Application of Selected TRIZ Instruments in Reliability Engineering

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Abstract. Reliability may be considered as the probability of proper operation of a technical object in certain time period and environmental conditions. Referring to such an assumption, lots of mathematical instruments for reliability evaluation were developed. These have a significant importance when one is aiming especially at the description of reliability of, in fact, any technical object. But another problem is reliability formation which requires the search for proper constructional, systemic and process solutions according to the identified needs resulting from the reliability evaluation. Therefore, the aim of the analysis presented in the paper is to discuss the possibilities of application of TRIZ instruments while conducting a technology development process in terms of reliability formation and to compare the application of these instruments with the typical methods traditionally used in this field. In many cases, these two kinds of instruments complement each other.

Keywords: Reliability Engineering, Reliability Formation, TRIZ Instruments, Designing.

1 Introduction

Reliability is an important feature of all technical objects (and processes) determining their proper functioning (or course). The consequences of failures of such objects can often be serious and dangerous, especially when leading to threats to human life and health, huge financial and material loses or inconveniences. Therefore, problems related to reliability engineering are considered in different contexts and engage different fields of science, e.g. mathematics, economy and technology. Regardless of the type of the problem, the complete reliability engineering tasks may be considered as design problems.

Solving design problems always requires the application of proper methods and models during the technology development process. Therefore, the question occurs: ‘how different the traditionally-applied instruments used for reliability formation are from the instruments designed for problem solving offered by TRIZ?’.

In the following sections of the paper some selected, traditional approaches to reliability formation (typically applied when considering the quantitative aspects of reliability in technology) were described and compared with the selected methods supplied by TRIZ. The analysis was mostly focused on indicating the methodological relations (that is mostly the similarities and differences) between these two ways of solving problems, when considering the field of reliability engineering. Finally, it was possible to formulate additional advice on using TRIZ instruments when solving reliability-related problems of the type presented in the paper.

2 Typical instruments used for reliability formation

The operation of technical objects always involves certain expectation of their users. They hope that the objects will perform their functions in an uninterrupted manner, ensuring that scheduled tasks are performed within a set time. The measure of trust that user adopts in reference to a technical object was considered to be its reliability. However, one can never be 100% sure that an object in given conditions and time will be in a technical condition that allows it to perform the desired task (that is called ‘the state of availability’). Therefore, the reliability of an object is expressed in a quantitative (and numerical) manner in the category of probability as a function of time. If, by the random variable T, the operating time to failure is defined, i.e. the time to the moment when the object ceases to be able to perform its function (it moves to the state of unavailability), then the reliability of the object can be presented as:

$$R(t) = P(T > t), \tag{1}$$

where:
$R(t)$ – reliability function of the object,
T – random variable describing the operation time to failure of the object,
t – time.

This is a typical way of defining the reliability function of an object.

2.1 Reliability estimation and formation

The reliability function is the basic characteristic used for evaluating a technical object in terms of its reliability [1, 2]. When examining objects that are observed until their first failures occurrences a few other reliability characteristics are applied, e.g. $F(t)$ – cumulative distribution function, probability density function of the time to failure $f(t)$, failure rate $\lambda(t)$ and the expected value of the operation time till the first failure $E(t)$. These characteristics are connected in a way expressed in dependencies [1]:

$$R(t) = \int_t^\infty f(t)dt, \tag{2}$$

$$F(t) = \int_{-\infty}^t f(t)dt, \tag{3}$$

$$R(t) + F(t) = 1, \tag{4}$$

$$f(t) = \frac{dF(t)}{dt} = -\frac{dR(t)}{dt}, \tag{5}$$

$$\lambda(t) = \frac{f(t)}{R(t)}, \tag{6}$$

$$E(t) = \int_0^\infty R(t)dt. \tag{7}$$

The course of changes of these characteristics for a given technical object is determined on the basis of historical data on the failures of such objects [3]. The selected set of objects operating under specific operating conditions is monitored, and their operation times to first failures are registered. With such a set of data, empirical values of reliability characteristics are determined and then, using statistical hypothesis testing, the probability distribution of operation time to failure of the examined objects can be determined, giving the mathematical dependencies of the reliability characteristics of the object [4].

The availability of the reliability characteristics and their changes over time is important from a practical point of view and used in the decision-making processes regarding the operation of technical objects. They are used, among others, for analyses related to: risk assessment of a given task, determining the number of redundant objects, estimating the number of necessary spare parts, optimising inspection time and preventive replacement of objects, determining the time of withdrawal from operation of an object, etc.

The reliability a given object will have during its operation is not a result of chance, but mainly the effect of its formation at the earlier stages of the object’s existence (its designing and manufacturing). Therefore, there are at least several typical, basic ways to form the reliability of technical objects.

One of the basic factors affecting the reliability of an object is the type of the material which the object is made from and the value of the adopted safety factor, which is to reduce the probability that the loads of random character will exceed the strength of the object. In this case, higher values of the safety factor will result in a higher level of the object’s reliability.

2.2 Reliability structures

Another method often used to form the reliability of objects is to design their reliability structures in the way, which despite the failures of individual elements of the object ensures the continuity of its operation (remaining in the availability state) as an entire system. Such a solution is called ‘the application of redundant reliability structures’. These include parallel and k-out-of-n structures (where *k* is the minimum required number of the object's available elements out of its all *n* elements) [5]. This procedure allows one to build objects with high reliability using elements with a much lower level of reliability. The redundancy introduced in these cases, usually in the form of additional elements, is one of the type mentioned: internal (when the redundant element is burdened and exposed to external factors as the basic elements), waiting (when the redundant element is less heavily loaded and exposed to external factors) or standby (when the redundant element is not loaded and it is idealistically assumed that the element is reliable in the sense of reliability, that is, it does not get damaged as long as it is a redundancy) [1]. Changing the reliability of an object obtained by using a single redundant element and by supporting a single element with one or two elements on the example of a k-out-of-n (koon) structure is presented in Figure 1. The value of reliability is calculated in this case according to the formula [1]:

$$R_S(t) = \sum_{i=k}^{n} \frac{n!}{i!(n-i)!} R_i(t)^i \left(1 - R_i(t)\right)^{n-i}. \tag{8}$$

The elements are non-renewable and identical in reliability, and the redundant element is an internal redundancy.

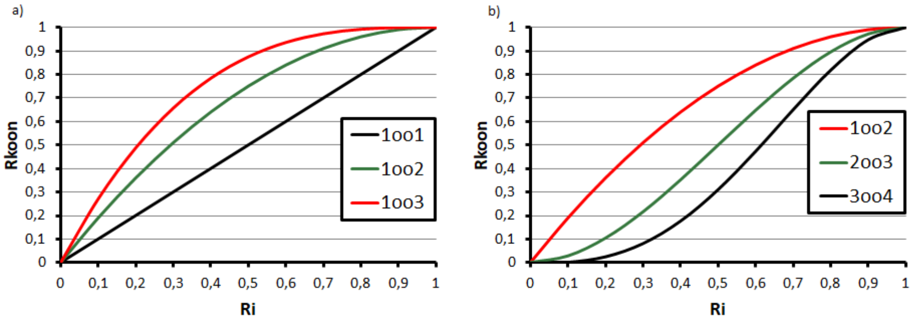

Fig. 1. The reliability of a k-out-of-n structure object depending on: the number of elements supporting one element (a) and the number of elements supported by one element (b)

However, because it is not always justified and not all elements of the objects can be supported by redundancies, a reliability analysis or research is conducted to identify the so-called weak links of the object or elements, the failures of which most and most often may lead to the transition to the state of unavailability of the entire object. Actions that form the reliability of an object may in such cases be based on the modernisation of the elements that were identified as the weak links, so that the level of their reliability gets adjusted to the levels of the other elements of the object.

2.3 Quality control

Presented ways to form the reliability of objects refer to the stage of their designing. Actions that affect the reliability of the object are also taken at the manufacturing as well as operation and maintenance stages. The process control and quality control methods applied in the manufacturing processes allow one to eliminate the elements defective and incompatible with design requirements, which significantly translates into the reduction in failure rates and thus a better level of reliability of objects that will be put into operation. Defective and non-compliant elements would most often cause failures in the burn-in period of their operation, leading to the failures of the whole objects and a quick deterioration of their reliability [3].

2.4 Preventive maintenance

However, in order to avoid failures of the objects and to forecast the time remaining until they reach the defined limit state, diagnostic tests of the elements and periodic inspections are carried out during the objects' operation. In particularly important cases when the failures of objects would cause significant financial losses, life threat or ecological hazard, preventive renewal of the elements or entire objects is performed when they are still in the availability state. These actions are performed at a strictly defined time, usually determined using optimisation methods and/or taking into account the data coming from periodic and diagnostic tests carried out [6, 7].

3 Analysis of the selected TRIZ instruments suitable for reliability engineering

Considering the statements presented in the previous paragraph, it becomes understandable that the problems of reliability engineering were in fact addressed since the very beginning of technology. Nearly every decision made during a design process affects the future reliability of the object or process being designed.

The reliability of a technical object or a process (e.g. a manufacturing process) is always dependant on the solution designed and the circumstances of the operation of the object or in which the process is conducted. Therefore, the design process (incorporating the act of new solutions finding) is strictly bounded with reliability formation. This is the reason why TRIZ concepts and instruments could and should be incorporated in reliability engineering.

The aim of the analysis presented in this section of the paper is to compare the methods and models traditionally used for reliability evaluation and formation with the ones supplied by TRIZ.

3.1 System operator application with the reference to reliability engineering

One may think that the whole traditional concept of reliability evaluation and formation could be successfully modelled in general using the typical (at least nine-screen) system operator. The scheme, dividing the selected part of the reality into a number of sections according to the passage of time and the complexity of the analysed area [8, 9], is probably the basis of the most of reliability formation activities. This is because:

- the reliability data acquired in the past is used today during the operations of analysis and synthesis in order to forecast and form the future reliability of technical objects and processes
- all of the data acquisition, management, processing and utilisation operations are to be done strictly according to the selected level of the object's (system's) complexity (and decomposition)
- indicating the specific relations between the reliability of the units present on the higher level of decomposition and the reliability of the units present on the lower

level (according to the division principle: subsystem – system – supersystem) may often be useful for practical applications of the analyses' results
- the whole reliability evaluation and formation have to be performed in relation to the specific circumstances of the analysed object's operation (or in which the analysed process is conducted).

Therefore, the works related to reliability modelling and engineering should be organised relatively to system operator modelling scheme (if they are not already organised in this way).

3.2 Exemplary application of the system operator

An exemplary application of the nine-screen system operator to the selected, typical reliability engineering problem solving pattern is presented in Figure 2.

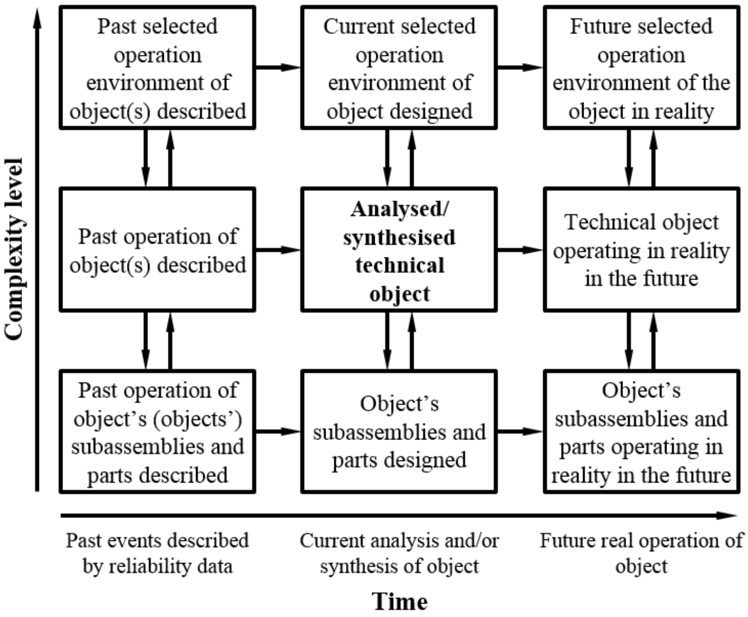

Fig. 2. Typical reliability engineering problem solving pattern modelled using system operator

Presented way of modelling, when deliberately and consciously introduced in reliability engineering, would offer great support at least during selecting the scopes of analyses and managing reliability data.

3.3 Application of the contradiction concept

The reliability-related tasks may often not refer to the problem of overcoming contradictions (so in all such cases they probably may be considered as optimisation tasks). This will take place when the aim of the task is, for example to indicate the sufficient number of the objects (elements) operating in a parallel or k-out-of-n structure (cf. the example presented in Figure 1), the safe operation time of the object till its renewal, etc. These tasks are solved using the proper formulas according to the chosen optimisation method, aiming at the desired result.

But the situation may get more complicated when it finally occurs that the calculated number of elements, though sufficient in the context of reliability requirements, is totally unacceptable because of the lack of space, high weight or excessive investment or operation and maintenance costs. The same might happen to the operation time till renewal, which may appear too short considering the technological requirements, servicing capabilities or costs of the entire maintenance process.

In these circumstances, the search for a solution to the reliability engineering task involves overcoming a contradiction and fully justifies the application of technical (or physical) contradiction concept supplied by TRIZ [10] as well as the use of TRIZ instruments (cf. [11]). At this stage of the technology development process the most of these instruments should be the ones oriented at defining the problem (e.g. functions analysis, substance-field analysis, root cause analysis or Root-Conflict-Analysis [12]). When the contradiction is already indicated and selected to be solved, another TRIZ instruments should be applied as usual in the design process.

3.4 Application of inventive principles

Inventive principles are probably one of the few TRIZ instruments directly addressing reliability. ‘Reliability’ is one of the 39 basic features of the technical solutions present in the contradiction table (matrix) [8, 12] (cf. [10]). It is defined as ‘the ability to fulfil a function with great certainty during specified time period’ [12]. This definition strongly corresponds with the one presented in paragraph 2, though it characterises reliability in a more qualitative way. Regardless of the difference indicated, the mentioned understanding of reliability considered in TRIZ fully justifies this part of the analysis conducted.

3.5 Analysis of the application possibilities of selected inventive principles

The object of this part of the analysis (according to the idea already from 2013) was the inventive principles system (version presented in [8, 13]), and especially the principles which have any relation to solving reliability-concerning problems (cf. [14, 15]). Therefore, the contradiction table was examined in two ways:

- first, analysing which inventive principles are suggested for overcoming the technical contradictions when aiming at reliability increase

- second, analysing which inventive principles are to be used for overcoming the contradictions when reliability decrease occurs as the result of another object’s feature change.

The most often proposed inventive principles for the above-mentioned cases were selected and are presented in Table 1 (the names of the principles are quoted after [10] and [16]).

Table 1. Number of applications of the inventive principles most frequently advised when overcoming reliability-related technical contradictions

Overcoming technical contradictions when aiming at reliability increase		
Principle number	Number of cases when application advised	Principle description
35	13	Change in the aggregate state of an object
11	12	Previously installed cushions
10	11	Preliminary action
3	8	Local quality (property)
28	8	Replacement of mechanical matter
40	8	Use of composite materials
27	6	Inexpensive short-life object as a replacement for expensive long-life one
Overcoming technical contradictions when reliability decrease occurs		
Principle number	Number of cases when application advised	Principle description
10	12	Preliminary action
35	11	Change in the aggregate state of an object
11	10	Previously installed cushions
40	10	Use of composite materials
27	8	Inexpensive short-life object as a replacement for expensive long-life one

Several obtained results (selected inventive principles) strongly correspond with the typical ways of reliability formation presented in paragraph 2. These are especially:

- ‘preliminary action’, which first recalls the whole group of preventive renewal actions
- ‘previously installed cushions’, which could refer to all types of redundant objects and spare parts present in a technical system
- ‘local quality’, which in the context of reliability formation especially recalls the technical objects of complex reliability structure, when their most important parts (the parts which are most important for their proper functioning) are characterised by significantly better reliability indexes and/or continuously monitored by diagnostic equipment and/or additionally supported by redundant parts.

The application of inexpensive short-life objects instead of expensive long-life ones could be considered as an interesting way of choosing the type of redundant objects when one is aiming at ensuring the continuous operation of a system.

The remaining principles (‘replacement of mechanical matter’, ‘change in the aggregate state of an object’ and ‘use of composite materials’) should probably be rather associated with typical constructional works of a designer (when the geometrical and material properties of a machine part or the principle of functioning of a subassembly are determined).

3.6 Application of functional idealisation

A typical problem for reliability engineering is the identification of weak links which are the objects of lower reliability or durability. Normally these elements should be modernised (by introducing changes in their construction) or supported using redundancies and/or diagnostic equipment.

The concept of functional idealisation (or, so called, trimming [12]) seems an interesting solution to the above-mentioned problems. Having the weak links eliminated (instead of modernised or supported) once their functions transferred to other elements of the object could often be a fruitful way of solving a reliability-related design problem (cf. [14]).

3.7 Exemplary application of functional idealisation

An exemplary application of such an approach to an object initially consisting of three elements is shown in Figure 3.

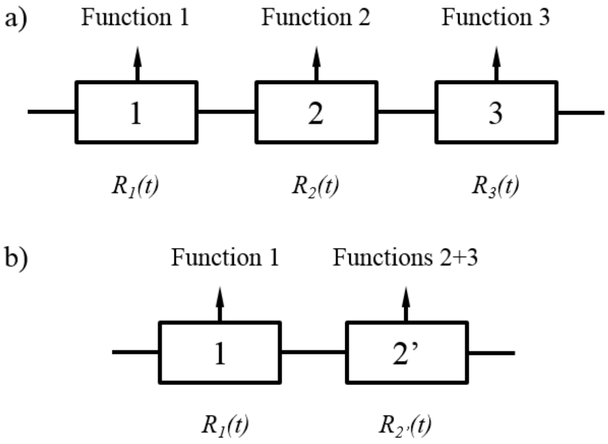

Fig. 3. A system of objects in a series structure before (a) and after (b) functional idealisation

However, the influence of the transition of the function on the other elements’ reliability indexes should always be discussed (in the presented example: how does the transition of the function 3 to the element 2 affect its reliability changing it from $R_2(t)$ to $R_{2'}(t)$?). This problem could probably be an important area of a further research.

3.8 Reliability engineering and the concept of ideality

The concept of ideality (or the model of an ideal machine) is present in the traditional approach to reliability engineering.

On the one hand, likewise in TRIZ, the ideality concept in reliability engineering provides a picture of a solution meeting some requirements in a way unavailable in the real world. On the other hand, it is difficult to say that this concept was intentionally created as a tool for fighting the psychological inertia of designers. Traditionally, an ideal part in terms of its reliability (a part which is always characterised by 100% probability of its proper operation; in other words, a part which cannot be broken), an ideal redundant object (an object described by the failure rate equal to 0; a redundancy which is always available) or an ideal complex technical object in the context of its durability (an object built out of the parts of equal durability [17]) are models providing a reference level of reliability indexes, indicating the desired direction of development of technical objects and/or included in calculations (but only in certain conditions, when specific assumptions applied).

3.9 Anticipatory failure determination

All of the reliability engineering problems are the ones formulated because of the possible occurrence of failures. Therefore, analysing and forecasting the modes and consequences of failures is an important issue related to reliability. There are different instruments designed to be used during such studies (e.g. failure modes and effects analysis, FMEA, cf. [18]) but the one linking TRIZ and reliability engineering together is definitely the anticipatory failure determination [19].

The concepts presented in the previous sections of the paper were aiming at the fulfilment of reliability requirements by technical objects or processes, therefore different types of activities were proposed and different solutions developed to achieve the desired reliability by restraining failure occurrence. The other way of considering reliability-related issues is introduced by the anticipatory failure determination, which instead of beginning with an analysis of possible ways of avoiding failures, starts with identifying ways leading to them [19, 20]. Such an analysis (supported by the use of typical TRIZ instruments) should allow one to finally indicate efficient solutions aiming at failure occurrence elimination as a reply to the identified possible threats.

The use of the anticipatory failure determination seems especially justified when solving reliability engineering tasks related to risk management (e.g. evaluating safety integrity levels, SILs, cf. [21]), work safety, etc.

4 Conclusions

Reliability theory (together with renewal theory) and TRIZ are two theories of different application areas. The first one mostly supports the problems of a specific range which are related to reliability engineering, whereas the second one refers to a wide range of inventive problems of at least several classes.

Despite these differences, the application areas of both of the theories are not completely separate. TRIZ concepts are useful in reliability engineering and could be helpful in general modelling, organising works related to reliability formation and obviously in conducting technology development process when optimisation procedures cannot deliver proper or feasible solutions. However, the solutions obtained using TRIZ instruments could be further developed and/or evaluated applying typical models and methods of reliability theory. Both of the mentioned theories relate to any technical objects of different kinds (e.g. mechanical equipment, electric/electronic equipment or buildings).

Application of a number of TRIZ instruments in reliability engineering should be further discussed and verified. The results of such a research could lead to obtaining new, useful models and methods supporting works related to reliability formation.

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