broadening an individual’s horizons with respect to a problem. This technique was the work of a Swiss astronomer, Fritz Zwicky. [14]

In morphological analysis, first all possible dimensions are listed which describe the problem or system being studied. No more than three dimensions could be represented diagrammatically, and they must be relevant and have a logical interrelationship. For example, if a company decides to alter its product in response to changing requirements, it may consider product shape and the material out of which the product can be made as two such dimensions. In this case, the dimensions would be represented on a two-dimensional grid (or on a cube for three dimensions), and a list of attributes is then generated under each dimension. [14]

The ideal morphological analysis identifies all possible combinations of means to achieve a desired end. After construction of a morphological box that, in principle, can contain all possible variants of a solution, solution to the problem could be reached. However, the main obstacle in front of problem solver would be to choose the right solution among all those combinations and be sure about it. As morphological analysis does not offer an unequivocal answer to this question, it is the main drawback of the morphological approach. [1] On the other hand, it works best as a visual aid to foresee the possible solutions. Again, this could prove difficult in circumstances where the problem is complex. Ideally, the problem should have two or three dimensions to permit construction of two dimensional or three-dimensional grids and it is unsuitable for problems where one must focus on a narrow band of options or where a problem only has a single dimension. [14]

3.2.2. Analogies

Analogies technique is one of the most powerful idea generation methods [5] . The notion is to compare the problem with something else that has little or nothing in common and gaining new insights as a result. In many situations, use of analogies facilitates new problem perspectives without which the solutions to problems might never be found. They provide the problem owner with a possible escape from ‘mental stuckness’. [14] When used properly, analogies could be a rich source of ideas for resolving almost any type of problem. [5]

The basic principle underlying analogies is that new perspectives on a problem can be gained by freeing problem solver from familiar patterns. If solver is too close and familiar to any problem, one is not likely to think of unique ways of viewing it. As a result, ideas for resolving it may be mundane and common. [5] There are at least 4 major guidelines for using analogies to provide new perspective to problem solver. In practice analogous situations are examined and compared with the real problem to see if any new insights emerge. Again, analogy could act as a proactive device which could be used to force a new way of looking at the situation and could also be used to provide movement or in making relationships which is one of the most powerful ways to develop new insights and new solutions. Problem solver can force a relationship between almost anything, and get new insights - chemicals and safety, hazardous process and natural process, and so on. [2]

Though being a powerful method that a lot of people have trouble using analogies appropriately. The challenge with the analogy-based methods is to find similarity among the problems and then modify old solutions to fit new problems. A common example of analogy technique is cased-based reasoning (CBR) which is often used in process industries to solve problems. This technique is used to solve new problems in process industry by reusing solutions that were applied for past problems with similar features. [50] Use of CBR technique was found to design distillation systems in process engineering [51-53].

On the other hand, the disadvantage of analogies could be very strong influence of old designs and the lack of sufficient adaptation methods to support innovative design. As a result, this method could possibly suggest solution, only if similar problems were tackled in past, whereas for problems requiring completely new solution, it draws complete blank. To have details guidelines on how to practice analogy method several literatures could be reviewed [2, 5, 14].

3.2.3. TRIZ

TRIZ (*Teoriya Resheniya Izobreatatelskikh Zadatch*) is the Russian acronym of what could be interpreted as 'the theory of inventive problem solving.' (TIPS) [1, 19] TRIZ is a problem solving methodology based on logic, data and research, and has nothing to do with intuition. TRIZ is a systematic methodology for innovation, supports in problem solving and addresses problems at different levels (system, subsystem, assembly, and part level) [19, 49]. Compared with other methods, TRIZ (and TRIZ-based methodology) is the only innovative knowledge-based and evolutionary-directed technique [54]. Due to this, popularity of TRIZ is growing as it is showing up commonly in success stories of innovative solutions to problems in technical and in nontechnical fields. With TRIZ, one would be able to generate better ideas faster, and also would have a basis for selecting best ideas, ideas that would solve the problem effectively and form a basis for further improvements. [55]

The origins of TRIZ could be found in analysis of engineering and utility patents of the former USSR, as those *40 principles* of TRIZ were constructed to tackle engineering problems (appendix II). [24] With the basic concept, 'somebody in some place has already solved the problem on hand (or one very similar to it)', initial work on TRIZ was started analysing past information. The only raw material available for solving problems is past knowledge and TRIZ was built by using past knowledge [56]. TRIZ research began with the hypothesis that there are universal principles of creativity that are the basis for creative innovations and technological advancement. It was found that new ideas are often built by combination of existing ideas, or borrowing an idea from an analogous problem situation. It was realized that if these principles could be identified and codified, they could be taught to people to make the process of creativity more predictable. TRIZ provides a means for problem solvers to access the good solutions. Basically, the principles of good inventive practice had been summarized and set them into a generic problem-solving framework. The underlying principle of TRIZ used for problem solving is illustrated in figure 5. [57]

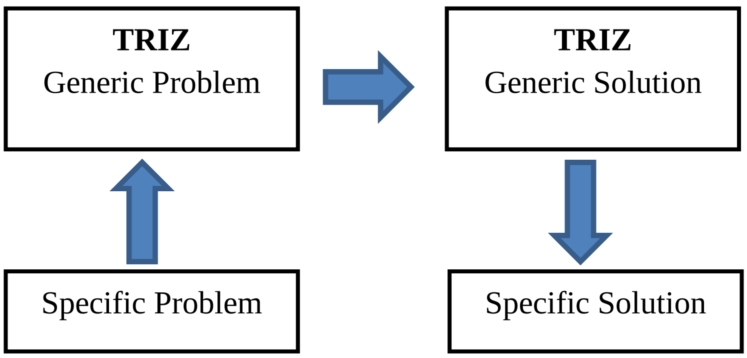

Figure 5 The TRIZ Problem-Solving Method [1]

TRIZ could be used in various ways as an overall process enables users to systematically define and then solve any given problem or opportunity situation. TRIZ involves a systematic study of the system to be enhanced and the use of a sequence of strategies for problem definition. The problem definition is very important stage, and once the problem is properly defined, it is virtually solved [58]. It is TRIZ system of understanding the problem, modelling the contradictions, removing them by using resources, and improving ideality of the system, not relying on intuition. It relies on knowledge of the system being improved and on knowledge of the systematic method for improvement. [55]

One of the strongest advances of TRIZ compared with all other problem-solving methods, design approaches, and creativity aids is its systematic ability to provide information about result of a problem-solving process (concept of Ideal Final Result), steps during a problem-solving process (TRIZ heuristics and instruments), clarification of initial situation of a problem (concept of contradictions), and simplification of technique and problem. Figure 6 illustrates a hierarchical perspective of TRIZ, which displays that the method is based on knowledge and a large amount of research work. [59] The four main concepts that make TRIZ methodological and distinct from other problem solving methods are such as; [1]

- Contradiction
- Ideality
- Functionality
- Use of resources

In TRIZ, these four concepts facilitates purification of a problem (for example, establishing correct statement of a problem), clarification of the contradictions (for example, detecting the problem’s roots), and imagining the best solution (for example, discovery of ideality) which had proven to be powerful steps during problem solving. TRIZ is a method of the identification of a system’s conflicts and contradictions aimed at the search for the solutions of inventive problems [60].

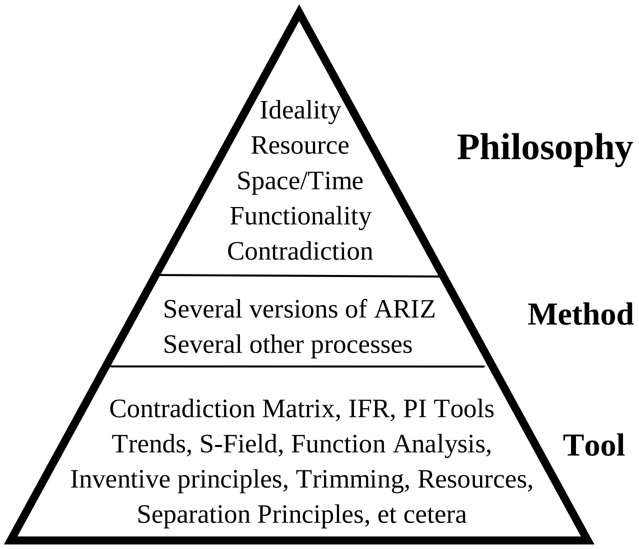

Figure 6 Hierarchical view of TRIZ [62]

Often the most effective inventive solution of a problem is the one that overcomes some contradictions. Contradictions occur when improving one parameter or *characteristic* of a technique negatively affects the same or other *characteristics* or parameters of the technique. [57] A contradiction shows where (in so called operative zone) and when (in so-called operative time) a conflict happens [1]. This concept of a contradiction is very important as there are contradictions (conflict between two features) behind every difficult problem. These are also called 'tradeoffs' as the problem solver trades improvement of one feature against decline in another feature. [55]

The contradiction could be divided in two types such as; technical contradictions and physical contradictions. A technical contradiction takes place when there are two parameters of the system in conflict, and the improvement in the value of one parameter worsens the value of the other. These technical contradictions could be solved by use of contradiction matrix, one of the most popular tools in TRIZ [61]. It is also regarded as the most commonly applied tool which contains a 39 x 39 matrix containing three to four most likely strategies for solving design problems (appendix I). On the other hand, physical contradiction takes place when a parameter should simultaneously have two different values and could be removed by applying four '*principles of separation'*. Four *Separation principles* suggested to overcome physical contradictions are such as; separation in space, separation in time, separation within a whole and its parts and separation upon conditions. [57] Additional material on contradiction matrix could be found in chapter 6.

TRIZ provides a logical way of thinking, to understand problem as a system, to image the ideal solution first, and to solve contradictions. TRIZ focuses to increase ideality by overcoming contradictions mostly with minimal introduction of resources. In other words, TRIZ ideality makes problem solver to start by focussing on possible solutions rather than on problems, then asking how to achieve ideal final result (IFR) using given limited resources and understanding what exactly prevents them to reach solution. Ideality is a general trend of behaviour of all systems and it consists in increasing the benefits of system while reducing the disadvantages. [62] Generally, used as a problem definition tool, the ideality part of TRIZ inspires problem solvers to break out of the traditional thinking pattern and seek for IFR. IFR could be defined as the solution which contains all of the benefits and none of the costs or 'harms'. This method helps users to evaluate situation and to find practical solution close to IFR. [1, 57]

The idea that a system possesses a main useful function (MUF) and that any system component which does not contribute towards the achievement of this function is ultimately harmful. For example, in a heat exchanger, the MUF is to transfer heat to the working medium whereas in case of filtration MUF is to separate desired components from the feed. The function analysis is a means of identifying the contradictions, unnecessary or even detrimental relationships in and around a system. Functionality is the common thread by which it becomes possible to share knowledge between widely differing industries. A mixer is a specific solution to the generic function 'homogeneity', just as a washing powder is a specific solution to the generic function 'remove dirt'. By classifying and arranging knowledge by function, it becomes possible for manufacturers of washing powder to examine how other industries have achieved the same basic 'remove' function. *'Solutions might change, but the function stays the same'* is the main concept used in TRIZ methodology. [1, 57]

Use of resources in TRIZ emphasizes on intensification of usage of everything contained within a system. In TRIZ terms, a resource is anything in the system which is not being used to its maximum potential. TRIZ stresses on a forceful and apparently persistent search of things in (and around) a system which are not being used to their complete potential. [57]

TRIZ methods have been proved to be a useful method for problem solving, along with exploring ideas and solutions systematically. All other approaches usually try to find a specific solution directly from the description of the given problem whereas TRIZ methodologically suggests various possible solutions and solver could follow the best ones. A systematic programme, which compares the different creativity tools, methods and concepts in terms of their relevance to primarily scientific, engineering, and business applications, has concluded that TRIZ currently offers the most useful foundation for a systematic creativity model. [63] As one gain extensive practice applying TRIZ, one will become so skilled in it that the problem-solving process will be less conscious and more automatic.[1] In order to handle various problems, number of tools are available in TRIZ, such as; *Inventive principles, IFR, Trends, S-Field, Function Analysis, Knowledge/Effects, PI Tools, Trimming, Resources, Separation Principles, Subversion analysis and Contradiction Matrix* (figure 7). [64, 65] Among these available tools, *contradiction matrix* seems to have many prospects for its usability in CPI, thus it is chosen to be adapted.

On the other hand, it would be inaccurate to say that TRIZ could resolve any technical problem, but many inventions created with TRIZ do confirm its power. [1] The popularity of TRIZ around leading industrial countries is not a surprise, as the use of innovation in a business strategy has been strong for at least past two decades [61, 66-69]. TRIZ effectively removes away all boundaries between different scientific, engineering and creative disciplines. Its usefulness has been evidenced across a wide scale of fields and problem types. Successful use of TRIZ methodology for different purposes, such as for generation of design alternatives and in selection of design techniques [70] along with a case study in which TRIZ was used to solve technological problems [71] were found. The advantages of TRIZ methods have been discussed in many articles [54, 63, 70]. Except for the area of science and technology, TRIZ also has been applied into the following aspects: (1) non-technical organizational problems relating to communication and personnel issues, (2) in combination with other design methodology, such as QFD and Taguchi and (3) diagnosing failure analysis problems. [64, 72-74]

For additional information on TRIZ, literatures from various authors are available [1, 23, 57, 61, 75-77]. A book, 'Simplified TRIZ' explains concept of TRIZ in

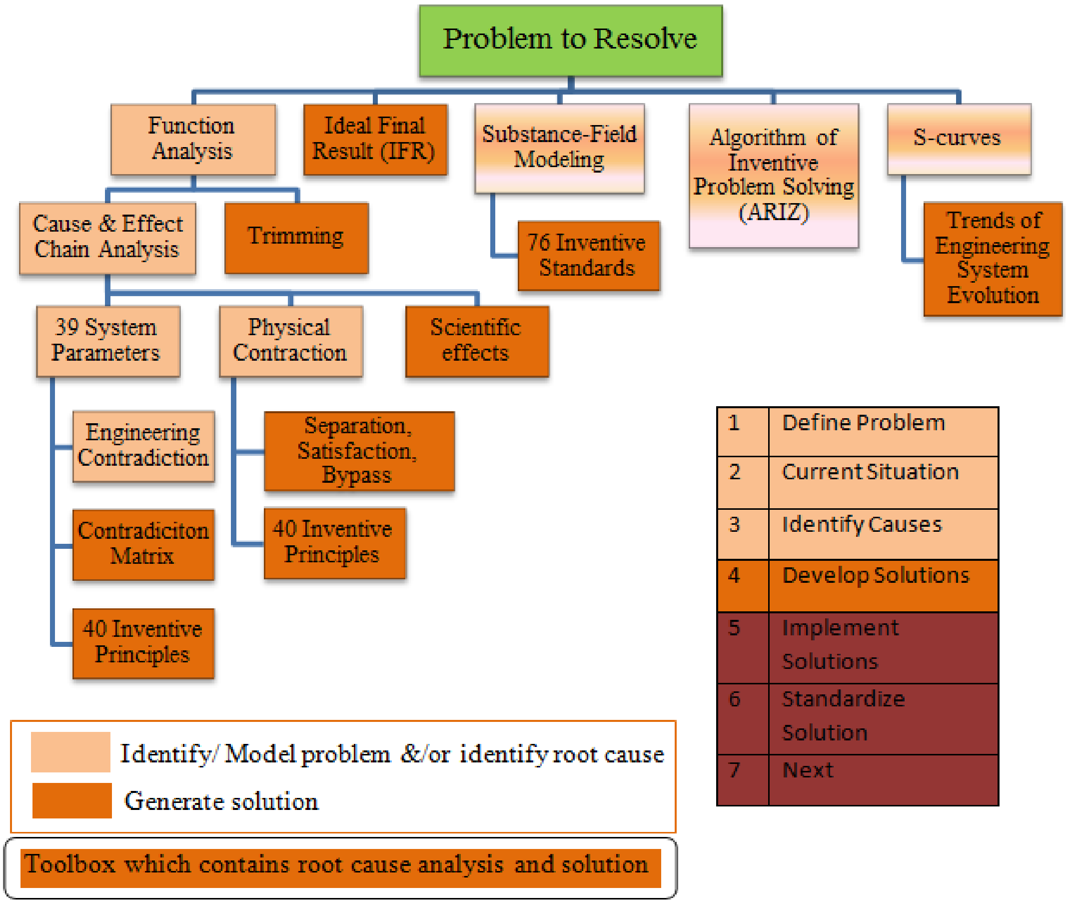

Figure 7 Various Tools Available to Resolve Problem [57]

layman language and would be a good choice for early stages learners of TRIZ [55] and for few remarkable examples of TRIZ in CPI [24, 78]. In the following chapter, various applications of TRIZ method and its importance to solve problems in CPI would be discussed.

4. APPLICATION OF TRIZ IN CHEMICAL PROCESS INDUSTRY

In recent years, TRIZ has gained popularity in process industries due to its simple and effective problem solving method. As TRIZ was constructed to tackle engineering problems, very few publications were found which aims TRIZ directly at chemistry and its applications in CPI. An interesting paper demonstrating on how those *40 principles* of TRIZ could be applied directly to problems related to chemistry was found [24] whereas, another fascinating paper explains TRIZ *principles* with variety of examples from CPI [78].

Application of TRIZ in process industry is not totally a new concept. Numerous attempts had already been made to use TRIZ in problem solving in various niche of process industry. Though, only handful of publications focused on applications of TRIZ in chemical and process engineering problems could be found, these studies [79, 80] were enough to grab attention of personnel in CPI. These studies had emphasized on possibility to practice TRIZ in process industry and also had illustrated pros and cons of its usage. During these studies, it was also found that the most common applications of TRIZ were for product improvement, by enhancing its useful features or by eliminating harmful ones [80] . Study had illustrated successful application of TRIZ methodology to a complex problem encountered in the field of chemical protection garments (product design), which was to be worn by soldiers potentially exposed to chemical or biological hazards. [81] In addition, use of TRIZ to design a distillation system [82] and in design of separation systems [83] confirms its usability in CPI.

Various applications of TRIZ in process industry were found from new product development task such as; product design and process design to maintenances or improvement of existing system (troubleshooting). In a case study concerning design of atypical heat exchanger, it was demonstrated on how TRIZ could be used to break out of existing archetype to produce an unconventional design solution [84]. A different case study of FBC (Fluidised Bed Combustion) boiler highlights on how the erosion of boiler problem was solved by use of TRIZ, when engineers encountered with the problem of tube erosion with coal in a particular process application in a utility plant [71]. In addition, various examples could be found which describes use of TRIZ for waste minimisation [85] and for purpose of trend identification and development of computer aided tools [86].

In majority of applications, TRIZ was used in its original form. However, some studies used modified version of TRIZ and few earlier attempts to modify TRIZ to fit chemical process industry also had been made. An earlier study, which attempted to modify TRIZ by reorganizing thirty-nine parameters of the original TRIZ into six categories (such as mechanic, operator, process upset, design, natural hazard and material) and later applied it to test a jacketed reactor and polyethylene reactor [79] (appendix II). In another case study about detection of water leakage, it revealed how creative problem solving could prove as valuable tool for solving practical problems. [87] For example, use of modified TRIZ was for troubleshooting operational problems, to be precise clogging of multi-drum filter with oil when used in textile process application. ARIZ (algorithm of inventive problem solving) process was followed in order to resolve problem. [88] In addition, a case study was found which examined relevancy of inventive *principles* of TRIZ to new food product development and innovation [89]. Use of TRIZ based creativity tool in design of food processing equipment [90] and on development of new methodology to design distillation process [91] were few classic examples of successful application of TRIZ methodology in food processing industries.

Though, TRIZ had proved to be very useful in CPI domain, its full potential had not been utilized. In chemical process industries, as the substances (raw material) that would be introduced in the beginning of the process undergoes various physical and chemical changes before product is formed, and these changes would be influenced by numerous parameters involved in the process. These parameters could be chemical reactions, temperature, pressure, reaction time, type of reactants used, reactant feed ratio, mixing, separations, shape transformations and so on. Due to these numerous parameters in play simultaneously, to pinpoint the exact location of problem had always been challenging task in process industries. This makes process industry different from other domain and application of TRIZ tough in CPI. [80]

On more than a few occurrences, while dealing with problems encountered in process industries using original contradiction matrix of TRIZ, due to lack of *characteristics* which could describe contradiction of physiochemical phenomena had made TRIZ methodology unusable. Whereas, in most cases, while using original contradiction matrix of TRIZ in CPI; the main challenge was to interpret concept conveyed by *40 principles* to suggest practical solution for CPI. Therefore, some new *principles* and *characteristics* requirement was acknowledged to make TRIZ readily usable in CPI with fewer complications. The adapted contradiction matrix for CPI would be suggested which contains some new *characteristics* and few *principles* which could be easily related to CPI. The methodology used for development of these new *characteristics* is discussed in next chapter and adapted contradiction matrix itself could be found in chapter 6.

5. NECESSITY OF ADAPTED CONTRADICTION MATRIX FOR CPI

In this chapter, necessity of adapted contradiction matrix to enhance usability of TRIZ in chemical process industry (CPI) is illustrated. Numerous case study and literature reviews were done to gather common problems existing in unit operations, which were later used to suggest new *characteristics* for adapted contradiction matrix. The methodology followed during this work is described (section 5.2). To clearly demonstrate the methodology, two case studies (section 5.3) are presented in details. The adapted version would not replace the original one but would be additional tool for better utility of TRIZ in CPI. The adapted version of contradiction matrix as outcome of this chapter is described in next chapter in details.

5.1. Adapted Contradiction Matrix Model

As mentioned in earlier chapter, the full potential of original TRIZ contradiction matrix is difficult to access to chemical aspect of CPI due to inapplicability and ambiguity of terminology in classification of these parameters. Contradiction matrix, being one of the powerful tools of TRIZ, seems necessary to be modified for better usability in chemical process industries. [79] Most of the earlier studies were found to be focused in small area in CPI, either in development of food product or to enhance safety of chemical process. No earlier works were found which seems to approach to address the entire domain of CPI. As unit operations could be found commonly throughout CPI, this study would propose a model framed on original contradiction matrix of TRIZ by using common problems encountered in unit operations as source. This new approach would be based on problem associated to various unit operations which would be grouped to suggest new *characteristics* to enhance usability of TRIZ in CPI. So various problems associated with unit operations, their possible sources and techniques used to solve those problems were studied and summarized as new *characteristics*.

Earlier modification of TRIZ for applicability in CPI had proven challenging task due to several reasons, such as [80]

- Lack of information

Original TRIZ was built after analysis of information contained in patents, but most production processes in CPI are usually not patented. The ingredients along with raw materials used in the process to manufacture certain product could be found, but it would not help without facts on exact procedures and process parameters used in manufacturing process. This seems to be a major setback while searching data. So, accessible scientific articles, books and journals were used to gather required information on procedures and process parameters used.

- Real causes of a problem in process industries are often difficult to be pinpointed exactly.

In processes, the actual cause of a problem (the ‘root cause’) is often hidden somewhere in the process. Very often, it is found that a series of various problems arises later in different processes due to minor problem in former phase, when it was not properly addressed. It could take much time for problem to be tracked down and with various possibilities to follow up, such as raw materials, chemistry, control loops, et cetera; it would be a tedious task. So, if a problem prevailing in any unit operation has to be solved, first of all, main problem source had to be accurately pinpointed. Solving any problem in early stage could prove much easier, economical and robust approach in CPI.

The purpose of any chemical process is to apply various operations in such a sequence that the differences in properties between raw materials and products are systematically eliminated. As a result, raw materials are transformed into desired products. [28, 92] In process industry, unit operations are used to perform such essential function. Unit operations are largely used to conduct primarily physical steps of preparing reactants, separating and purifying products, recycling unconverted reactants, and controlling energy transfer into or out of chemical reactor. Unit operations are as applicable to many physical processes as to chemical ones. [93] So, any chemical process may be represented as a series of unit operations [94]. This series of unit operations are laid out in such a way that it would always follows the anatomy of chemical manufacturing process (figure 8), which is essential to convert the raw material into final product.

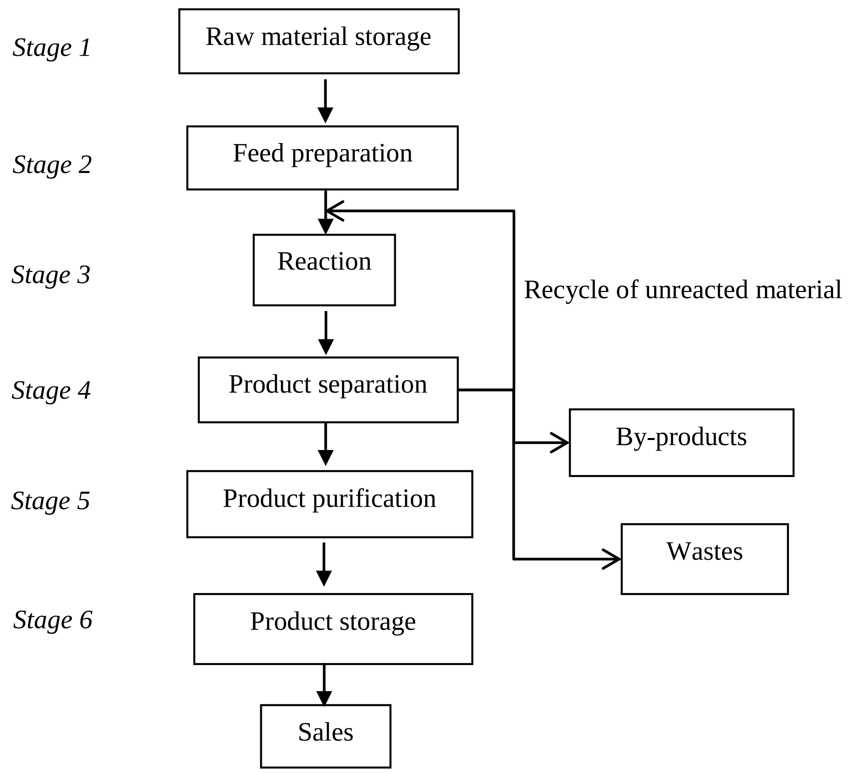

Figure 8 Anatomy of chemical process [158]

In any chemical process, combination of unit operation connected in series affects efficiency of the process. Failure in performance by any one of these unit operations may result in failure of entire process. So, in order to improve efficiency or to solve any kind of problem regarding process, best option is to start by pinpointing unit operation with the problem and troubleshooting it. This is very important concept, as typically same unit operation (for example; separation) is used in chemical industries for potable water treatment plants (for purification), food and beverage (for separation and concentration of milk components). Same unit operation performs various tasks depending where it is being used. Hence, problems existing in most commonly used unit operations were searched along with the techniques used to solve those complications. This provides information to suggest new *characteristics* to solve problems. In CPI, most processes are interlinked with each other in direct or indirect way. Changes made in one unit operation (debottlenecking) may increase overall efficiency of complete process so, it could be said that various problems in process industries could be solved if individual unit operations problems would be addressed. Following this concept, idea of the development of generic systems that performs these functions with new *characteristics,* is suggested. The new *characteristics* suggested would to able to link the problems and solve them as these *characteristics* are developed by summarizing contradictions found in various unit operations.

5.2. Methodology

First and foremost, unit operations that were commonly used in chemical process industries were chosen. List of possible problems and solution applied to resolve those problems were created and later used to suggest *characteristics* that were in contradiction. After review, new *characteristics* for contradiction matrix that could be used in CPI were suggested, which would be discussed in subsequent chapter. Detail explanation of methodology used is presented below.

For the purpose of search, Science Direct database was used to find research articles, whereas web based patent search and management platform called 'ACCLAIMiP' was used to find, sort and classify various patents. These databases gave insight into current situation, direction and resolved problems in various field of CPI.

Initially, commonly used unit operations prevailing in chemical process industry were listed and it was found that generally unit operations could be classified into 4 different types, such as; fluid mechanics based, mass transfer based, heat transfer based, and mechanical based (figure 9). Numbers of case studies were performed to find problems encountered with unit operation throughout CPI. Among those, as an example to explain the procedure of work, two case studies are presented (section 5.3).

Once most of the unit operations were listed, common problems related to each unit operation were collected (for example, table 1, page 49). Possible reasons for those problems were also considered and the action due to which conflict occurred was searched. Those actions were tabulated, along with pros and cons due to that particular action involved in the process (for example, table 2, page 50). Once the action which was improving some useful feature and simultaneously reducing other useful feature was found, it could be seen that contradiction had occurred.

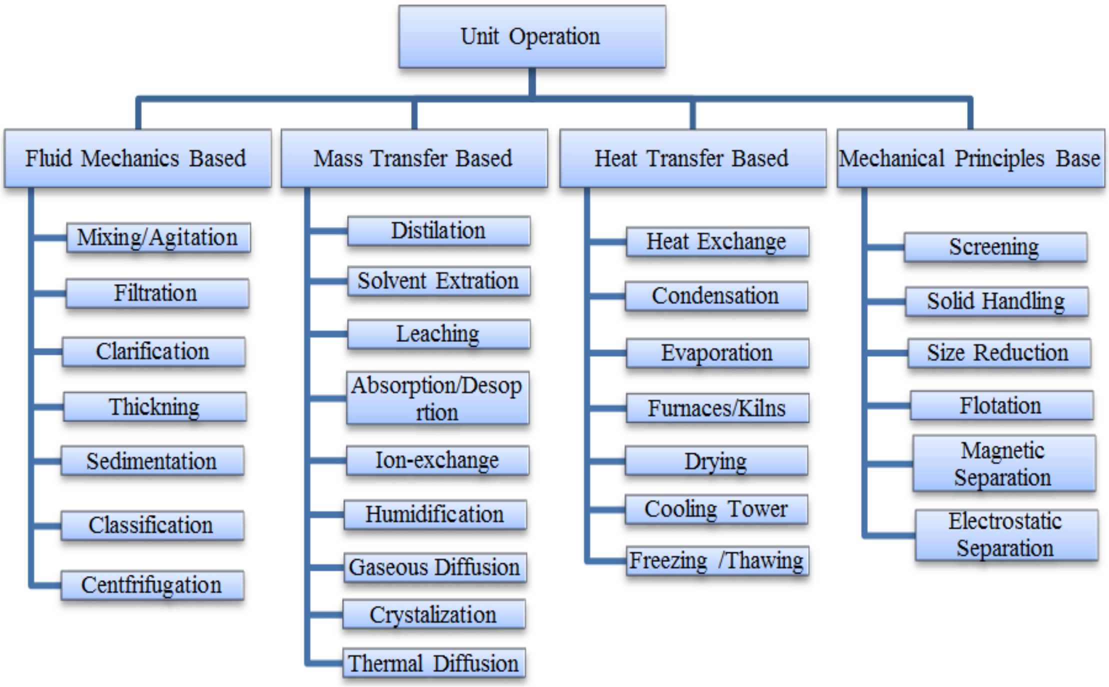

Figure 9 Most Common Unit Operations in CPI

To resolve these contradictions, similar types of problems were summarized to suggest a *characteristic*. So basically, frequently occurring problems in unit operation were grouped and summarized as *characteristics* such as: complexity, quality, duration of operation, process safety, et cetera.

Along with the *characteristics*, set of *principle* were suggested which could provide possible clues to solve those types of issues. *Principles* are known solutions to solve contradictions. The *principle* would help to find probable solution by pointing towards possible option or route. *Principles* are basically used to resolve conflicts that arise during problem solving. Figure 10 on page 39 clearly illustrates the method used to suggest new *characteristics* and *principle* suggested to handle those conflicts.

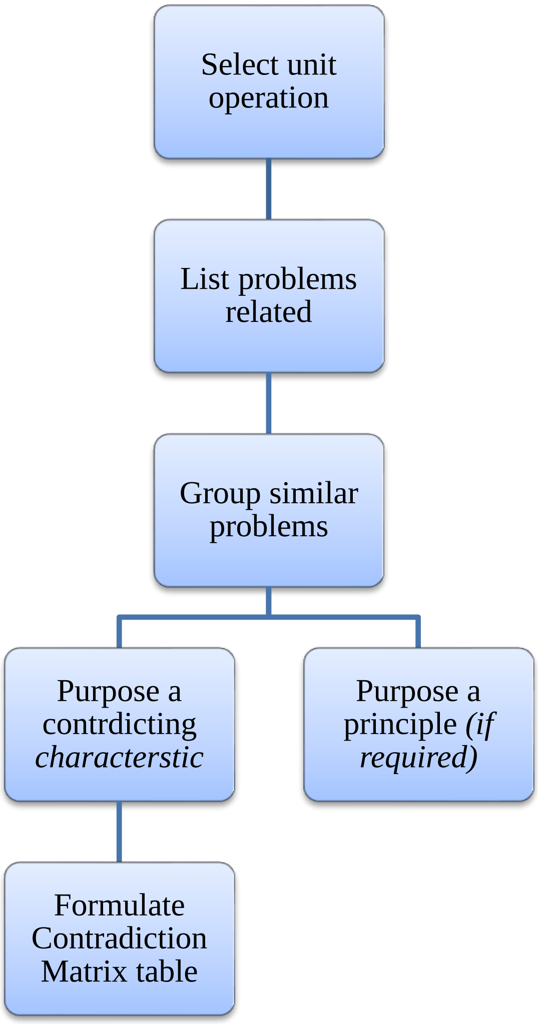

Figure 10 Methodology applied to formulate Contradiction Matrix

5.3. Case Study of Unit Operations

Few commonly used unit operations in CPI were reviewed. While reviewing, focus was directed to those unit operations, whose problems were initially difficult to describe by contradiction matrix of classical TRIZ due to absence of *characteristics* that could define problem found in CPI. Due to this very fact, those problems were often difficult or impossible to solve by using *39 characteristics* proposed in classical TRIZ. Out of several case studies made in formulation of new *characteristics*, details of only two case studies are presented. Thus, this chapter presents two different case studies of unit operations (mixing and membrane separation) used in formulation of new *characteristics.*

5.3.1. Mixing

Mixing operation is common to several industries, and a great deal of engineering effort throughout the history had gone into designing and improving mixing processes. Here, various issues related to mixing were collected and studied. In total, 27 scientific articles and 11 patents were reviewed after screening more than hundreds of articles concerned to mixing related issues and inventions in the field to solve any existing problems. As an example, in Elsevier's ScienceDirect journal articles database, as of June, 2013, there were around 9000 articles dealing with mixing. The keywords used in course of search were such as: *mixing problems; homogeneous mix; efficiency of mixing* and so on.

5.3.1.1. Basics of the Process

Mixing operations are encountered widely throughout productive industry in processes involving physical and chemical change. [95] Liquids, solids and gases have to be mixed in all combinations to satisfy a very variable process or product quality requirement. Mixing is vital operation in CPI which is carried out in various scales. [96]

Mixing is the reduction of inhomogeneity in order to achieve a desired process result. Under the influence of shear and extensional forces generated by mixing, the rates of heat and mass transfer can be improved during processing. The inhomogeneity could be such as; concentration, phase, or temperature. If the mixing fails to produce the required product yield, quality, or physical attributes, the result could be disaster. [96] A good mixing result is important for minimizing investment and operating costs, providing high yields when mass transfer is limiting feature, and thus enhancing profitability. In order to estimate mixing efficiency, it is necessary to define the objectives of process. Few common objectives of mixing are such as; [93, 96-98]

- Suspension and distribution of solids in liquids
- Homogeneous blending in tanks and in-line mixers
- Emulsification
- Facilitate mass transfer

- Facilitate chemical reaction (homogeneous and heterogeneous)
- Maximize interfacial contact surface
- Blending miscible liquids, e.g., methyl alcohol and water
- Dispersion of gases in liquids with subsequent mass transfer
- Liquid–liquid dispersions
- Promoting heat transfer between the liquid and a coil or jacket

When a mixing operation is performed, the ultimate objective is to achieve a target level of homogeneity of above mentioned objectives within the mixture, and to do it in the fastest and cheapest way. [98] Whereas for any mixing process that includes chemical reaction and/or mass transfer, effectiveness of the operation could be evaluated by factors such as; reaction yield, extent of mass transfer, and product rheology. A simple mixing process is depicted in figure 11, where the entire process volume is represented with a square domain. Starting from a highly segregated condition, dark fluid in one side of the square domain and light in the other, the mixing process generates a state at which two colours are indistinguishable on length scale of the system.

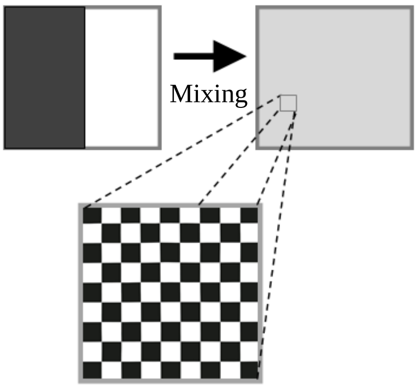

Figure 11 Simple Mixing Process [99]

Mixing plays a key role in a wide range of industries such as; fine chemicals, agrichemicals, pharmaceuticals, petrochemicals, cosmetics, consumer products, et cetera. Various ranges of mixers are available to fit the suitable task. Selection of mixer could be based on process requirements, target mixing quality, and mixing cost. [95, 96] A wide range of mixing equipment is now available, as no single mixer would be able to carry out huge range of duties efficiently in various industries. Thus, range of mixing equipment such as; mechanically agitated vessels, jet mixers, in-line static and dynamic mixers, dispersion mills, valve homogenizers, ultrasonic homogenizers, and extruders could be found to fit various process. [96]

5.3.1.2. Problems and Challenges

Mixing operations in any type of industry has its own basic requirements and challenge to meet those requirements depending on the process. None the less, these problems associated with mixing in most industrial processes were found to be similar. In order to achieve earlier mentioned objectives and have efficient mixing, following common difficulties were found from various process industries. [98-100]

- Too long mixing time
- Nonhomogeneous mixing
- Huge energy consumption
- Undesired by-product formation

In addition to above mentioned problems, mixing operation involving solids in suspension include clumping, agglomeration, fouling, and scaling. [96] Yield losses of 5% due to poor mixing are considered typical in chemical industry [98].

Too long time required to reach target mix depends on different parameters related to fluid being mixed and also in conditions in which mixing is being performed. These parameters could be viscosity, speed of mixing, type of flow, and so on. These parameters are also related to nonhomogeneous mixing.

Non-homogeneity in mixing is often results of insufficient mixing which could be due to short mixing time, uncertainties in properties of fluids or materials being mixed, less understanding of fluid being mixed or equipment being used. Due to the fact that, it is not always easy to estimate how much mixing is enough, in some cases it was found that over-mixing could occur and prove to be damaging to yield or quality. There are a number of situations where excessive mixing in some form or other is not only wasteful of energy but also counter-productive. For example, in mixing of mycelia (biological materials), over-mixing in agitated bioreactors may damage the cells. Yet another example, in crystallizers, high mixer speeds to enhance mass transfer are often counter-productive to the overall process as they cause a huge increase in secondary nucleation and thus producing smaller crystals. According to a study, different levels of mixing could have influence on product weight means size in semi-batch reaction crystallization [101]. Whereas, fast stirring to achieve homogeneity would be impractical in several biotechnological applications, wherever materials are shear-sensitive (proteins and other macromolecules, fibres, cellular materials) and high shear rates often lead to widespread damage to the product. [102] Often, segregated regions as shown in figure 12 could be found despite of long mixing time which shows a typical problem commonly encountered during mixing operation. [103]

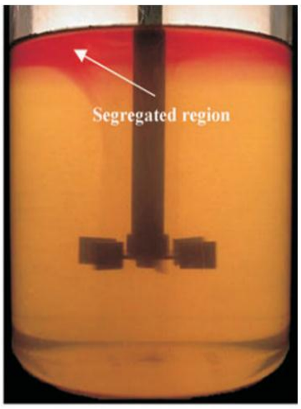

Figure 12 Segregated region as common issue [110]

Use of incompatible mixing device would increase the power consumption directly or indirectly, thus reduces the mixing efficiency. Figure 13 shows vortex formation which is by use of incompatible mixing equipment.

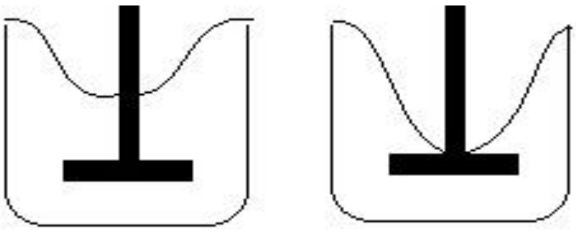

Figure 13 Vortex (a), Sever Vortex (b)

For a mixing sensitive reaction, it was found that the rate of mixing affects both the yield and selectivity of the reaction. Studies had shown that the way in which reagents are mixed could have a large influence on the product distribution of a chemical reaction and poor mixing could lead to side reactions and undesirable by-products in competitive reactions. [104] If a chemical reaction is involved in mixing, mixing time depends on the relative rates of mixing and reaction kinetics. The mixing rate is important in case of fast chemical reactions, as turbulence and molecular diffusion can bring the components together, and reaction proceeds quickly. On the other hand, for slow chemical reactions, reaction proceeds much more slowly governed solely by reaction kinetics, hence product yield do not seem to be affected by mixing.[98] In cases where, the yield drops from the pilot-scale to the plant-scale reactor when all other important variables (temperature, pressure, and composition) have been held constant, then it could be said that there is certainly a mixing problem. [105]

5.3.1.3. Approach to Handle the Problems and Challenges

On the basis of articles and materials reviewed, common problems related to mixing were resolved by various techniques. Problems were solved to some extent with good mixer designs, by change in operation parameters and using different mixing technique [106, 107]. Information on the degree of mixing and mixing efficiency could prove helpful for cost optimisation. Relevant information and understanding the under phenomena governing mixing such as; viscosity, factors related to vessel and impellor, flow pattern in different types of mixers, and so forth, problems in mixing could be handled. In other word, the key issues to mixing could be solved by meeting following demands.

- Minimize mixing time
- To achieve homogeneous mixing
- Minimize energy consumption
- Avoid by-product formation
- Improve selectivity
- Location of feed point

Approaches to minimize time required to reach target mix had been a problem from long time. Solution to this problem was found in sound design of mixing equipment, proper understanding and use of fluid dynamics principle and in most cases by improving the existing equipment to fit for particular process. Mixing being complex operation, depends upon various parameters such as; viscosity, phase of material being mixed, shear rate, type of mixer used, type of propeller used, position of propeller (figure 14), et cetera. For example, position of propeller plays vital role while creating a stable emulsion between light and dense liquid phase. The impeller should be placed in the phase which is going to be the continuous phase and with time the other phase is then drawn into this phase. Figure 15 illustrates on how to mix light and dense phase. [108]

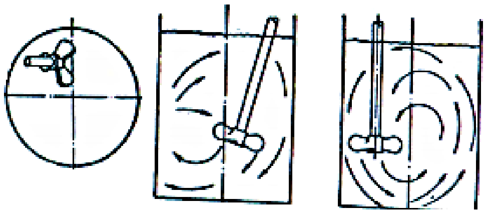

Figure 14 Propeller off center, inclined & unbaffled

Use of incompatible mixing device will reduce the mixing efficiency in manner such as; higher power consumption, longer mixing time, and inhomogeneous mixture. Numbers of researches are being done to find suitable design of mixing vessel or operation parameters to enhance mixing efficiency of any process. For example important design criteria for a commonly found stirred vessel could be impeller type, size and speed, and baffle design. [98, 109]

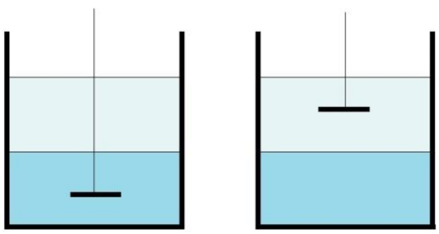

Figure 15 Methods for dispersion of a light and a dense liquid phase [176]

By use of especially designed equipment or impeller that fits the process best could influence shear and extensional forces generated by mixing which improves the rates of heat and mass transfer during processing. Depending on the impeller type, mixing process result could be highly influenced by the impeller flow patterns (axial and radial). In addition to the impeller type, flow patterns below the impeller could also be varied by different tank bottom heads that results in different mixing efficiencies which are important for suspension and distribution of solids in liquids. For solids suspension in flat-bottomed tanks, solids tend to accumulate in corners which could be avoided by redesigning tank bottom heads conical. In similar manner, axial flow impellers were found to be efficient for liquid blending and solids suspension, while radial flow impellers were best used for gas dispersion. This can effect both time required to mix and also the quality that had to be achieved (homogeneity). [96]

To achieve homogeneous mixing in processes, suggestion for uses of wall baffles were found to be cited in numerous studies. Wall baffling has a significant influence on flow behaviour and resulting mixing quality (figure 16). In absence of baffles, the flow created by impeller rotation is two dimensional and causes swirling action whereas wall baffles transforms tangential flows to vertical flows, provide top-to-bottom mixing without swirl, and minimize air entrainment. On the other hand, baffles increases drag and power draw of impeller which seems to be drawback of wall baffle. [98]

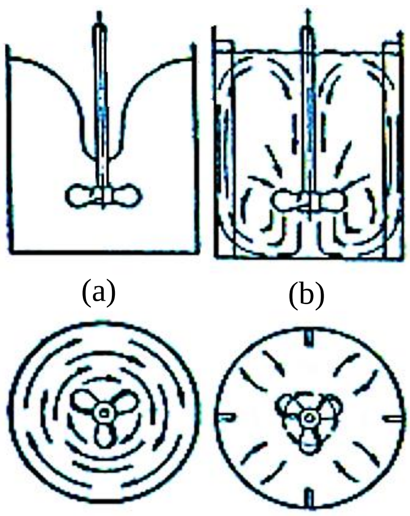

Figure 16 Proper vertical, centered with unbaffled (a) and baffled (b)

Study had shown that efficient mixing can be achieved not only by increasing turbulence but also by using a controlled periodic fluctuation of impeller rotation rate which could prove useful in biotechnological applications, where turbulence is not an option for efficient mixing [102]. To achieve complete homogenization in a minimal time, wider impellers or higher rotational speeds could be used, but both would increase energy consumption [103].

Minimization of energy consumption had always been topic of interest as a fair amount of cost in any process depends on power consumed in mixing operation. In order to ensure an optimum productivity, energy consumption must be optimised which can be done by having better understanding of hydrodynamic and mass transfer mechanisms.[99, 110] For example, static mixers are often employed in industry for viscous mixing applications, as heat and mass transfer promoters, or even as chemical reactors in a variety of applications, as they contain no moving parts, it reduces energy consumption in long run. Static mixers acquire its energy for flow from pressure drop across the mixer. [98]

Again, flow patterns with different impellers also make significant difference in mixing power consumption (figure 17). Various studies had found that the mixing mechanisms were strongly dependent on flow patterns, impeller type and diameter of impeller. [99, 103]

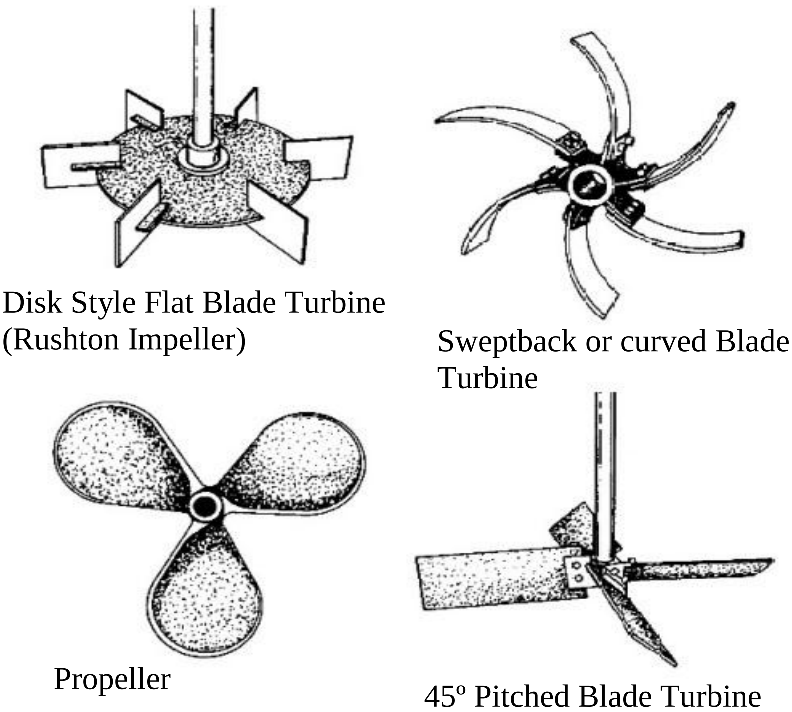

Figure 17 Typical Turbulent Impellers [108]

In order to get desired product, selectivity is uttermost important in any reaction, as slight change in conditions might lead to by-product formation reducing the yield of target product. In order to improve selectivity for chemical reactions, which are carried out in combination with mixing, often one reactant has to be dispersed in bulk scale into another reactant. Only after this, finer scale mixing and molecular diffusion occurs at a reasonable rate, which improves selectivity. A case of by-product formation as an example where Bromination of an aromatic ring was the intended reaction, but due to overreaction, second bromine was being added. This reduced selectivity could be caused by intensity of mixing. Therefore, insufficient mixing could result in lower selectivity due to competitive or consecutive side reactions. Along with the position of feed point, reactor geometry could also affect reaction yield and selectivity. [96, 98]

The conversion to undesired by-product varies depending on feed location of reagents being added in mixer. This type of issues could be solved by feeding reagents in high turbulence zone or near to impellor, which had proven to be effective solution. In addition to that, mixing intensity could affect the product distribution obtained. This often means that reagents could be wasted on manufacturing unwanted products and, further, extra energy would be wasted to separate required product, which had been manufactured at low selectivity, from unwanted materials. [96] As outcome of section, table 1 is presented with common problems and solution applied in mixing.

Table 1 Common problems and solution applied in mixing

Problems	**Applied Solutions**
Too long mixing time	+ Induced turbulence + Controlled periodic fluctuation of impeller rotation rate
Nonhomogeneous mixing	+ Use of different type of mixers, propeller (difference in design, shape, size), baffles. + Change in propeller design (shape and size), operation speed, number of blades, propeller’s location as well as

	position in tank
By-product formation	+ Use of especially designed mixers, propeller, baffles + Variation of reagent feed location
Huge energy demand	+ Use of different type of mixers, propeller (difference in design, shape, operation principle),
Reduced product Yield	+ Induced turbulence + Use of different type of mixers, propeller (difference in design, shape, size), baffles. + Change in propeller design (shape and size), operation speed, number of blades, propeller's location as well as position in tank

5.3.1.4. Method of Conflict Solving

In order to handle conflict situation, first action, pros and cons table (table 2) has to be constructed. This would aid to realize how an action would affect any system and what would be the pros and cons of any particular action.

Table 2 Pros and cons of various actions in mixing

Action	Pros	Cons
Long mixing time ↑	Quality ↑	Energy consumption ↑ By-product formation ↑
Specially designed mixers, propellers ↑	Processing rate ↑ Heat transfer ↑ Mass transfer ↑	Operation expense ↑ Multi-use ↓
Turbulence ↑ **Fluid flow rate ↑** **Short and intense mixing ↑**	Homogeneity ↑ Chemical reaction ↑ (for highly viscous liquid),	Energy consumption ↑ Homogeneity ↓ Chemical reaction ↓ (for low viscous liquid)

Using data from table 1, which covers common problems that would directly or indirectly impact mixing performance (found in earlier phase of study) and common techniques applied to solve them, table 2 was constructed. Table 2 clearly displays how certain action would affect the mixing process with concept of action, pros and cons. From table 2, after evaluating various action's pros and cons, contradicting characteristics in the process could be derived.

Contradicting characteristics derivation process could be assumed as follows. As in table 2, up arrow (↑) denotes increment and down arrow (↓) denotes decrement in intensity of action and response of that action. From action column, if '**Turbulence**' is taken as an example; increasing the turbulence (↑) increases homogeneity (↑) which is desired outcome as it would promote mixing and increases homogeneity in short time. However, energy consumption rises as the mixing operation had to be operated in higher power to induce turbulence. Thus, arrow is pointed downwards (↓) for energy consumption, which undesired effect.

In similar manner after reviewing all the actions from table 2, it could be said that in case of numerous operation, time plays a vital role. The duration of operation always seems to affect most chemical process, and is found to be important to produce desired results. In cases where operation is not performed up to required time, problems might arise in process or with product in later stages, whereas excess duration of operation may not always harm the process or product but also would increase expenditures.

Though, some of the contradictions in table 2 could be explained with classical TRIZ, it is unable to resolve domain specific problems in CPI like duration of operation required, if chemicals were to be added in process to modify property of feed according to process requirement. Hence, acknowledging the necessity of '*duration of operation'* to solve different problems in CPI, it would be suggested as new *characteristics.*

5.3.2. Membrane Separation

Membrane process is one of the fastest growing and fascinating fields in separation technology [111]. Here, various limiting factors affecting membrane separation were collected and studied. In total, 35 scientific articles and 7 patents were reviewed after screening more than hundreds of articles concerned to membrane related problems and inventions in the field to solve any known problems. As an example, in Elsevier's ScienceDirect journal articles database, as of July, 2013, there were around 14000 articles dealing with membrane separation. The keywords used in course of search were such as: *membrane problems; membrane fouling; common problems in membrane separation* and so forth.

5.3.2.1. Basics of the Process

Membrane separation processes is based on a semipermeable membrane, which would permeate only particle under a certain molecular size range. The membrane is at the heart of every membrane process and could be considered as conventional filters but with much finer mesh (much smaller pores) to enable the separation of tiny particles [111, 112]. Schematic representation of membrane separation could be found in figure 18, where the feed stream has been separated into a retentate and a permeate stream. During membrane separation, solute could be partly or completely retained while the solvent (water) molecules pass through the membrane. The driving forces might be gradients in pressure, concentration, electrical potential or temperature (figure 19). [113]

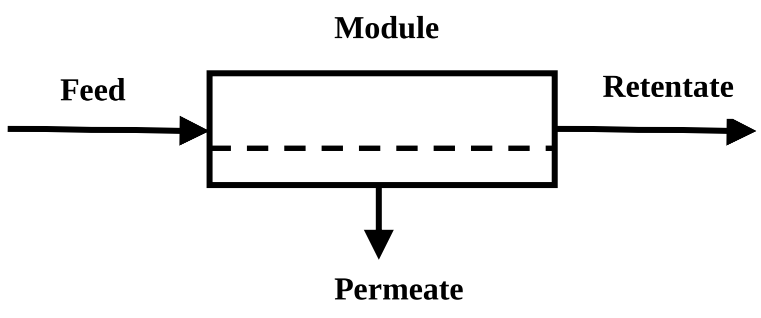

Figure 18 Schematic representation of a membrane process [114]

In recent decade, membrane processes had gained huge popularity due to its advantage over traditional evaporation method, which is lower energy consumption as no phase change is required in membrane processes, thus saving huge energy costs. [114] Therefore, membrane processes are well applicable for either pre-concentration instead of evaporation, or for such cases, where the process fluid cannot be heated over its boiling point. [115] Compared to conventional processes, no chemical, biological, or thermal change of the component is involved for most membrane processes. [111]

Especially, usage of membrane process seems to be increasing where damage to the product could occur particularly when heat-sensitive components had to be produced, such as in pharmaceutical industry (enzymes, antibiotics, vitamins) and being high-value products, and loss minimization is essential. [113] Escalating popularity of membrane separation could be seen in food industry to manufacture dairy products [116] as well as in automotive industry for recovery of electro painting baths [117]. Desalination of seawater by reverse osmosis (RO) to produce fresh water is one of the most widely used applications of membrane techniques. [118, 119]

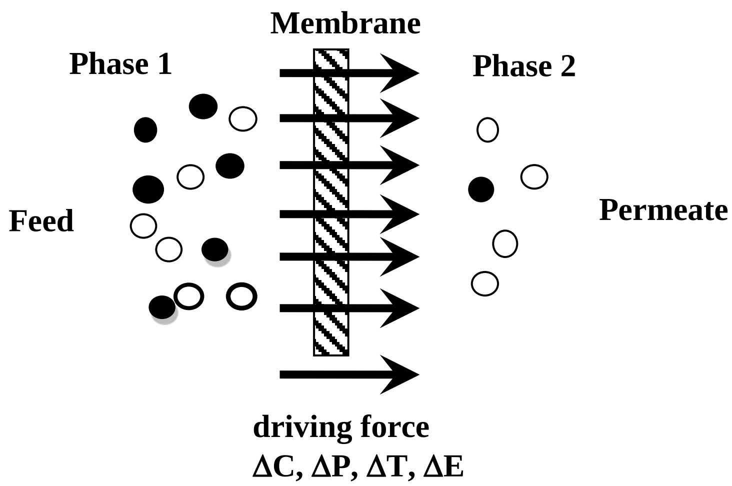

Figure 19 Schematic representation of a two-phase system separated by a membrane. [114]

Today, membranes are considered amongst the best available technologies (BAT) in many processes. [111] Though being relatively new type of separation technology, several membrane processes such as; reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) had already been applied on an industrial scale. Various industrial applications of these membrane processes were cited in several studies. [120, 121]

5.3.2.2. Problems and Challenges

Practically, any operation in industry has its operating range, advantage and disadvantage, which often proves to be restrictive factor in most processes. These restraining factors of operation are the main reason behind failure of most industrial equipment as it would set criteria on various parameters. In case of membrane separation, key reasons behind decrease in process capacity could be due to fouling and concentration polarisation (CP) (figure 20). [111, 113, 122]

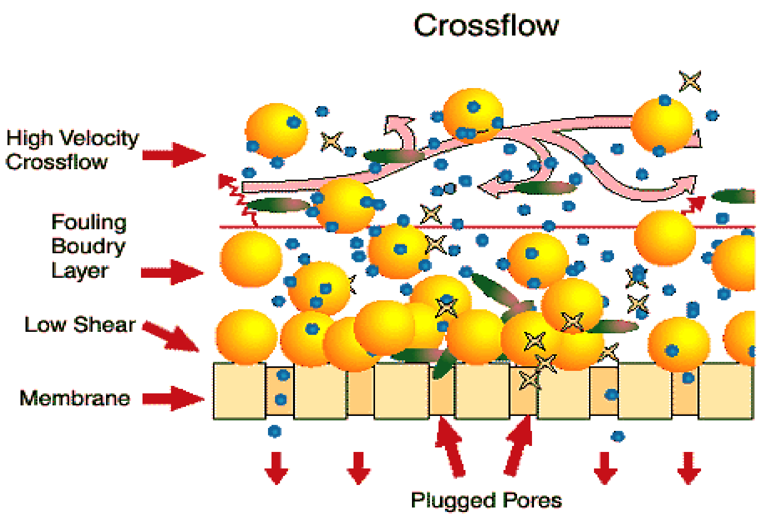

Figure 20 Main reasons behind membrane failure [124]

Membrane fouling could be due to possible changes in membrane structure or by adsorption of chemicals on the membrane surface or into the pores, or by pore blocking. This phenomenon reduces efficiency of membrane and is partly irreversible. [115] Several parameters which could affect membrane performance and leads to fouling would be such as; [111, 118, 123]

- Surface characteristic and material of membrane
- Membrane type
- Nature and concentration of solutes and solvents
- Temperature of feed

- Turbulence in the flow channel.
- Hydrodynamics of membrane module
- Processing condition (density, viscosity, diffusivity and osmotic pressure)
- Pore size distribution

Surface morphology of membrane seems to affect fouling to a greater extent. [124] The efficiency of any given membrane is determined by two parameters; selectivity and flow through membrane. The latter is often denoted as flux. [113] Fouling occur particularly by several industrial solutions which reduces the flux. Fouling could be due to several reasons such as adsorption, chemical interactions, cake formation, and pore blocking by particles. Thus, membranes need periodic cleaning to maintain their performance at the desired level. [111]

In general, temperature increase would lead to increased flux, if no unusual effects occur simultaneously, such as fouling due to precipitation of insoluble salts at higher temperatures or denaturation of proteins or gelatinisation of starch at higher temperatures. The effect of temperature on flux is due to its effect on fluid density, viscosity, and diffusivity of solutes. [111]

Pore size distribution is also one of the most essential membrane characteristics affecting on fouling tendency. Membranes with smaller pore size (RO membrane) has higher blocking tendency compared to ones with bigger pore size (MF membrane).

For examples, foulants in membrane processes could be particles present in the original feed or developed in the process by scaling which could block module channels, and if macromolecules are present in feed, gel or cake formation on membrane is common issue. Very often with increase in concentration and raised pH, precipitation of salts and hydroxides occurs on membrane surface which also leads to fouling. [111, 125] On the other hand, with some types of feed, continuous growth of bacteria on the membrane surface had proven to be challenge. [126]

Another well-known problem for membrane process is concentration polarization, which leads to crystallisation or gel formation on membrane surface. [119]

Concentration polarization is the concentration gradient over the laminar film which directly effects on the operation of membrane. [115] Concentration polarization has a decreasing effect on the membrane performance. [114, 127]

Concentration polarization mainly occurs due to two different reasons, first due to increase in concentration of solute on high-pressure side of the membrane and second, when concentration increases near the surface of membrane. In general, with increase of concentration of solute in the process fluid, the capacity of membrane process decreases, as increasing concentration increases density and viscosity, and decreases diffusivity. All these effects decreases the permeate flux. [114] Increasing concentration on membrane surface also decreases effective pressure difference across membrane, due to increasing osmotic pressure of the solution. High CP might lead to saturation concentration of solute, which would cause crystallisation or gel formation on the membrane surface, thus hindering the membrane process. Fortunately, CP is a reversible phenomenon which makes problem bit easy to tackle. [119] For examples of earlier mentioned problems, in RO, where osmotic pressure is often the main reason which limits maximum concentration of solute to approximately 6-10 % of total solids and in case of UF maximum concentration, which could be accepted, would be between 20-30 % of total solids. These limitations had often proven to be serious restrictive factor for membrane separation process. [114]

In following section, various approaches to handle fouling and concentration polarization problems would be discussed in details. These approaches would mainly be to counter act the above mentioned problems and challenges.

5.3.2.3. Approach to Handle the Problems and Challenges

On the basis of articles and materials reviewed, problems related to membrane fouling and concentration polarization were resolved by various diverse approaches, either by making physical improvement or by chemical treatment. [128] In order to control fouling, various developed approaches are such as: [111, 113, 119]

- Hydrodynamic management

- Back flushing and pulsing
- Membrane surface modification
- Feed pre-treatment
- Flux control
- Effective membrane cleaning

In general, prevention of fouling and CP would be difficult but in most cases, fouling tendency could be affected by hydrodynamics of membrane module (channel geometry, module design, fluid flow, turbulence), by pre-treatment of the solution, or by altering membrane characteristics.

Hydrodynamic management aims at promoting local mixing close to the membrane surface which reduces concentration at the membrane surface leading to reduced adsorption of molecules, hence reduces fouling. By simply increasing cross-flow velocity leads to limited effect of fouling but results in much higher energy consumption. Example of physical improvements could be seen in all UF and RO modules, which operate in cross flow mode, in which feed is pumped across or tangentially to the membrane surface. This mode is advantageous, as it limits build-up of solids or solutes on membrane surface, hence decreasing both fouling and concentration polarization. [111, 114]

Yet another technique that could be used to reduce fouling would be back flushing or pulsing. The purpose behind back flushing or pulsing would be to remove cake layers on the feed side and, therefore, reduce the influence of fouling. On the other hand, modification of membrane surface and feed pre-treatment, both could act by altering the interactions between the filtered molecules (microparticles) and the membrane surface, either by introducing charge groups or by increasing hydrophilicity. Studies had suggested that surface charge to be an important factor in order to influence membrane fouling. Thus, commonly used idea to improve membrane surface characteristics were by increasing hydrophilicity, or reducing roughness and also by introducing polymer brushes, which enhances the antifouling property (figure 21). [129-132] In addition, when fouling particularly occurs due to growth of biological organism on the surface of membrane, use of hybrid thin film composite (TFC) membrane which consists of TiO_2 nanoparticles has photocatalytic destructive capability on micro-organisms and could also reduce membrane biofouling.[133]

For pre-treatment, most widely used methods, such as; filtration, chemical clarification, pH adjustment, chlorination, or adsorption by activated carbon could be used. [114, 129] Pre-treatment would be necessary in some types of operation such as secondary treated wastewater effluent, which displays high fouling

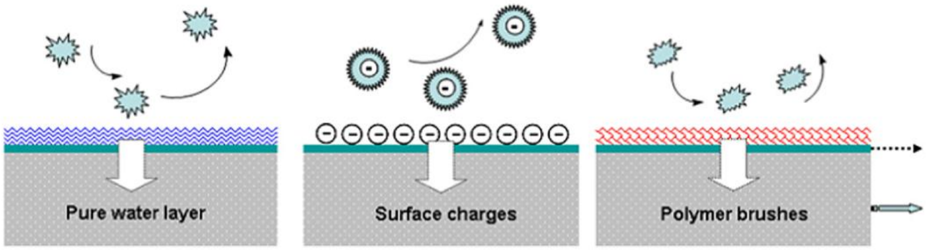

Figure 21 Schematic diagrams of antifouling mechanisms: (a) pure water layer; (b) electrostatic repulsion; (c) steric repulsion. [130]

potential and reduces the performance of membrane filtration significantly. So, to ensure removal of foulants prior to membrane filtration, pre-treatment such as sand filtration could be used. [134]

Common practice followed in industry to increase the reduced efficiency of membrane due to fouling was by membrane cleaning, which could be done mainly by three different methods, namely by hydraulic, chemical, or mechanical cleaning (table 3). [117] A common technique, chemical method is performed using aggressive chemicals at moderate temperatures but it would not in result a complete (100% effective) performance recovery. Typical clean in place systems (CIP) would be used. [111] Atypical work in which by utilization of DC (direct current) electric field and its electrokinetics, possibility to control membrane fouling and improvement in performance of membrane was demonstrated [135].

On the other hand, increasing local turbulence or mixing close to the membranes, by use of various methods to introduce flow instability and secondary flow could prove relatively easy and useful. [136] This could be performed in various ways, such as; using turbulence promoters, corrugated membrane surface, various spacers, vibrating/rotational membranes, reverse or pulsatile flow, use of sponge balls, gas bubbles, et cetera. It has been demonstrated that these techniques generate secondary flows which improves local mixing and therefore improves mass transfer.

As concentration polarization is a reversible phenomenon, increasing turbulence (by use of turbulence promoters) in the fluid flow may reduce its effect and also it could be done by increasing the flow velocity which increases turbulence and decreases thickness of the polarization layer on the membrane surface. This gives higher permeate flux. [111, 137] To summarize, problems and applied solution used for prevention as well as minimization of fouling and concentration polarization could be seen in table 3.

Table 3 Common problems and solution applied in membrane separation

Problems	**Applied Solutions**
Concentration polarisation (CP)	+ Increased turbulence + Pulsed flow + Hydrodynamic management + Tangential feed flow to the membrane surface
Fouling	+ Increased turbulence + Timely cleaning + Surface modification + Tangential feed flow to the membrane surface + Pre-treatment of feed
Reduction of active membrane area	+ Timely cleaning

5.3.2.4. Method of Conflict Solving

In this part, method of conflict solving would be described and *characteristic* would be purposed to relate the problems and solution based on table 3. Using the list of factors affecting the membrane performance found in earlier phase of study, alike problems were shortlisted in groups and common techniques being used to solve them are shown in table 4 with concept of action, pros and cons. As each action has pros and cons, contradicting *characteristics* in the process could be derived from it. The derivation process is similar to one used earlier to develop '*duration of operation'* after reviewing turbulence and its pros and cons related to various phenomena shown in table 2 (page 50).

Table 4 Pros and cons of various actions in membrane separation

Action	Pros	Cons
Membrane pore size ↓	Quality ↑	Flux ↓ Membrane resistance ↑
Pre-treatment ↑	Processing rate ↑	Operation time and expense ↑
Turbulence ↑ **Fluid flow rate ↑**	Fouling ↓ CP ↓	Mass transfer resistance ↑
Concentration ↓	Permeate flux ↑	Operation time and expense ↑
Temperature ↑	Permeate flux ↑	Expense ↑ Operation criteria ↓
Pressure ↑	Permeate flux ↑	
Cross flow velocity ↑	Fouling ↓ CP ↓	Energy consumption ↑

From table 4, it could be said that while performing some action there is always pros and cons of that particular action to the whole process. Change of single variable in chemical process often leads to multiple changes and these parameter changes as response of action often contradict with each other. As contradicting *characteristic(s)* makes process unpredictable and also might bring difficulties to operation. Yet, some of these phenomena could be explained with classical TRIZ, such as; mechanically increasing turbulence or velocity to decrease concentration polarisation (CP), it is unable to solve domain specific problems. Like in CPI, application of chemical to modify property (chemical added to alter the membrane or feed property), hence considering the requirement of chemical modification to solve various problems often in CPI, suggestion of '*chemical modification'* as a *characteristic* is made.

In similar manner, '*driving forces'* which can be gradients in pressure, concentration, electrical potential or temperature is also suggested. This would help to uncover other potential driving forces existing. The procedure used to formulate this *characteristic* is similar to one explained above.

The purposed contradicting *characteristic* would be added to the contradiction matrix which could be found under chapter 6, adapted contradiction matrix for CPI. With similar approach, other *characteristics* were also developed as finding of other case studies, whose stepwise descriptions had been omitted here.

6. ADAPTED CONTRADICTION MATRIX FOR CPI

The *characteristics* and *principles* found in classical TRIZ were formulated to solve issues related to physical and mechanical systems, whereas CPI, being based on chemical system makes usability of classical TRIZ quite a challenge. To enable a process engineer to solve conflicts that arises while designing a new process or plant, or in course of improving existing process, features specific to chemical processing had to be incorporated in contradiction matrix. This would increase performance, reliability, and productivity of solver resolving problems found in CPI. In this section, a set of *14 characteristics* to explain various phenomena taking place in chemical system, *9 principles* to suggest potential resolution to problems arising in CPI, along with the adapted version of contradiction matrix for CPI is proposed. This adapted version would aid in process of creative problem solving associated to CPI but, would not absolutely replace the original one.

Former work on development of contradiction matrix to fit domain of CPI was attempted by few individuals [18, 79]. A fascinating paper which modified classical TRIZ and incorporated some new terms to design inherently safer chemical processes [18] created spark for this thesis work. On careful review, it seemed possible to expand similar concept as their work concerned only on safety aspects in CPI. After considering concept presented by pioneers and following key outline of original TRIZ, adapted contradiction matrix for CPI is purposed. This purposed contradiction matrix would be aid process engineers enormously to resolve innumerable issues found in CPI.

Contradiction matrix, one of the first tools of TRIZ, remains one of the most popular where information is organized in a matrix form. [74] The contradiction matrix consists of technical contradictions between the *characteristics* to be improved and the *characteristics* that could be adversely affected and makes use of inventive *principles* to resolve those contradictions. [1, 55] Contradictions occur when improving one parameter or *characteristic* of a technique negatively affects the same or other *characteristics* or parameters of the technique. Purposed contradiction matrix handles technical contradictions which occur when an action is simultaneously useful and harmful to any process. In Table 5, adapted contradiction matrix purposed for CPI could be found and the original contradiction matrix suggested by Altshuller is accessible in appendix I.

6.1. Adapted Contradiction Matrix for CPI

The proposed adapted contradiction matrix for CPI (table 5) aims to provide process engineers with promising passage to resolve conflicts in chemical process industries by use of problem solving tool, based on CPS technique. In addition, this tool would also help users to get familiar with classical TRIZ contradiction matrix which could be used to some extent in problem solving by process engineers and other personnel directly or indirectly related to the field.

Contradictions were characterized by a desire to improve one aspect of a system and when this was done, another property declined in performance or value. To use the contradiction matrix (table 5), one has to go down the left hand side until one reaches to the desired property to be improved. Then, parameters or properties that degrade or get worse had to be considered. These could be found on the X axis. At the intersection of these two (or more) one will find the number of the TRIZ inventive *principle(s)* that would most often be used to resolve this contradiction. An empty box indicates that many of the *9 principles* may apply and so all of them should be considered.

These *principles* and *characteristics* are explained below in details with practical examples taken from various chemical process industries. In order to understand the methodology on how various *characteristics* were formulated and go through case studies, detail descriptions could be found in previous chapter 5.

Table 5Adapted Contradiction Matrix for CPI

Characterstics to be improved		Characteristics that is getting worse →	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	1	Complexity	x		1,3,8	8		5,8		1,3		1				
	2	Concentration	6	x	1,3,6					1,3	1,3,6	2		1,3		1
	3	Conversion	3	4	x				1,3			1,4				
	4	Economics	7,8		1,3,5	x			2		1,3,5	1			1	
	5	Environmental Impact	1,3				x	3,4		3	1,3,5					
	6	Hazardous Nature					1,3,5	x		3	1	6,7		1,8	1,9	
	7	Processing Conditions	1	2,3	1,3	1,5	2	6	x	3	1,3	1,6				
	8	Quality	1,7	6		5,8			1,5	x		1,6				3,4
	9	Rate	1					3	1,3		x	1				
	10	Size		6	1,4			5			1,3,4	x				
	11	Duration Of Operation		3					1,3		3,4		x			
	12	Process Safety	8	3,4,8	4,5			1,3,9		3,9	1,6			x		
	13	Chemical Treatment	3,4		5	1		9	4,9			1			x	
	14	Driving Force		4					3,4	8			1,3			x

Principles

1	Change Equipment Type or Design	**6**	Generate Materials as When and Where Required
2	Change Operation Sequence	**7**	Make Operation Simpler
3	Change Process Chemistry	**8**	Use Simple Design
4	Change Processing Conditions	**9**	Make Process Sustainable
5	Convert Harmful into Benefits		

6.1.1. Principles

Principles are basically used to resolve conflicts that arise during problem solving. *Principles* are known solutions to solve contradictions. The *principle* helps to find the solution by pointing towards possible option or route. Here, nine specific *principles* that have been suggested and described in details were formulated using the methodology shown in figure10 (page 41).

1. Change Equipment Type or Design

Problem solver tends to stuck in situation where one tries to find solutions inside some criteria or periphery. This *principle* supports to think of possibilities out of such criteria. Very often changing the equipment type or design helps to solve the issue, especially in process design phase. As various factors differ depending on type and design of equipment used, and other attributes (for example; feed capacity, operability range) could alter with variation in type or design of equipment. For example, by use of continuous reactors instead of batch reactors or vice-versa could solve certain problems as the working principle might vary. Again, by use of special impellor to best fit the process instead of general ones could provide better result with fewer complications, however by use of conical shape tank bottom head instead of flat (changing design of bottom head of tank) to improve mixing could prove to be an economical way.

2. Change Operation Sequence

This *principle* suggests a change in sequence of unit operation. If applicable new sequence could be made either adding extra new equipment or changing some equipment orders in the process. Occasionally, reverse sequence could prove helpful. For example, performing thickening before pressure filtration or carrying out thickening followed by centrifuge to separate solid and liquid. Making change in operating sequence or in some case by skipping certain step could save time, expenses, utilities consumption and so forth. Plenty of examples where altering operation sequences might solve manufacturing problems could be seen in various manufacturing plants commonly compared to processing industry.

3. Change Process Chemistry

Process chemistry is the heart of any process. Often equipment would be designed to fit for general processes, and in such cases, product quality could be altered to some extent by varying operating conditions or process chemistry being used. Often changing process chemistry could bypass lots of complications. An excellent example could be taken from pulp and paper industries which traditionally made use of acid process to produce pulp from wood chips, where final product had lots of issues such as; poor yield and quality, instability in colour, less usability and so forth. Fair amount of work was done to improve the acid process but satisfactory results were never achieved. Revolution came, when a German chemist invented the sulphate (Kraft) process based on strongly alkaline solution. This new process solved huge range of problems (product quality and life increased drastically) that were encountered with old process and proved to be much economical, environment friendly, and reliable process. [138]

Yet again, example of how changing process chemistry could have impact is demonstrated below. Here, two possible routes to produce final product are available and selection of route could be based on choice of feedstock, atom economy, reaction conditions, environmental exposure, and resource conservation. In this particular case, to synthesize eight moles of aluminium hydroxide, it could be seen that the second reaction scheme utilizes fewer moles of sodium hydroxide and sulphuric acid (equation 1). [139]

$$\begin{aligned} &Al \xrightarrow{H_2SO_4} Al_2(SO_4)_3 \xrightarrow{NaOH} Al(OH)_3 \\ &Al \xrightarrow{NaOH} Na\left[Al(OH)_4\right] \xrightarrow{H_2SO_4} Al(OH)_3 \end{aligned} \qquad (1)$$

Alternative syntheses of Aluminum hydroxide

4. Change Process Condition

Making change in operating conditions solves issues associated with production and quality by changing parameters such as; concentration, temperature, and pressure. This could solve problems existing in system or improve overall efficiency of system. Various studies support the fact that processing conditions effects on final product. [140] In processes where product yield depends on selectivity, processing condition could make significant influence. In such cases, changing the process condition has huge effect on product. For example in pyrolysis process, process condition (temperature and pressure) directly affects the amount of final product.

Very often preventing problems before hand could be resourceful rather than implementing various procedures to correct afterwards. It could be done by controlling process condition to acquire desired output which not only saves time but also expenses by reducing need of additional downstream processing of material to meet required quality. One of such example could be seen in purification process by crystallization. If operating conditions of the crystallizer could be controlled effectively, primary properties of the crystal product could be controlled which is very important for upcoming filtration process. As in filtration, characteristics of a solid/liquid-suspension are controlled by the primary particle properties, any possible issues that may arise in the filtration process could be eliminated by changing processing conditions in earlier step, which is crystallization. [141]

5. Convert Harmful into Benefits

This *principle* emphasizes on possible use of harmful situation or by-product to use for benefits. For example, use heat from exothermic reactions to heat up other streams. Other example could be to convert toxic intermediates to less toxic ones, or sellable products that could be used in any other process.

6. Generate Material as When and Where Required

To reduce storage of harmful substance and improve safety, generation and use of materials as produced is much safer alternative. In order to generate hazardous materials, less hazardous materials could be used in the particular reaction. In this way, generation of hazardous materials could be done at the plant itself just before it had to be used which reduces the risk during import and storage. For example, production of bleaching solution in pulp industry is done on site when require and only the amount required. This is prepared from material which is less hazardous compared to bleaching solution. In another example, aged catalysts in industrial reactors may be regenerated in place (in situ) without being removed from the reactors.

In cases, where storage and transportation certain materials could be very expensive and challenging, onsite production of such material might prove to be cheaper, less dangerous, and efficient.

7. Make Operation Simpler

Making procedures simpler and easier to understand would increase efficiency of process, decreases possible hazard situation, and increases reliability of operation. Use of some systematic procedure or automation to run operation could be beneficial too. [142, 143] Use of automation would prove advantageous wherever the operation is complicated and multiple tasks had to be controlled in series or at same time, such as (maintaining minimum feed flow, adjusting tank level, stabilizing operation pressure, upholding required temperature range, and regulating ratio of feed being mixed). In these cases, use of automation would not only reduce the effort and uncertainties in process, but also ensures the safety, quality and productivity of process.

For example, the entire above mentioned task might have to be done simultaneously, while start-up of an operation, shutdown of operation or might had to be performed during regular maintenances and in emergency shutdown. This process can be automated. An example could be used of automation in membrane separation process where process shuts down automatically after certain time or pressure is reached and back flushes to clean itself.

Generally, operators of any process would be less aware about the overall process going on in any given industries; process designer should always consider operator's perception while designing any new processes and should try to make it as modest as possible. In addition, it would be beneficial to follow general norms while designing operation to ensure safety.

8. Use Simple Design

Use a simpler design for the system, one that is easier to operate and needs fewer controls. Simple design helps to understand the basic facts behind the process and makes it easy to control. Use of codes, standard vessels and basic strategy to follow would prove be useful. Often designers tends to focus much on complexities of process and overlooks basic underlying facts that above all everything should be made easy to understand, control and with less knowledge as possible.

Designers should never forget who would be operating those designed processes. As people operating might have less or no knowledge of underlying basics of operation, the responsibility comes to designer to ensure their safety. In addition, simple design makes handling easy, hence increasing productivity as well as reliability of process.

9. Make Process Sustainable

Process could be made sustainable in various ways. Changes could be made from basic materials being used, such as renewable raw materials to environment friendly catalyst, or by use of less toxic or volatile raw materials. [144] Making change in type of reactant being used or using a marginal method to accomplish desired task. In traditional chemical process design, attention was given primarily upon reducing cost, while ecological impacts of practice were often ignored. In numerous occasions, it might lead to creation of huge amounts of waste materials. It would be a smart move to decrease generation of these wastes and their environmental impact by revising design of the process itself to make it more environments friendly.

Process could also be made sustainable by efficiently utilizing materials and energy being used in any process. Earlier studies had revealed that an increasing degree of heat integration leads to a lower production cost of ethanol compared to standalone ethanol production plant [145]. Recently, pulp mills seem to be interested in integration of various processes to produce much valuable products out of various waste that used to be burned in past to harvest energy. After integration, those industries produced biofuel using excess heat from pulp mills [146] and by gasification [147] .

In addition, sustainable alternative routes being investigated for production of caprolactam, adipic acid, methyl methacrylate, and vinyl chloride could be found [148, 149]. Similarly, reducing wastewater effluents usually leads to reduced freshwater intake. [150-152]

6.1.2. Characteristics

Here, 14 *characteristics* which would be described below relates to properties of materials (such as reactants, catalysts, solvents, materials of construction), unit operations, reactions, equipment, process, and plant. These *characteristics* effect on productivity, operability, safety, performance and so forth whereas, contradiction occurs among these *characteristics* when a process is being designed or being operated.

1. **Complexity**

Chemical processes are very much dependent on conditions, feed material quality, and equipment being used, parameters assigned on equipment and so on. These all adds complexity to the process, and as a result, it is often very difficult to predict how process would behave when certain parameter is altered. With increasing complexity, controllability or operability of equipment and process becomes a challenging task, as numbers of parameter to be controlled increases. This creates uncertainties in qualities of product or in behaviour of process. In complex process, even a slightest change in any process parameters could drastically affect others parameters, thus deviating the whole process from its original course.

In general, complexity problems could be solved to substantial extent by use of automation. In recent years, use of computer simulations to simulate possible problematic or catastrophic scenario virtually, without risking the real process had empowered process industries to great extent in problem solving, safety improvement, better productivity and list carries on. Often simulations are used to predict operability range of newly designed process or equipment which had proven very valuable tool for today's process designers.

2. Concentration

In processes involving any type of reaction, concentration of reagents has direct or indirect effect on reactions, as it could alter various qualities of final product. Quite often, increase in concentration of reactants increases rate of reaction for most reactions involving liquids or gases. Various studies had illustrated that the reagent concentration effects on rate of reaction in different types of reaction. [153-155] Concentration, generally defined as abundance of a constituent divided by total volume of a mixture, with higher amount of constituent in mixture, it tends to effect on various properties of mixture. [156] Few examples presented below to illustrates the effect of concentration. When reaction between zinc and hydrochloric acid take place, zinc granules react fairly slow with dilute hydrochloric acid, but much faster if the acid is concentrated (equation 2). [157]

$$Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g) \qquad (2)$$

In another example, during catalytic decomposition of hydrogen peroxide where solid manganese (IV) oxide is used as a catalyst, oxygen would be given off much faster if hydrogen peroxide is concentrated than if it were to be dilute (equation 3). [157] So, it would not be wrong to say that concentration plays quite an important role in chemical reactions.

$$2H_2O_2(aq) \xrightarrow{MnO_2(s)} 2H_2O(l) + O_2(g) \qquad (3)$$

3. Conversion

In processes involving reaction, conversion shows fraction of reagent that reacts to form product. Generally, while optimising reactor design or minimizing by-product formation, conversion of a particular reagent often would be assumed to be less than 100%. [158] In addition, conversion of reagents into by-products would be wasteful and increases further need of separation and purification stages which certainly would directly upsurge the operating costs of any process. As yield of product could depend on conversion ratio of reactants (reagents), especial attention had to be given to ensure that required amount of limiting reagent is being fed to the reactor required in process. The limiting reagent in a reaction is the first reagent to be completely used up and prevents any further reaction from occurring.

In industrial reactions, components would be seldom fed to the reactor in exact stoichiometric proportions. A reagent would be supplied in excess to promote the desired reaction; to maximise the use of an expensive reagent; or to ensure complete reaction of a reagent. On the other hand, though excess reagent might be available, conversion rate had to be kept low in some cases to avoid by-product formation. For example, during manufacture of vinyl chloride by pyrolysis of dichloroethane, reactor conversion is limited to 55% to reduce carbon formation, which fouls tubes of reactor.[159]

4. Economics

From capital cost required to establish plants to necessary operation cost in order to run any plant, plays vital role. Very often, as choice of a sustainable process often leads to higher capital and operating cost, economic issues seems to outweigh environmental concerns. On the other hand, selection of processing conditions and equipment used in any process determines ancillary, which affects the cost of production. Production quantity (yield), amount of by-product formed and quality would directly affect profitability. As most products needs number of separation and purification steps depending on type and amounts of by-products formed, in order to acquire target quality or to remove by-product, increased number of separation or purification steps might be essential which makes process uneconomical. [159]

The relationship between environmental goals and industrial competitiveness has normally been thought of as involving a trade-off between social and private cost. Often in CPI, problem for process engineers would be to maintain balance in society’s need for environmental safety with marginal financial drain on industry. [160] To some extent, economic problems could be reduced by reducing consumption of resources, typically achieved by increasing internal recycling, and reuse of energy and material streams instead of fresh resources and utilities. Thus, projects for improving process resource efficiencies could offer economic benefits [161].

5. Environmental Impact

Environmental impacts could be by discharge of waste on streams, land, and sewerage system. Likewise, additional impacts due to occasional chemical spills in industry and air pollution could be controlled to some extent by optimizing processes. Often these environmental impact or substantial damage to environment cannot be avoided or remedied through mitigating measures. None the less, any given industrial process has certain extent of negative impact on environment which had to be reduced to conceivable range. This could be possible by following 'green' approaches while manufacturing chemical product which would help to reduce environment impact up to certain point. [162] In addition, studies had emphasized on importance of identification of potential safety, health, and environmental hazards in order to avoid possible negative consequences. [163]

Environmental impacts could be reduced to large extent by focusing on potential environmental impact (PEI), which is a relative measure of the potential for a chemical to have an adverse effect on human health and environment. Now a day, by use of WAR (waste reduction) algorithm, a methodology for determining the potential environmental impact (PEI) of a chemical process to limit environmental impact of a designed process seems popular. [164, 165] A study focused on use of PEI to analyse the environmental impact of butylacetate process through the WAR (waste reduction) seems to be a good example which demonstrates its importance in CPI. [166]

6. Hazardous Nature

Any process or activity which involves use, storage, manufacturing, or handling of highly hazardous chemical could prove dangerous. Hazardous chemical are those substances which possess toxic, reactive, flammable, or explosive properties. Use of these chemical in any process always poses high level of danger and special care had to be taken to ensure safety of personnel working with or around these chemicals. Special rules should be followed while handling these chemicals.

On the other hand, process involving hazardous nature in CPI could be reduced significantly by designing chemical products and processes that could reduce or eliminate the generation of toxic substances. [167] Often handling of explosive, toxic, carcinogenic, or otherwise risky materials is simply believed to be part of chemical process industry and not much effort is made to improve the situation. [168] Alternatives had to be considered while designing or using a hazardous process.

7. Processing Conditions

Processing conditions contribute largely to any industrial process. With minor change in processing parameters, such as; temperature, pressure or pH, certain process could take a huge turn which could give different result then expected ones. In addition, making change in one parameter often affects the others too. [169]

Manipulating processing conditions is not a new notion in process industry. For example, in many process industries required change in the concentration of a gas is achieved by changing its pressure. This technique could be seen in production of ammonia by the Haber process (equation 4), where the rate of reaction between hydrogen and nitrogen is increased by the use of very high pressures. In fact, main reason for using high pressures is to improve percentage of ammonia in the equilibrium mixture, but there is a useful effect on rate of reaction as well. [157]

$$N_2(g) + 3H_2(g) \Leftrightarrow 2NH_3(g) \qquad (4)$$

Various examples of influence of processing conditions on ultimate products could be seen throughout CPI. Effect of processing conditions on morphology and yield of carbon nanotubes, [170] and effects of pre-treatment and processing conditions on quality also had been studied throughout several process industries.

[171, 172] Similar study on effect of processing conditions in crystallization (cooling, agitation rates, crystallization temperature, and chemical composition of the blends on the morphology, crystal size distribution, and polymorphism) was studied. [173, 174]

8. Quality

Quality of product could be considerably influenced by quality of raw materials used, production process applied, kind of equipment used for material processing, and so forth. As product quality depends on process quality, improving process quality should be the basic target of any process engineer. The process quality could be improved by identifying key process variables (for example, those variables with the greatest effect on product quality), measuring these variables, adjusting the process based on these measurements, and checking what happens to product quality. [169, 175]

In case of quality of final product, Garvin's 8 dimensions in (product) quality helps to understand different requirements to be a quality product, such as; performance, features, reliability, conformance, durability, serviceability, aesthetics, perceived quality. [176] If performance (the primary operating characteristics of a product) is taken as an example from Garvin's 8 dimensions, the key reason behind production of crystalline product would be to have pure product in appropriate form as required. By some means, if crystallization process fails to deliver the demanded target purity or form, the product could not use, as it lacks required quality. So, conserving quality is always a challenge in CPI.

9. Rate

Rate could be reaction rate, mass transfer rate, or production rate depending on the process and chemistry involved. These rates could make important contribution during certain processes. Reaction rate, defined as the speed at which a chemical reaction proceeds is involved in process which involves reaction. It would be advantageous to be able to predict whether an action will affect the rate at which a chemical reaction proceeds or not. Several factors that could influence rate of a chemical reaction are such as use of catalyst, temperature, and concentration.

Usually, change in concentration of a solution affects the rate of reaction as well as, with the increasing temperature, the rate of reaction increases.

On the other hand, use of catalysts lowers the activation energy of a chemical reaction and increase the rate of a chemical reaction without being consumed in the process, plus the catalyst with more surface area, increases the reaction compared to same amount of catalyst with less surface area. As an example, powdered calcium carbonate reacts much faster with dilute hydrochloric acid than if the same mass was present as lumps of marble or limestone (equation 5).

$$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + H_2O(l) + CO_2(g) \qquad (5)$$

The catalytic decomposition of hydrogen peroxide.

In another familiar lab reaction, solid manganese (IV) oxide is often used as the catalyst. Oxygen is given off much faster if the catalyst is present as a powder than as the same mass of granules (equation 6). This demonstrates how different form of chemicals could affect the rate.

$$2H_2O_2(aq) \xrightarrow{MnO_2(s)} 2H_2O(l) + O_2(g) \qquad (6)$$

10. Size

In process industries, from process to product everything is somehow dependent in size. Various characteristics of process could be affected by size (size of equipment or size of various raw materials used in process). Often product testing which was initially performed in smaller size pilot plant could not be exactly scaled in larger size, as all the physiochemical phenomena would not act as it did on small pilot plants scales. To overcome this problem, in numerous cases as it could be seen, numbers of small or medium sized equipment would be linked in parallel or series.

In addition, problems that could occur by use of inappropriate size of raw materials could be readily found in paint industry. For examples, size of pigment has effect on rheology of paint which would make it difficult to pump during handling. On the other hand, in filtration process which is a mechanical process based on physically trapping particles that are larger than the effective pore size of the filtering media, small size often leads to clogging of filter materials. [177]

11. Duration of Operation

Any unit operation requires minimum duration of operation to provide target product or intermediate product which would be used for next steps in the process. Length of operation (duration) could be exact time or range depending on the process. Processing any materials below required time would generally reduce the quality and yield of product, whereas occasionally materials would be unusable in further steps. As material conversion and product yield would be dependent on duration of operation, it seems to effect on economy of process. For example in processes involving chemical reaction, filtering, or brewing, duration of operation plays vital role to balance between time and economic feasibility. Minor change in operation such as; pressure, temperature, pH, concentration would affect the time required for processing. Reducing duration of operation would not always help as in some case, such as crystallization, trying to speed up the process would form different product and also affect the yield making process uneconomical.

12. Process Safety

Process safety is vital in CPI due to possible disastrous consequences, whenever neglected. Safety issue could rise from the chemicals and materials being used in process or even by design of process itself. Some chemicals are highly toxic or flammable which had to be used in the process, so special attention had to be paid to make process as secure as possible. By use of intrinsic or extrinsic safety during design, process safety could be drastically improved [178].

Safety of process could be improved by using intrinsic or extrinsic safety measures. Intrinsic safety is embedded in design or process, whereas extrinsic safety is to protect in ground level by use of various safety devices, such as; alarm, containment chamber and so forth. Very often due to ill design of process, safety would be compromised. These types of situation would lead to disaster which is basically waiting to happen. So, whenever safety is in contradiction, special attention to be given and in no situation, safety should be compromised over economy or any other *characteristics*.

13. Chemical Treatment

In CPI, chemical treatment could be used to enhance or modify certain characteristics of process or equipment. Such modifications could benefit as it improves selectivity of process, enhances operatively, increases stability of process, decreases complexities in process, and so on. For example, pre-treatment of raw materials to meet basic standard increases usability and process-ability as well as ensures quality of product. Basically, chemical treatment such as surface modification in membrane could change characteristics of membrane surface, thus reducing fouling and increasing permeate flow. On the other hand, pre-treatment of water by using different chemical to make it suitable for required process is commonly observed in process industries such as; food processing, fine chemicals, cosmetic and so on.

14. Driving Force

The driving force could be defined an action which propels something towards certain direction. The driving forces might be gradients in pressure, concentration, electrical potential or temperature. [113] In case of reaction, driving forces would be factors responsible for any reaction to proceed on to completion (for example entropy).

The driving force for mass transfer is typically a difference in chemical potential [179] Gravity; difference in pressure, temperature gradient, electrical potential, concentration difference, et cetera could be used as driving force to govern various processes. For example, supersaturation acts the driving force for crystallization, whereas in case of heat exchanger, temperature difference between the fluids could be considered as the driving force which makes the heat exchange possible and electrical potential acts as driving force in ion exchange. [180] Understanding of these driving forces is necessary to be able to manipulate various processes and increase efficiency without making compromises.

6.2. Improving Quality of Crystalline Product (An example of problem solved using adapted contradiction matrix)

Crystallization is one of the most common unit operation generally used for wide range of operation (such as; concentration, purification, separation) to increase the purity of a product in chemical process industry. During crystallization, phase-change occurs in which a group of randomly organized molecules, ions or atoms in a fluid come together to form an ordered solid structure called a crystal. [181-183]

The final goal of any industrial crystallization process is to produce a crystalline product with specified properties. Typical requirements for the properties of a crystalline material might include certain average crystal size, narrow size distribution, desired crystal shape, adequate crystal purity, correct crystal structure, and good stability of the product crystals. [141, 184] Failure to achieve required specified properties could be undesired product quality, such as; low yield, more fines, a wide size distribution, low quality and inappropriate solid form which could not be used (especially in case of pharmaceuticals and nutraceuticals industries). The impurity level is also industrial relevant as it has a direct impact on the price of the product: different grades of a product can have significant differences in price. In addition, fouling of vessel and heat transfer surface are problems related to operability of process due to complex nature of crystallization operation [185].

The challenge in case of crystallization process to any chemist/engineer is to achieve required quality product. This example demonstrates how adapted contradiction matrix could be used for this purpose. Here, problem would be formulated and solved in steps to provide clear idea on problem solving process being used.

Step 1.

To improve the desired quality (increased yield and appropriate solid form) of the product, the process has to be operated by controlling various parameters during crystallization. With numerous parameters to be controlled at same time, complexity of process increases; hence performance of process could not be predicted. Without knowledge on how the process would behave to certain parameters adjustment, it would be impossible to obtain target quality. So, this would result in reduced conversion and yield of the desired product.

The tradeoff between two useful *characteristics* is shown in figure 22. It is always useful to express the tradeoff as a conflict between two features, it clearly illustrates the problem in hand and how it could be solved. Here, if one tries to improve quality of product, duration of operation increases (worsens), as crystallization process would need longer time to produce quality crystals. A simple diagram, figure 22 clearly illustrates the conflict between two useful features in crystallization.

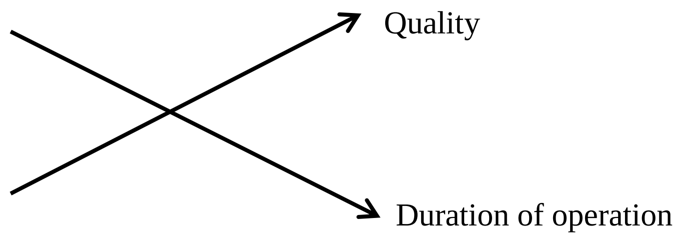

Figure 22 A conflict between two useful features.

Step 2.

The contradiction can be shortened as follows (figure 23):

Characteristic to be improved: Lower yield of product, low quality and inappropriate solid form (*Characteristic 8*).

Characteristic that is getting worse: complexity of process (*Characteristic 1*).

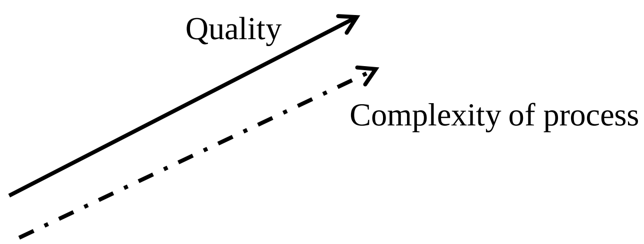

Figure 23 A conflict between useful and harmful features. Here, the dotted line in the figure means a harmful feature.

Often, the improvement of a useful feature is connected with the strengthening of a harmful feature (see figure 23). When the quality of the crystalline product is increased, the complexity of process also increases.

Step 3.

To resolve contradiction, adapted contradiction matrix (table 5) could be used. From table, purposed or suggested *principles* would be *Principles 1, 4 and 7*. Let's say *Principle 1* is selected, which recommends to *'change equipment type or design'* to solve the problem in this case, then one has to see the possible ways to improve the design or completely change it. Various studies could be found to supports the undisputable facts that actually this is very likely case. Several studies had described hybrid processes combining distillation with melt crystallization [186-188] or membrane separation/crystallization processes [189]. Emerging technologies typically offer one or several advantages, such as increased product quality, higher yield, better efficiency or being more sustainable.

Two types of emerging technologies had appeared in last few years: first, the formation of particles using supercritical fluids, and second, hybrid separation processes combining crystallization with another separation technique. The supercritical fluid processing of particles uses relatively green, non-toxic and non-flammable process fluid and a dry powder at high purity could be obtained as final product. On the other hand, second emerging technology is a hybrid crystallization process which focuses on combining crystallization with existing unit operation which is used in separation of chiral mixtures into pure enantiomers [190]. This technology could considerably increase efficiency and productivity of the crystallization step or to make purification by crystallization thermodynamically feasible. [181] In addition, properties of the products obtained from crystallization processes are strongly influenced by the geometry and type of the crystallizer used, by the operating conditions applied during the process, and by the chemical and physical properties of the liquid and the solid phases. These claims directly support the route presented in *Principle 1*, which suggested change in equipment type or design to solve the problems. [191]

However, if *Principle* 7 is selected, which recommends to *'make operation simpler'* could be achieved by use of automation which seems very popular to handle complexity problems by performing several tasks simultaneously with absolute precision and in desired mode. [192] Automation could prove very important in case of crystallization, as various parameters had to be adjusted with time and automation can execute either pre-planned instructions or make desired change in some parameters while process is running to achieve desired target result. [142, 193] In addition, by use of process analytical technology (PAT), real-time process information could be used and have an optimal control of the process. PAT takes account of sensors that could measure critical process properties, such as supersaturation, and desired product qualities such as size, shape, and polymorphic form. [194, 195] Study had suggested application of PAT to crystallization processes seems feasible. [196]. When designing an industrial crystallization process, engineers usually need to determine fundamental data such as; liquid-solid equilibria, nucleation and crystal growth kinetics or phase transitions.[181] However, once these fundamental data are established, process could be controlled by use of automation, reducing complexity by using appropriate parameters during the process.

None the less, use of *principle 4* suggests '*change in process conditions*' to attain final quality. Following this *principle*, adjustment in process condition could be made to resolve problems. Such adjustments could be thru by controlling supersaturation and magma density and by adjusting average residence time of crystals. On the other hand, precaution had to be followed, as typically high crystal growth rate may adversely affect the purity, since some of the foreign substances may get entrapped within the crystals. [185] In addition, as quality, productivity, and batch-to-batch consistency of the final crystal product could be affected by the conditions in case of batch crystallizers, several factors had to be considered such as; batch cycle time, supersaturation profile, external seeding, fouling control, CSD control, growth rate dispersions, and mixing. Studies had shown that small change in processing conditions could drastically affect the product qualities. [191, 197, 198]

7. CONCLUSION

As problems solving skills being increasingly recognized as one of the most important quality to have to be a successful engineer, this thesis presented some popular creative problem solving techniques available which could be feasibly used in chemical process industries. Creative problem solving method had proven to be the most efficient and effective mode to solve ill-structured types of problems, compared to ordinary problem solving process, which solely depends on problems solver ability to deal with problems depending on solver's past experiences. Though various intuitive methods (brainstorming, lateral thinking, and synectics) and analytical methods (morphological analysis, analogies, and TRIZ) follows CPS model, intention behind this work was to adapt one of the analytical methods of problems solving which could be readily used in process industry. TRIZ, one of the analytical methods and being knowledge-based systematic methodology of inventive problem solving, it appeared to be adaptable with potential use in process industry.

In recent years, TRIZ has gained popularity in the process industry due to its simple and effective problem solving method. Conclusions can be drawn that successful application of TRIZ in process industry is possible based on information presented in this thesis. The increasing use of TRIZ as a methodology for solving problems in CPI would benefit and adapted contradiction matrix suggested in this thesis would aid in solving various problems related specific to chemical process industries and also could prove much help for new engineers to learn and develop problem solving skills. As the original TRIZ contradiction matrix is difficult to express chemical aspect of CPI due to inappropriateness and ambiguity of terminology in classification of these parameters, new contradiction matrix is proposed. The proposed adapted contradiction matrix for CPI aims to provide process engineers with promising route to resolve conflicts in chemical process industries by use of problem solving tool, based on CPS technique. A systematic approach to problem solving makes solver more efficient, and also could result in higher-quality solutions.

Adapted version of contradiction matrix presented in this work contains *9 principles* and *14 characteristics* which offers route to solve key issues related to field of CPI. To show how those 14 *characteristics* were developed two case studies were presented. *Principles* are merely the possibilities that could be used to handle the issues, whereas *characteristics* would be used to describe various properties of material, unit operations, reactions, equipment, process, plant and so forth.

Finally, newly formulated contradiction matrix for CPI was used in improvement of crystalline product quality. Step wise method was used in formulation of contradiction and for problem resolution. This provides clear idea on how TRIZ could be used to solve problem methodologically. Problem formulation which is often known to be the most challenging task was done easily by following the steps, and solution finding seems much more accurate by use of *principles*.

It is believed that the proposed version would aid in problem solving, especially those encountered in chemical process industries related to unit operations. In addition, this thesis would help fresh process engineers to recognize importance of various available methods for creative problem solving. It would also provide idea on how to modify TRIZ based methods according to ones requirements to fit in particular niche area and solve the problems efficiently in creative way.

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APPENDICES

APPENDIX I: Original Contradiction Matrix of TRIZ

Improving Feature	Worsening Feature	Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary ob	S
		1	2	3	4	5	6	7	8	9	10
1	Weight of moving object	+		15, 8, 29,34		29, 17, 38, 34		29, 2, 40, 28		2, 8, 15, 38	8, 10, 18, 37
2	Weight of stationary object		+		10, 1, 29, 35		35, 30, 13, 2		5, 35, 14, 2		8, 10, 19, 35
3	Length of moving object	8, 15, 29, 34		+		15, 17, 4		7, 17, 4, 35		13, 4, 8	17, 10, 4
4	Length of stationary object		35, 28, 40, 29		+		17, 7, 10, 40		35, 8, 2,14		28, 10
5	Area of moving object	2, 17, 29, 4		14, 15, 18, 4		+		7, 14, 17, 4		29, 30, 4, 34	19, 30, 35, 2
6	Area of stationary object		30, 2, 14, 18		26, 7, 9, 39		+				1, 18, 35, 36
7	Volume of moving object	2, 26, 29, 40		1, 7, 4, 35		1, 7, 4, 17		+		29, 4, 38, 34	15, 35, 36, 37
8	Volume of stationary object		35, 10, 19, 14	19, 14	35, 8, 2, 14				+		2, 18, 37
9	Speed	2, 28, 13, 38		13, 14, 8		29, 30, 34		7, 29, 34		+	13, 28, 15, 19
10	Force (Intensity)	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37	13, 28, 15, 12	+
11	Stress or pressure	10, 36, 37, 40	13, 29, 10, 18	35, 10, 36	35, 1, 14, 16	10, 15, 36, 28	10, 15, 36, 37	6, 35, 10	35, 24	6, 35, 36	36, 35, 21
12	Shape	8, 10, 29, 40	15, 10, 26, 3	29, 34, 5, 4	13, 14, 10, 7	5, 34, 4, 10		14, 4, 15, 22	7, 2, 35	35, 15, 34, 18	35, 10, 37, 40
13	Stability of the object's composition	21, 35, 2, 39	26, 39, 1, 40	13, 15, 1, 28	37	2, 11, 13	39	28, 10, 19, 39	34, 28, 35, 40	33, 15, 28, 18	10, 35, 21, 16
14	Strength	1, 8, 40, 15	40, 26, 27, 1	1, 15, 8, 35	15, 14, 28, 26	3, 34, 40, 29	9, 40, 28	10, 15, 14, 7	9, 14, 17, 15	8, 13, 26, 14	10, 18, 3, 14
15	Duration of action of moving object	19, 5, 34, 31		2, 19, 9		3, 17, 19		10, 2, 19, 30		3, 35, 5	19, 2, 16

To download TRIZ original contradiction matrix, please visit

www.innovation-triz.com/TRIZ40/TRIZ_Matrix.xls or scan QR code.

APPENDIX II TRIZ: 40 Principles and 39 Characteristics (A-Z)

Sno	40 Principles alphabetically	39 Characteristics
1	Application of heat expansion	Adaptability or versatility
2	Asymmetry	Area of moving object
3	Be prepared	Area of stationary object
4	Changing colour	Device complexity
5	Cheap and short lived	Difficulty of detecting and measuring
6	Composite materials	Duration of action by stationary object
7	Consolidation	Duration of action of moving object
8	Continuity of useful action	Ease of manufacture
9	Convert harm into benefit	Ease of operation
10	Copying	Ease of repair
11	Counterweight	Extent of automation
12	Dynamicity	Force (Intensity)
13	Equipotentiality	Illumination intensity
14	Extraction	Length of moving object
15	Feedback	Length of stationary object
16	Flexible film or thin membranes	Loss of Energy
17	Homogeneity	Loss of Information
18	Inert environment	Loss of substance
19	Local quality	Loss of Time
20	Mechanical vibration	Manufacturing precision
21	Mediator	Measurement accuracy
22	Move to a new dimension	Object-affected harmful factors
23	Nesting principle	Object-generated harmful factors
24	Parameter change	Power
25	Partial or excessive action	Productivity
26	Periodic action	Quantity of substance/the matter
27	Phase transition	Reliability
28	Pneumatic or hydraulic construction	Shape
29	Porous material	Speed
30	Prior action	Stability of the object's composition
31	Prior counter-action	Strength
32	Rejecting and regenerating parts	Stress or pressure
33	Replacement of a mechanical system	Temperature
34	Reverse	Use of energy by moving object
35	Rush through	Use of energy by stationary object
36	Segmentation	Volume of moving object
37	Self-service	Volume of stationary object
38	Spheroidality	Weight of moving object
39	Universality	Weight of stationary object
40	Using strong oxidizers	

APPENDIX III: 39 engineering parameters of TRIZ for the main causes of chemical accident

39 engineering parameters of TRIZ for the main causes of chemical accident [79]						
Parameters	Mechanic	Operator	Process upsets	Design	Natural hazard	Material
1. Weight of moving object						
2. Weight of stationary						
3. Length of moving object						
4. Length of stationary						
5. Area of moving object		X				
6. Area of stationary						
7. Volume of moving object						
8. Volume of stationary						
9. Speed	X	X	X			
10. Force (Intensity)	X		X			
11. Stress of pressure	X		X			
12. Shape	X			X	X	
13. Stability of the object	X		X	X	X	X
14. Strength	X			X	X	
15. Durability of moving object	X		X	X		
16. Durability of non-moving object	X		X	X		
17. Temperature	X		X			
18. Illumination intensity		X				X
19. Use of energy by moving					X	
20. Use of energy by stationary						