FROM RELIABILITY TO RESILIENCE: MODERN CHALLENGES OF SAFETY AND RELIABILITY THEORY AND APPLICATIONS

OD NIEUSZKADZALNOŚCI DO ODPORNOŚCI: WSPÓŁCZESNE WYZWANIA TEORII I INŻYNIERII NIEZAWODNOŚCI I BEZPIECZEŃSTWA

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Abstract: *There are several trends of development of modern reliability theory; some of them are subjects of everyday engineering activity, like: quality control of mass production or “pure” reliability. But most of these issues, such as: effectiveness, survivability, safety, security, are currently the subject of many works of conceptual, modeling, case study or survey nature. The aim of this article is show how the performance requirements of technical objects were supplemented with: customer expectations (quality), abilities to prevent the loss of the object properties in operation time (reliability and maintainability), the effects of undesirable events and protection against them (safety and security) and the ability to restore performance (resilience).*

Keywords: *reliability, resilience, technical object, development*

Streszczenie: *Można wyróżnić główne kierunki rozwoju współczesnej teorii niezawodności; niektóre z nich są przedmiotem codziennych działań inżynierskich, jak np.: kontrola jakości w produkcji masowej czy „czysta” analiza niezawodności. Ale większość tych wyzwań, takich jak: efektywność, odporność czy bezpieczeństwo są obecnie przedmiotem wielu prac koncepcyjnych, modelowania i badań. Celem artykułu jest pokazanie jak wymagania w stosunku do osiągnięć obiektu technicznego były poszerzane o: oczekiwania klienta (jakość), zdolność do zapobiegania utracie właściwości przez obiekt podczas eksploatacji (nieuszkodzalność i obsługiwalność), skutki niepożądanych zdarzeń i ochrona przed nimi (bezpieczeństwo) oraz zdolność do odtworzenia osiągnięć (odporność na zagrożenia).*

Słowa kluczowe: *niezawodność, odporność, obiekt techniczny, rozwój*

1. The beginnings of reliability engineering

J. H. Saleh in his article devoted to the history of reliability [11] observed that reliability is a concept that has been used for years as a attribute of a person or an artefact object. He found that the first recorded usage of the word reliability dates back to 1816 and it was written by English poet Samuel T. Coleridge in praise of his friend the poet Robert Southey.

Use of the word reliability to describe the properties of a technical object was more than 100 years later. According to Saleh [11] rising of reliability engineering is associated with the creation of three factors: the development of applications of probability and statistics, implementation mass production methods to practice and, what is not so obvious, the invention of the vacuum tube. The tube, because it initiated the electronic revolution, enabled a series of applications such as the radio, television, radar and others. But [1] the vacuum tube was also the main source of equipment failure. Tube replacements were required five times as often as all other equipments. This experience with the vacuum tubes prompted the US department of defence to initiate a series of studies for looking these failures. These efforts consolidated and gave birth to a new discipline, reliability engineering.

Thus, the emergence and development of reliability engineering required access to appropriate theoretical knowledge and the possibility of collecting large samples of data – production of a large number of identical elements / objects and a large number of failures of these objects.

I. Ushakov [13] focused in analyzing the reasons of reliability engineering rising on reliability theory development by W. Wiebull and B. Gnedenko. W. Weibull, analyzing strength of materials, reduced the problem of assembly failure to the model of a “weakest link”. He suggested a simple and convenient mathematical model for description, which is known as Weibull distribution. This well-known distribution is good because of two parameters of scale and shape it is very flexible and allows one to approximate almost any field data. Almost simultaneously and independently B. Gnedenko found three classes of limit distributions, one of which corresponded to Weibull distribution. Those fundamental results were proven and their applicability was shown.

Following Saleh concept, in the seventies, we have in Poland excellent conditions for the development of reliability engineering: relatively modern mass production of very low quality and highly qualified scientists. A good example is the program of the first Winter School on Reliability in 1972, which includes: mathematical basics of reliability theory [15], relations between reliability and quality [9], reliability theory and engineering applications in design [12], production [14], operation [2], and failure analysis [10] and reliability field test results [8]. This potential has been well spent; Winter School on Reliability is active up today [6].

2. Present challenges of object / system reliability

In the twenty-first century, as defined reasons for the development of the science of reliability are ceased. But there are many new challenges of reliability theory and engineering.

In 2000 year I. Ushakov [13] presented the main trends of development of modern reliability theory. He distinguished several directions; some of them are subjects of everyday engineering activity, like: quality control of mass production or “pure” reliability analysis (structural models, functional models, maintenance models). But most of these issues, such as: effectiveness (“performability”), survivability, safety, security, are currently the subject of many works of conceptual, modeling, case study or survey nature. Because of the subject of this paper, we should focus on the meaning of term survivability.

Survivability is defined by Ushakov [13] as a special property of a system to “withstand impacts”. These impacts can be unpredictable inner failures (usually due to operator errors), environmental influences (earthquakes, floods, hurricanes) or hostile human nature actions (enemy military operations or terrorist acts). It is assumed that this impacts are directed to the most critical components of the system. Survivability analysis is usually performed in minimax terms and reduced to “bottleneck analysis”, or searching out “minimum cut”. Usually survivability consideration is related to large terrestrial systems (telecommunication or power networks, transportation systems). The same type of reliability indices is applied to military objects that are subjected to statistically unpredictable impacts. The survivability measure is usually expressed in the power of set of system units whose destruction leads to the system “death”. Thus, we very close to critical infrastructure resilience and vulnerability problems which are considered here.

Other examples of important problems which are awaiting solutions concern [13]:

- software reliability,
- unique system analysis,
- global terrestrial systems,
- communication networks,
- developing systems,
- spare stock system,
- time redundancy,
- “continuous” models,
- units with several states,
- realistic accelerated testing,
- aggregation of filed data,
- methodology of failure analysis,
- warranty claim rate projection.

Eight years later, E. Zio prepared [16] a number of considerations on problems and challenges of current reliability engineering research.

He emphasizes that a fundamental issue in reliability analysis is the uncertainty in the failure occurrences and consequences. E. Zio believes that, reliability engineering is a well-established, multi-disciplinary scientific discipline which aims at providing a set of formal methods to investigate the uncertain boundaries between system operation and failure. The following problems are formulated [16]:

- concepts of reliability physics to discover causes and mechanisms of failure and to identify consequences;
- developing reliable systems, e.g. by reliability-based design;
- measures and testing reliability in design, operation and management;
- maintaining systems dependability, by maintenance, fault diagnosis and prognosis.

Thus, these old problems develop into new challenges when addressed with respect to the modern complex systems and operation tasks. These relate to:

- the representation and modelling of the system,
- the quantification of the system model,
- the representation, propagation and quantification of the uncertainty in system behaviour.

One of the issues that are now in the centre of attention is now problem of complex system (critical infrastructure) vulnerability and resilience [5].

3. Concept of system resilience

The main goals of vulnerability analysis could be connected with [3] :

- identification of the set of events and event sequences that can cause damages and loss effects – providing the information about system end state,
- identification of the relevant set of initiating events which affect the system performance,
- identification of the set of events respective to event consequences that would cause the given end state of the system,
- identification and determination of events and observed outcomes dependencies (within the system and among the system).

Moreover, the vulnerability is closely related to resilience. Following this, resilience engineering issues should be considered during vulnerability assessment performance.

A development approach of the resilience concept is shown in Figure 1. The figure shows how within last fifty years [7] the performance requirements of technical object were supplemented with: customer expectations (quality), abilities to prevent the loss of the object properties in operation time (reliability and maintainability), the effects of undesirable events and protection against them (safety and security) and the ability to restore performance (resilience). It was

distinguished four levels of analysis related to the number of parameters that describe the concepts.

3	maintainability <i>and</i> SAFETY	RESILIENCE <i>and</i> DEPENDABILITY	effect <i>and</i> maintainability
2	effect <i>and</i> time	SAFETY <i>and</i> RELIABILITY	DEPENDABILITY <i>and</i> maintainability
1	time <i>and</i> SAFETY	RELIABILITY <i>and</i> QUALITY	QUALITY <i>and</i> SAFETY
0	QUALITY <i>and</i> SAFETY	SAFETY <i>and</i> RELIABILITY	RELIABILITY <i>and</i> QUALITY

Fig.1 Schema of relations between reliability and resilience

Level 0 refers to the proper functioning of the new facility.

Level 1 refers to the introduction of operating time as a parameter affecting the loss of object properties and deterioration of its quality. The result is a random occurrence of damage. And the ability of an item to perform a required function under given conditions for a given time interval is described by reliability function.

Level 2 means that the individual terms are described by two parameters. In the first case the time parameter has been updated with a parameter indicating the effects of the damage and there are analyzed safety issues. In the second case, the parameter of time to failure has been supplemented by a time parameter of repair. Then it is considered the ability of an item under given conditions of use, to be retained in, or restored to a state in which it can perform a required function – maintainability. Combining together: reliability performance, maintainability performance and maintenance support performance we can describe availability and dependability of an object / system.

Level 3 takes into account the three parameters analyzed before: time to failure, repair time and the effects of damage /disruption. This allows, in a simplified way, to define the concept of resilience, particularly while we need to develop resilience measures or indicators.

According to the literature, the key aspects of supply chain resilience include:

- readiness – probability of disruptions occurrence,
- response – the level of consequences of those disruptions occurrence,
- recovery – time to recover to normal state from disruption state.

Following this, the Vulnerability Priority Number may be estimated as [4]:

$$V_N = f(\text{Readiness}, \text{Response}, \text{Recovery})$$

This approach bases on the metric known as Risk Priority Number analysed in risk management method – FMEA. The approach to quantify given vulnerability metric is presented in Figure 2.

Fig.2 Schema of VPN metric.

The application of that metric was discussed on the problem of supply chain vulnerability assessment; a simple example of supply chain from the sawmill industry performance was analysed [4].

4. Conclusions

The paper in the shortened way shows the relationship between reliability and resilience. The basics of reliability theory and engineering are mentioned and some modern challenges of reliability science are presented. The analysis shows up to date possibilities of resilience assessment for real complex system, while more detailed statistical analysis of the problem is very limited by lack of certain information.

However, taking into account the uncertainty of expert opinions, lack of information, and the variety of approaches to resilience assessment problems, this research area still demands further investigation and development of new complex framework for system vulnerability and resilience measurement.

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