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Application of Root Conflict Analysis (RCA+) to formulate inventive problems in the maritime industry

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Key words: invention, TRIZ, root conflict analysis, contradiction, cause and effect chain, problem analysis

Abstract
Over the past decades, demand for innovation in diverse industries, including the maritime industry, has been steadily growing. One of the primary sources of innovation has been the finding of inventive solutions to the most challenging problems. Until recently, the search for inventive ideas relied heavily on random and chaotic methods of boosting creative capabilities, thus drastically reducing productivity in the generation of new concepts and solutions. With the emergence of systematic methods for generating inventive solutions, the situation has changed. Modern methods such as TRIZ suggest a process of solving problems in a systematic way whereby each phase of the process is supported by the relevant analytical techniques and heuristic tools. This article presents Root Conflict Analysis (RCA+), a technique for problem analysis developed for the top-down decomposition of problems to chains of causes and contradictions. The article provides an example of applying RCA+ to discover the causes and contradictions which led a ferry to lose stability at sea.

Demand for Inventive Solutions

Problem solving has been one of the major sources of technology and product innovation. The development of any industry comes from implementing all sorts of solutions proposed to improve underlying technologies, and products based on these technologies. All technical solutions can be divided in two large classes (Newell, Shaw & Simon, 1962):

1) *Non-inventive solutions*, which result primarily from optimisation of system parameters and from introducing obvious modifications. Such solutions improve existing technologies and technical products without producing considerable or disruptive changes; for example, finding an optimal speed during cruising helps a ship to save fuel;
2) *Inventive solutions*, which result from finding novel, non-obvious and value-adding ideas that satisfy the criteria of an invention as defined by patent law and, therefore, can be protected by patents. Such solutions range from incremental ones which produce disruptive changes of a small scale to radical solutions which might lead to the launching of whole new industries. For example, the invention of a sail helped to create a radically new type of a boat – the sailing boat. The invention of the catamaran launched a new sub-industry of boats with considerably increased stability at sea. When implemented successfully, an inventive solution is regarded as an innovation.

While it is obvious that the total number of non-inventive solutions produced every day greatly exceeds the number of inventive ones, inventive solutions nevertheless have a greater impact on the development of an industry. The maritime industry is no exception to this (Theriault, 2001). Technological advances in the past few decades and increased competition have led to a situation in which industries demand more innovations, to be introduced within shorter intervals of time.

Much research has been carried out on how to accelerate the production of new inventive solutions. In contrast to non-inventive optimisation problems, which can be solved either through mathematical calculations or experiments, inventive solutions utilise knowledge which resides outside a specific engineering domain. For this reason, problems which require inventive solutions cannot be approached in a formal way. To date, most of the research into creative problem-solving has focused on attempts to understand the psychological aspects of creativity; however, the effectiveness of purely psychological methods based on a random solution search for complex problems remains low (Kohn & Smith, 2011).

Nevertheless, a certain success in understanding how problems can be managed and solved inventively in a systematic way was achieved through the development of TRIZ by G. S. Altshuller and his associates (Altshuller, 1984). TRIZ stands for *The Theory of Solving Inventive Problems* (*Teoria Reshenia Izobretatelskih Zadach* in Russian). Developed over 50 years, TRIZ introduces a theoretical background of technological innovation based on extensive studies of patent collections within diverse industries. Among major TRIZ discoveries was the understanding that the evolution of a technology is a systematic process governed by a number of domain-independent basic laws, while inventions most frequently result from overcoming a certain conflict of opposite demands which cannot be resolved by either trade-offs or the optimisation of solutions available in the industry. Most importantly, long-term TRIZ studies made it possible to extract and formulate domain-independent generic principles which provide directions for finding a specific solution to a specific problem by using heuristic patterns of previously solved inventive problems. In recent years, a number of companies and universities have been exploring the application of TRIZ in the maritime industry (Weitzenböck & Marion, 2006; Nocerino et al., 2011).

Contradiction as a means to formulate an inventive problem

As mentioned above, to successfully solve an inventive problem, a conflict of demands must be eliminated. In TRIZ, such conflicts are called contradictions. A typical contradiction presents a conflict of demands and is formulated in the following way: "*A certain (physical or technical) parameter of a system must have value A in order to satisfy a certain condition, and at the same time the same parameter must have value B to satisfy some other condition*". The meaning of contradiction is that the same parameter may not have two different values at the same time, and often these values reside at opposite points of a scale. Due to this, a contradiction in TRIZ uses qualitative descriptors of values rather than specific numbers, for example "*high* vs. *low*", "*hot* vs. *cold*", "*heavy* vs. *lightweight*". Sometimes, instead of a physical parameter, a state of a physical object (e.g. "*transparent* vs. *opaque*", or aggregate state, like "*liquid* vs. *gas*") is used. A contradiction thus becomes a means to formulate an inventive problem.

Examples of problems presented as contradictions are: a) "the surface area of a sail on a sailing yacht must be *large* to capture more wind and must be *small* to enable quick and easy managing of the sail"; or b) "the weight of an anchor should be *high* to effectively prevent the boat from being moved by the wind and at the same time should be *low* in order to avoid overloading the boat while the anchor is on board".

An inventive solution must decouple the conflicting demands. For example, non-inventive solutions in both cases would be: a) finding the optimal size of surface area in the first case; and b) calculating an optimal value for the weight of the anchor. Such solutions present trade-offs. In turn, inventive solutions require the full elimination of the contradictions by a transition to new inventive designs to completely satisfy both demands. For example, splitting and replacing a single large sail into many smaller sails meets the demand to have a large overall surface area to capture more wind, and at the same time makes it easy to manage each individual small sail. In the second problem, the anchor can be made hollow inside and be filled with outboard water just before use. In these two inventive solutions, both conflicting demands are fully met.

Root Conflict Analysis (RCA+)

While the concept of contradiction has long been used as a means of formulating inventive problems in TRIZ, there have been a number of issues:

1) An inventive problem can be formed by more than a single contradiction;
2) It is not easy to extract most critical contradictions; and
3) The same problem can be considered at different levels of abstraction, which makes it difficult to recognise a relevant contradiction.

To eliminate these and similar drawbacks, a technique called "Root Conflict Analysis" has been developed on the basis of the paradigms of TRIZ and the theory of constraints (Goldratt, 1999; Moura, 1999). The acronym "RCA+" is used to differentiate it from another well-known technique, "Root Cause Analysis", which uses the acronym "RCA" (Ishikawa, 1991). Although the two techniques have a similar approach to the analysis of problems through the identification of chains of causes and effects, RCA+ has a range of different procedures, and targets discovering and formulating contradictions rather than causes only (Souchkov, 2005).

Often, problems cannot be easily solved even after we have identified a root cause. Such situations usually emerge either when the elimination of a root cause would require considerable change to a system, or the elimination of the root cause is not possible due to constraints, for example, those defined by laws or nature.

In addition, difficult problems are often a feature of situations in which eliminating a cause of a certain problem, once found, nonetheless does not make it easy to solve that problem because the same cause contributes to a positive effect. As mentioned above, if a sail on a sailing boat has a very large surface area, it is difficult to manage. Thus, the cause "*large surface area*" can be considered as a cause of negative effect and, therefore, should be eliminated if one follows the rules of classical RCA. On the other hand, we need a large surface area to capture more wind. In this example, the large area of the sail is a cause of both negative and positive effects and if we decrease the sail area, we reduce the positive effect as well. Therefore, to create a more complete picture of our problem, one should not limit problem analysis to the identification of the causes of negative effects only, but, in addition, define whether these causes contribute to positive effects. RCA+ helps to identify such contradictions, rather than focus on creating a chain of causes only.

The second important difference between classical RCA and RCA+ is that instead of trying to find the lowest cause in a chain, RCA+ targets discovering all contradictions which contribute to a problem.

Process with RCA+

The goal of performing RCA+ is to decompose the top problem, which is presented as an undesired effect in a tree of causes and effects, by following a number of rules. Due to the constraints of the paper, we will only mention most important rules.

RCA+ starts with a statement of a top problem. The following categories of top problems can be distinguished:

1) *Negative effect*. Something that happens which should never happen. This can be damage as a result of an accident, loss of control, the irreversible emergence of a defect, process failure, etc. Examples: a) biofouling grows on the ship hull; b) a ferry loses stability at sea;
2) *Insufficient effect*. A positive result which we wish to obtain, but which is not achieved with a desired degree of performance, speed, completion or quality. Example: a heavily loaded LNG tanker takes too much time to come to a full stop after it starts braking;
3) *Excessive effect*. A positive effect which causes excessive waste of a costly resource. Example: an excessive amount of anti-corrosive paint is used when painting a steel boat;
4) *Ineffective control*. A positive effect which is related to control of something. Example: it is difficult to hold a boat at a certain angle to the swells during a storm.

Next, a series of questions is asked to identify the causes of the top problem. In most techniques developed for cause and effect analysis, this is done by asking the question "*Why*?". However, in RCA+, it is done by asking the question "*What is a cause of (undesired effect)?*", or "*What causes (undesired effect)*?". The question "*Why*?" is not allowed in RCA+ due to a possible ambiguity in the answer, given that it might lead to two types of responses: a) physical causes; and b) purposes. In RCA+ we are only interested in physical causes because we would like to model the existing reality.

When answers have been obtained, a top problem (undesired effect) is decomposed to a chain wherein each next cause might, in turn, become a negative effect, and so forth. Once the first cause of the top problem is identified, it is verified against being a cause of a contradiction. If the cause identified does not lead to any positive effect, it is marked as a negative effect, and the particular chain in which the cause belongs is explored downwards until either a contradiction or a non-controllable cause is found (Figure 1).

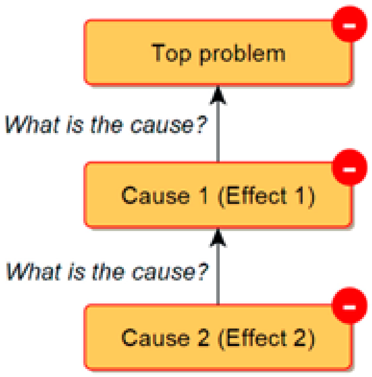

Figure 1. Top-down decomposition of a top problem to a chain of causes and effects

A contradiction in the RCA+ diagram is depicted as a cause which contributes to both negative and positive effects. A contradiction is always depicted as a triad: "a cause which leads to a positive and a negative effect" (Figure 2).

In a RCA+ diagram, a cause must be formulated as a sentence presenting a description of a function, property, etc. The use of a single word is not allowed.

All negative causes are tagged with a minus (–) sign, and all positive effects with a plus (+) sign. Causes with both positive and negative effects are identified as contradiction causes. A contradiction cause is tagged with a combined plus-minus (+/–) sign.

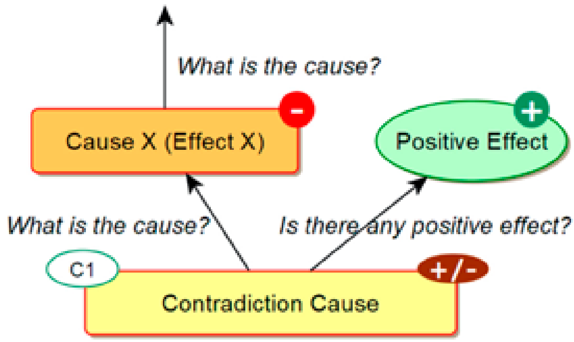

Figure 2. Identification of a contradiction in a RCA+ diagram

Top-down exploration of a chain stops as soon as i) a contradiction is identified; or ii) a so-called "non-changeable" cause (which for whatever reason may not be controlled) is identified. This categorisation of causes means that there is no sense in continuing to explore sub-causes since one may not influence them (or is not willing to). These can be laws of nature, weather conditions, local and international policies, legal obligations and so forth. The non-changeable causes are tagged with a double minus sign (– –).

After the first chain has been explored, the process is continued in breadth until all causes have been identified. Each cause can produce its own subtree or several sub-trees.

Process with RCA+

The RCA+ process consists of extracting all factors that contribute to the top undesired effect and each subsequent negative effect by revealing and presenting all interrelated contradictions and non-changeable causes. For example, we would like to develop an inventive solution to prevent a lifeboat from drifting too far. It is obvious that a small, lightweight lifeboat will drift to a considerable distance from the location of the accident if the wind is strong.

To start building the RCA+ model (a final diagram is presented in Figure 3), one starts by asking the first question related to the top problem, "*What causes the lifeboat to drift too far?*". A typical answer is that the boat is lightweight. As soon as there is no positive effect from this, we continue by asking the question "*What is a cause?*" to which the answer is, "*The lifeboat capacity is low*". Finally, the capacity of the lifeboat is low because the lifeboat is of small size. However, its small size leads to a positive effect: it occupies little space when stored on a ship. Therefore, we mark this cause as a contradiction

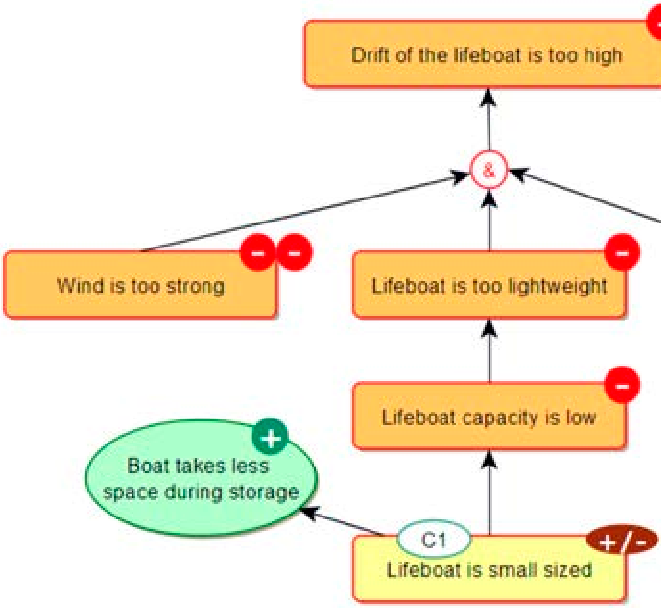

Figure 3. Top-down decomposition of a problem with a drifting lifeboat

cause, presenting a positive effect and stopping the exploration of the chain downwards. If a cause provides more than a single positive effect, only the most important one is shown.

However, the low weight of the boat is not the only condition allowing a high degree of drift. Clearly, more conditions are needed when the boat is used in real situations.

An RCA+ diagram can involve two types of horizontal relationships between the causes: a) "OR", when a negative effect can be caused by two different causes independently; and b) "AND", when both or more causes must act together to provide the negative effect. RCA+ checks against such additional conditions by exploring whether any described cause of the effect would lead to the effect without any additional conditions. If not, additional conditions must be introduced to the RCA+ diagram as new effects through the relationship "AND" ("&" in a circle in the diagram).

Two additional conditions (effects) are brought to the original model: first, there must be a strong wind (which is tagged as a non-changeable cause); and second, the anchor which is used to reduce drift is too small. This cause becomes a contradiction cause since the anchor should be as small as possible to provide as much space in the lifeboat for people as possible.

An important observation is that once we have identified a contradiction and studied its roots, it is very probable that other causes contributing to this particular contradiction will be contradictions as well because there is an inheritance effect. These contradictions might be coupled with other negative effects via OR/AND relationships or caused by non-changeable conditions that lead to the creation of conflicts.

Below we will illustrate the use of RCA+ within an analytical phase of innovative improvement of a ferry's stability at sea, which was a part of the research analysing the accident of the "*Estonia*" ferry on September 28, 1994.

Case: Inventive improvement of a ferry to avoid an accident at sea

The accident happened as the ship was crossing the Baltic Sea. Later investigation found that in stormy weather conditions, the ship's bow door opened unexpectedly and the ship took on a heavy starboard list as water flooded into the vehicle deck. The entering water created a free surface effect which

Figure 4. The "Estonia" ferry (picture source: https://maritimecyprus.com)

caused the movement of a heavy mass of water between the walls of the deck. Soon afterwards the ship lost stability due to the strong displacement of its centre of gravity, rolled 90 degrees and capsized. Despite rescue attempts, 852 lives were lost (Estonia, 1998). What exactly caused the vessel's bow door to open has not been identified.

Soon after the accident, different experts and members of the Maritime Safety Authorities argued that large open vehicle decks are not safe for ferries. Such decks are, nevertheless, necessary, and therefore a novel solution must be obtained (Woodyard, 1988). Very soon the debate in the media and technical magazines was focusing on the degree of partitioning or the number of fixed bulkheads on the car deck. The partitioning could be along the ship to prevent the water from running to the side and causing a big shift in the centre of gravity. A number of solutions based on this concept had already been patented, for example splitting the car deck into three large compartments with watertight doors (Brown, 1993). Another patent was filed by Kvaerner Ships Equipment for a bulkhead in the form of a door that could swing across a section of the car deck (Schwenzer & Bark, 1991)

Although introducing crosswise partitioning solves the problem of preventing flooding, it introduces another problem by considerably increasing the time necessary to load and unload cargo. Even if there is fine weather in harbour, one must still engage the swinging doors, since the captain is unable to engage them at sea. This makes loading and unloading slow every time, regardless of weather conditions. Although really bad weather only occurs on a few days a year, the ferry must, unnecessarily, use a slow loading and unloading process almost every day of the year. Another problem caused by this solution is that a certain limit is placed on moving and transporting bulky cargo. Therefore, the decision was made to apply TRIZ to explore whether any new non-obvious solution ideas could be obtained in a systematic way.

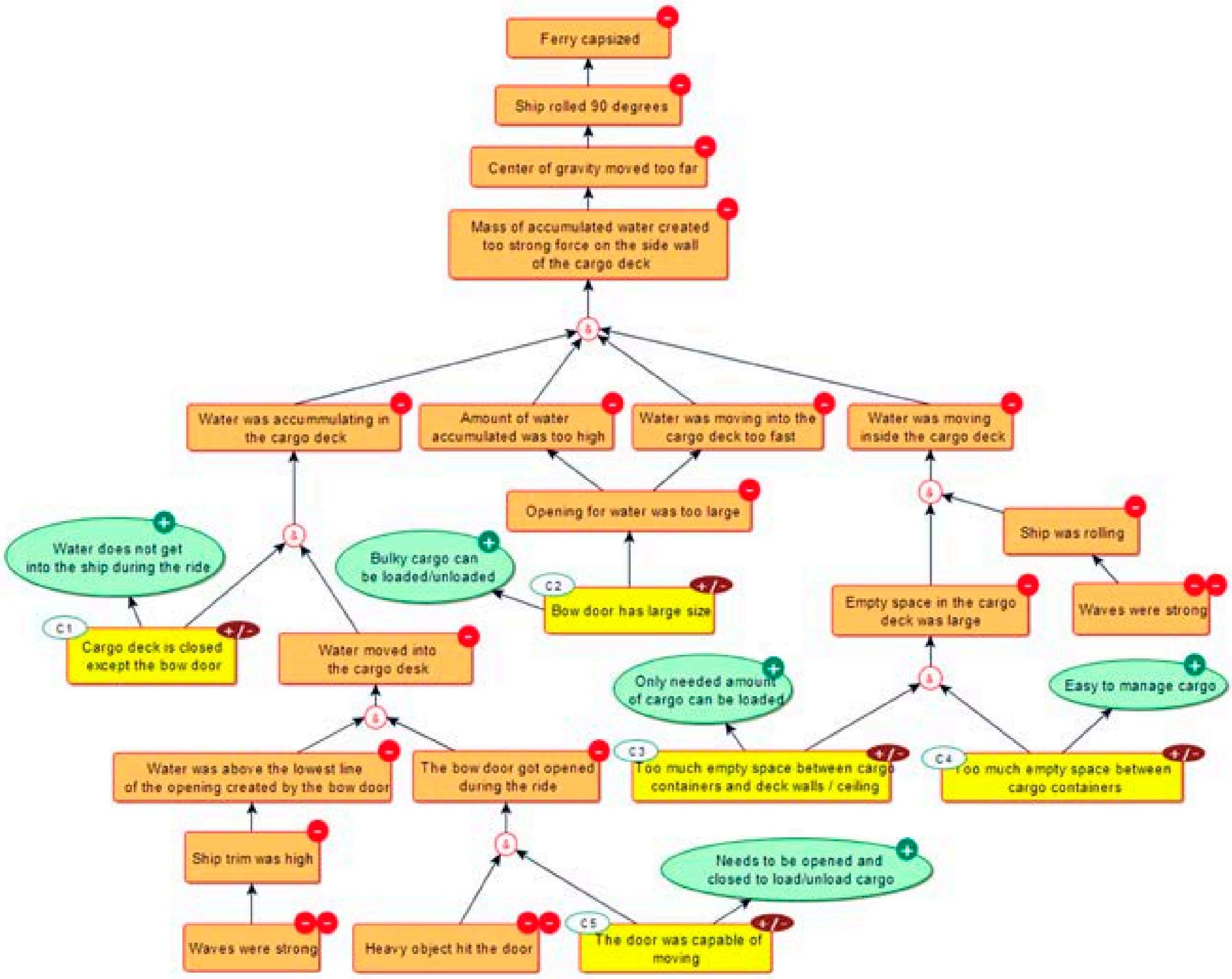

Figure 5. RCA+ model of a problem with the "Estonia" ferry

Case: RCA+ Diagram

Although the original project was undertaken the year following the accident (Killander & Souchkov, 1995), a new analysis of the problem with the use of RCA+ was recently performed to see whether it could identify even more opportunities to find inventive solutions to the problem. A final RCA+ diagram of the case of the "Estonia" ferry is shown in Figure 5.

The top undesired problem was defined as "*Ferry capsized*", and its first cause was defined as "*Ship rolled 90 degrees*". Next, the cause-effect analysis led to the negative effect "*Mass of accumulated water created too strong a force on the side wall of the cargo deck*". Unlike the causes and effects above it, it is obvious than more than one cause is needed to create this effect.

In the diagram, this situation is presented by the relationship "AND" ("&"), which means that the following four causes must act together to produce the negative effect:

- Water was accumulating in the cargo deck;
- The amount of water accumulated was too great;
- Water was moving into the cargo deck too fast;
- Water was moving inside the cargo deck.

It is important to note that only when all these causes are present will the negative effect occur. Since none of these causes represents either a contradiction cause or a non-changeable effect, the RCA+ analysis was continued for each of them until either a contradiction or non-changeable case was achieved. A correctly completed RCA+ diagram is self-explanatory.

Case: Analysis of RCA+ Diagram and Problem Solving

The first very important conclusion which can be drawn by looking at the resulting RCA+ diagram of the "Estonia" ferry accident was that all the contradictions in the diagram are connected with an "AND" relationship. This means that by eliminating any cause from the diagram, whether a contradiction cause or an intermediate negative cause/effect, the top undesired problem will be completely eliminated as well.

The question is to define which cause should be eliminated. There are a number of rules in RCA+ which help to select the most promising contradiction cause. In general, the overall complexity of a problem is defined by the number of contradiction causes contributing to the top undesired effect. Contradiction causes that are closer to the top-level problem contribute more strongly to it. For this reason, focusing on the top-level contradiction causes would eliminate the main negative effect with a more limited scope. Resolving the bottom-level contradictions (root conflicts) usually results in a broader range of consequences for the entire system.

Our experience has shown that solving bottom-level contradictions leads to long-term solutions with potential side benefits, and solving top-level contradictions helps to obtain faster but short-term solutions. The danger of causing unwanted effects in related systems by solving bottom-level contradictions is eliminated by using a holistic approach to the whole system and by iteration of solutions that do not survive evaluation.

A strategy for finding new solutions is defined by the analysis of contradiction causes either for the entire RCA+ diagram or for the particular branch where all the causes are connected with an "AND" relationship. In our case, we identified five contradictions (Table 1).

Each of these contradictions can be chosen and used to generate inventive solutions. For example, to solve contradiction cause C5, a new locking mechanism was patented (Lahtinen & Holtta, 1999). However, if we target solving a broader problem caused by flooding, one can select contradiction cause C3,

Table 1. Contradictions contributing to creating the problem "Ferry capsized"

	Cause	Positive effect	Negative effect
C1	Cargo deck is closed except the bow door	Water does not get into the ship during the voyage	Water was moving into the cargo desk
C2	Bow door has large size	Bulky cargo can be loaded /unloaded	Opening for water was too large
C3	Too much empty space between cargo containers and deck walls/ceiling	Only the amount of cargo needed can be loaded	Empty space in the cargo deck was large
C4	Too much empty space between cargo containers	Easy to manage cargo	Empty space in the cargo deck was large
C5	The door was capable of moving	Needs to be opened and closed to load/unload cargo	The bow door opened during the ride

which resides closer to the top problem, and investigate how this particular contradiction can be solved. As stated above, to resolve a contradiction a solution must be found which will provide the positive effect desired without producing the negative effect mentioned, and without producing other negative effects. In the present case, this means that while only the needed amount of cargo can be placed in the cargo deck, there should be no empty space available to avoid the displacement of a large mass of water inside the deck.

This situation indicates a typical conflict of demands: we want a part of the deck to remain empty, and we do not want any part of the deck to remain empty. This kind of conflict can be solved by using basic principles to overcome contradictions. The TRIZ principles of contradiction elimination serve as patterns of solutions or recommendations in the search for solutions. For example, one of the most commonly used TRIZ solution principles recommends "*Separat(ing) conflicting demands in time*". By following this principle, one comes to the conclusion that there must be empty space during the loading/unloading of cargo, and there must be no empty space during the voyage. More exactly, the empty space can be present on the deck, but must instantly "disappear" when the accident has started or become unavoidable.

As a result, the empty space must only disappear in the event of an emergency. Several solution ideas were suggested, for example:

1. Using tanks with a substance that, together with micro voids, will make a large volume of foam. These tanks can be attached to the ceiling of the cargo deck. In the event of an emergency, the substance is sprayed, and converts into a foam which fills the empty space between the walls, ceiling and floor, thus creating a partitioning;
2. Installing a number of bags or balloons that will expand from the side/floor/ceiling like giant airbags, using macro voids and elastic sheets.

These solution ideas are quite different from the typical solutions of using sealed compartments to provide ship safety. Clearly, such concepts should be later checked against feasibility. Similarly, the TRIZ principles for contradiction elimination can be applied to the remaining four contradictions listed in Table 1.

Conclusions

RCA+ helps with understanding factors that cause problems which require inventive solutions, helping to structure the problem and recognise potential directions in the search for solutions. As the case study with the "Estonia" ferry demonstrates, RCA+ can usefully be applied to the analysis of problems in the maritime industry.

Currently, RCA+ is used in three situations:

- Exploring causes and contradictions of a specific problem related to a certain product or technology. It is the most frequently used situation;
- Exploring broad problems related to families of products;
- Forecasting potential failures of products and technologies, either by identifying possible problems which might be related to a newly developed product or predicting potential causes of process failure.

In summary, RCA+ helps with:

- Decomposing a problem to a number of causes and effects, extracting contradictions that contribute to the problem;
- Structuring causes and effects;
- Extracting and presenting contradictions;
- Visualising a problem;
- Reaching a common agreement on causes contributing to a problem;
- Improving collaboration among team members when defining and solving a problem;
- Providing direct input for contradiction resolution techniques.

RCA+ can be used independently of TRIZ to analyse problems and situations. However, coupled with TRIZ techniques for resolving contradictions, RCA+ provides a powerful platform not only for understanding problems, but for supporting creative problem-solving as well.

At this moment, further research is being performed on improving the rules of ranking and selecting contradictions in RCA+ problem models.

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