Application of Subversion Analysis in the Search for the Causes of Cracking in a Marine Engine Injector Nozzle

Leszek Chybowski, Artur Bejger, Katarzyna Gawdzińska

***Abstract*—**Subversion analysis is a tool used in the TRIZ (Theory of Inventive Problem Solving) methodology. This article introduces the history and describes the process of subversion analysis, as well as function analysis and analysis of the resources, used at the design stage when generating possible undesirable situations. The article charts the course of subversion analysis when applied to a fuel injection nozzle of a marine engine. The work describes the fuel injector nozzle as a technological system and presents principles of analysis for the causes of a cracked tip of the nozzle body. The system is modelled with functional analysis. A search for potential causes of the damage is undertaken and a cause-and-effect analysis for various hypotheses concerning the damage is drawn up. The importance of particular hypotheses is evaluated and the most likely causes of damage identified.

***Keywords*—**Complex technical system, fuel injector, function analysis, importance analysis, resource analysis, sabotage analysis, subversion analysis, TRIZ.

I. Introduction

SUBVERSION analysis, also called sabotage analysis, is one of the tools used in the TRIZ methodology – Theory of Inventive Problem Solving [1], [2]. Apart from anticipatory failure determination (AFD), it is one of two powerful tools used in the cause-and-effect analysis of the occurrence of undesirable situations, such as damage, errors, environmental effects and intended or unintended effects of the human factor [3], [4]. AFD focuses on the assessment of the consequences and prediction of potential undesirable events and is used for existing and newly developed products and technologies, including one-off items and those existing in small numbers (nuclear power plants, space vehicles, specialised naval vessels, etc.) [5]-[7]. Subversion analysis helps to find the causes of certain phenomena and events (defects, errors, negative influence) when the root causes of the phenomena are not obvious [8]-[12]. Subversion analysis allows one to identify hypotheses concerning the causes of a particular consequence and supports the selection of the most likely hypotheses.

Mitrofanov, the founder of the Leningrad University of Technical Creativity, created the principles of subversion analysis [13]. In the following years, a number of modifications were made to the method in various stages of TRIZ development [13]. Mitrofanov efficiently used subversion analysis to explain the nature of two physical phenomena [13], [14]:

1) In 1974 he explained the Russell effect [15], discovered in 1897;
2) In 1990 he explained the Twyman effect [16], discovered in 1905.

The basic concepts of subversion analysis were developed in the 1980's [17] in the works written at the Kishniev TRIZ school [18], [19] and in Kaplan's studies [20]. AFD was later created on the basis of these concepts. Both of these tools have been developed by Ideation International – now based in Detroit, Michigan, USA [17], [21].

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II. Subversion Analysis Process

Subversion analysis is based on two major TRIZ tools, namely function analysis and resource analysis. The key paradigm of subversion analysis is based on the inversion of the problem [13]: instead of asking "what causes the effect?" the question is reversed to "how to create the effect?" Many modifications have been made to the method [22], but it usually consists of the following basic steps [13], [23]:

1) Identification of the problem (negative or undesirable phenomenon) and reversing it to form a task aimed at generating the identified problem. Formulation of the task by asking: how to create or produce the negative effect?
2) Determining how to generate a problem using functions (function analysis) and resources (resource analysis) available in the system being analysed and its supersystem.
3) Formulation of hypotheses about the root causes of the problem, determination of their ranks and selection of the most likely hypotheses.
4) Verification of hypotheses and a search for solutions to the original problem.

Function analysis is a TRIZ tool derived from the theory of systems used at the stages of mapping and decomposition of the problem [24]. The main objective of using function analysis to support subversion analysis is to understand problems (phenomena or effect) by identifying the relationships between elements of the system and the supersystem. Fig. 1 shows the main stages of function analysis.

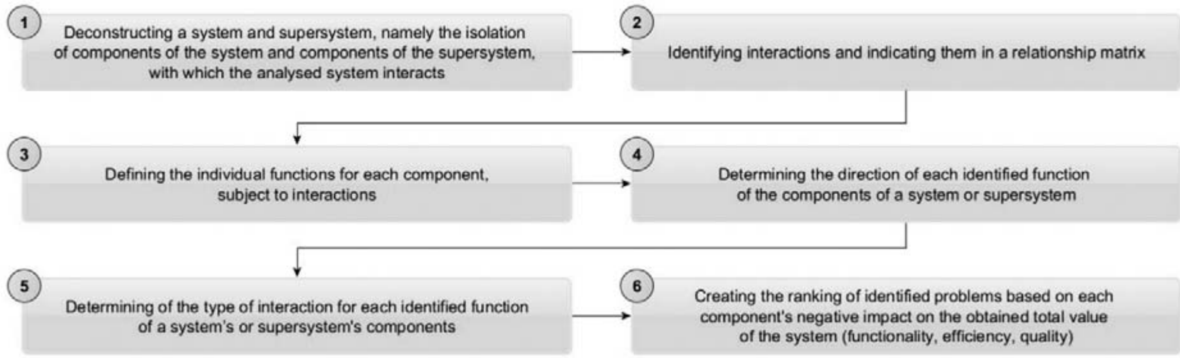

Fig. 1 The process of function analysis (derived from [25])

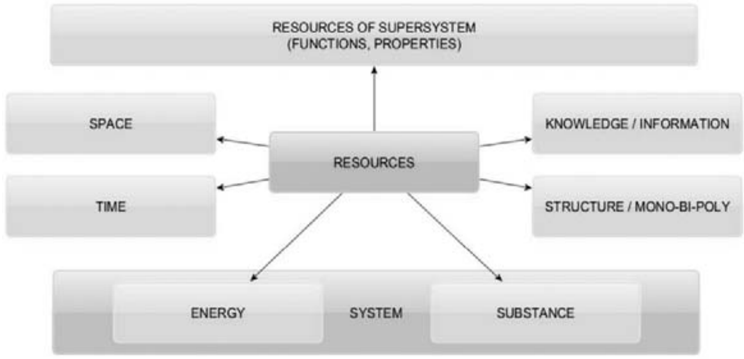

Fig. 2 Breakdown of resources according to type and location of availability

Fig. 3 A cracked tip of a nozzle body in the fuel injector of a diesel engine [26]

Within TRIZ, resources are objects or phenomena which can be used to solve a given problem and are available in the right place, in due time, in the right form (type), in an appropriate quantity (dose) or intended for the right recipient. Resources can be classified by their type and location of availability, as presented in Fig. 2.

In the case of subversion analysis, the analyst solves an inverted problem, i.e. identifies the presence or absence of what resources result in an undesirable situation.

III. Fuel Injector Nozzle Body Failure Analysis

An analysis will be carried out to explain the negative phenomenon (effect) defined as “a cracked tip of a nozzle body in the fuel injector of a diesel engine”. An example of such damage is shown in Fig. 3.

Such damage may eventually lead to a very serious engine failure, due to the possibility of the injector cooling agent flowing out of the spray nozzle and into the combustion chamber, including cracking of the cylinder liner, piston, cylinder block and galling of tribological pairs of the engine. The inverted question to the problem is: “How to create a crack in the nozzle body of the fuel injector of a diesel engine during operation?”

The subject of analysis is a fuel injector of the marine diesel engine [27], [28]. It is an object that is designed to feed the fuel, at the correct pressure, to the combustion chamber and to spray it properly. The cross-section of the analysed object and the critical components are shown in Fig. 4. The main components of the system are: 1 – retaining nut, 2 – nozzle body, 3 – needle valve, 4 – nozzle cap nut, 5 – intermediate spindle, 6 – spring, 7 – O-ring, 8 – dowel pin, 9 – adjusting nut and washer, 10 – injector body.

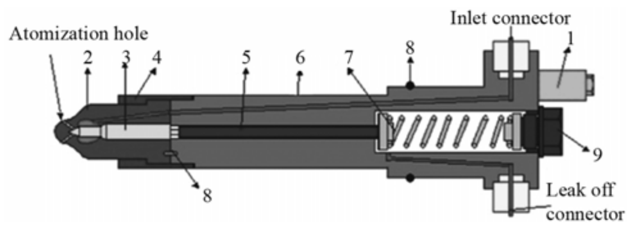

Fig. 4 Object of analysis (fuel injector) and its components [29]

For the purposes of this analysis, the system (nozzle of fuel injector) is formed by elements directly related to the analysed phenomenon, i.e. the pair including the injection nozzle body and needle valve. Individual relations between the elements of the system and identified elements of the system are described and presented in the form of a function model of the supersystem, as shown in Fig. 5.

For the current analysis, the most important elements of the supersystem are the engine block, injector body, fuel oil, cooling agent (water or oil), combustion chamber and injector inner assembly (spindle, spring, bolt and nut).

IV. Potential Causes of the Failure

For the studied system, we carried out the analysis of potential causes of cracking of the tip of a nozzle body in the fuel injector of diesel engines. Making use of the available literature and knowledge of a team of experts, we sought to answer the question of how to generate the problem using functions (function analysis) and resources (resource analysis) available in the analysed system and its supersystem. Potential functional causes are summarised in Table I and the causes related to resources are summarised in Table II.

After eliminating repetitive hypotheses, 19 potential causes of cracking of the tip of an injector nozzle body have been analysed for causes and consequences, as shown in Fig. 6.

In further analysis, corrosive and erosive impacts of fuel on the nozzle body due to the presence of identical resources were combined into a single event. The description of the remaining root events remains unchanged.

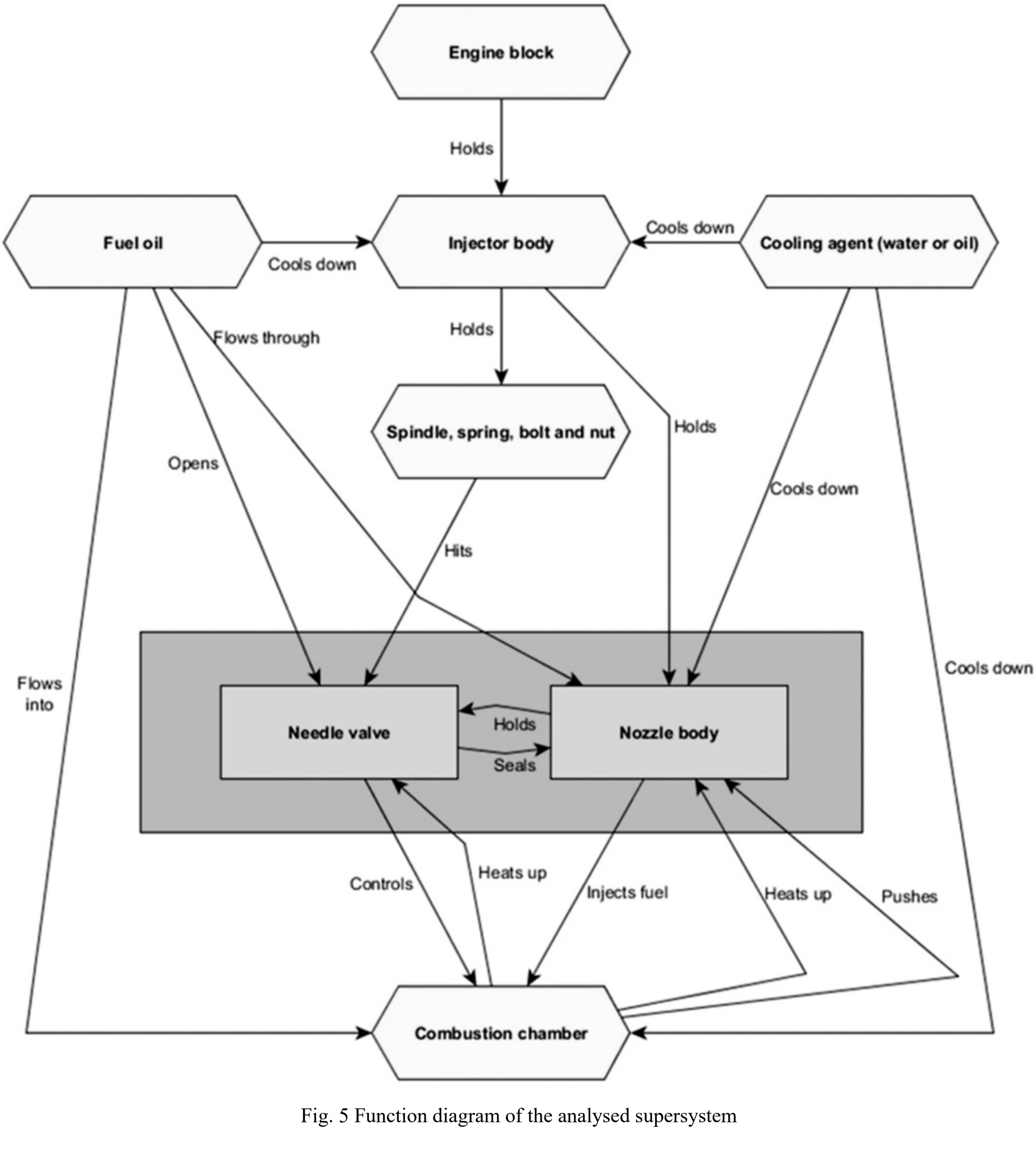

Fig. 5 Function diagram of the analysed supersystem

TABLE I
POTENTIAL FUNCTIONAL CAUSES OF THE PROBLEM

No.	Function	Possible failure / fault
1.	Spindle hits (cyclically pushes) the needle valve	The needle valve is overloaded by spring pressure; The needle valve is overloaded by inertia force
2.	The nozzle body holds the needle valve	The nozzle body internal surface is worn due to friction with the needle valve
3.	The needle valve seals the nozzle body	
4.	Fuel oil opens the needle valve	The needle valve is overloaded by fuel oil pressure
5.	A cooling agent cools the nozzle body down	The nozzle body is thermally overloaded due to temperature gradients
6.	The nozzle body injects the fuel oil into the combustion chamber	Fuel oil corrodes the nozzle body; Fuel oil erodes the nozzle body; Fuel oil clogs atomisation holes (carbonisation of fuel oil)
7.	The combustion chamber heats the nozzle body up	The nozzle body is thermally overloaded by exhaust gas
8.	Fuel oil flows through the nozzle body	The nozzle body is corroded and eroded by fuel oil
9.	The combustion chamber pushes the nozzle body by exhaust gas (combustion pressure)	The nozzle body is overloaded by combustion pressure; The nozzle body is corroded by exhaust gas
10.	The needle valve controls parameters (temperature and pressure) of the combustion chamber	The needle valve is thermally overloaded
11.	The combustion chamber heats the needle valve up	
12.	The injector body holds the nozzle body	The vibrations from the engine block are transmitted to the nozzle body

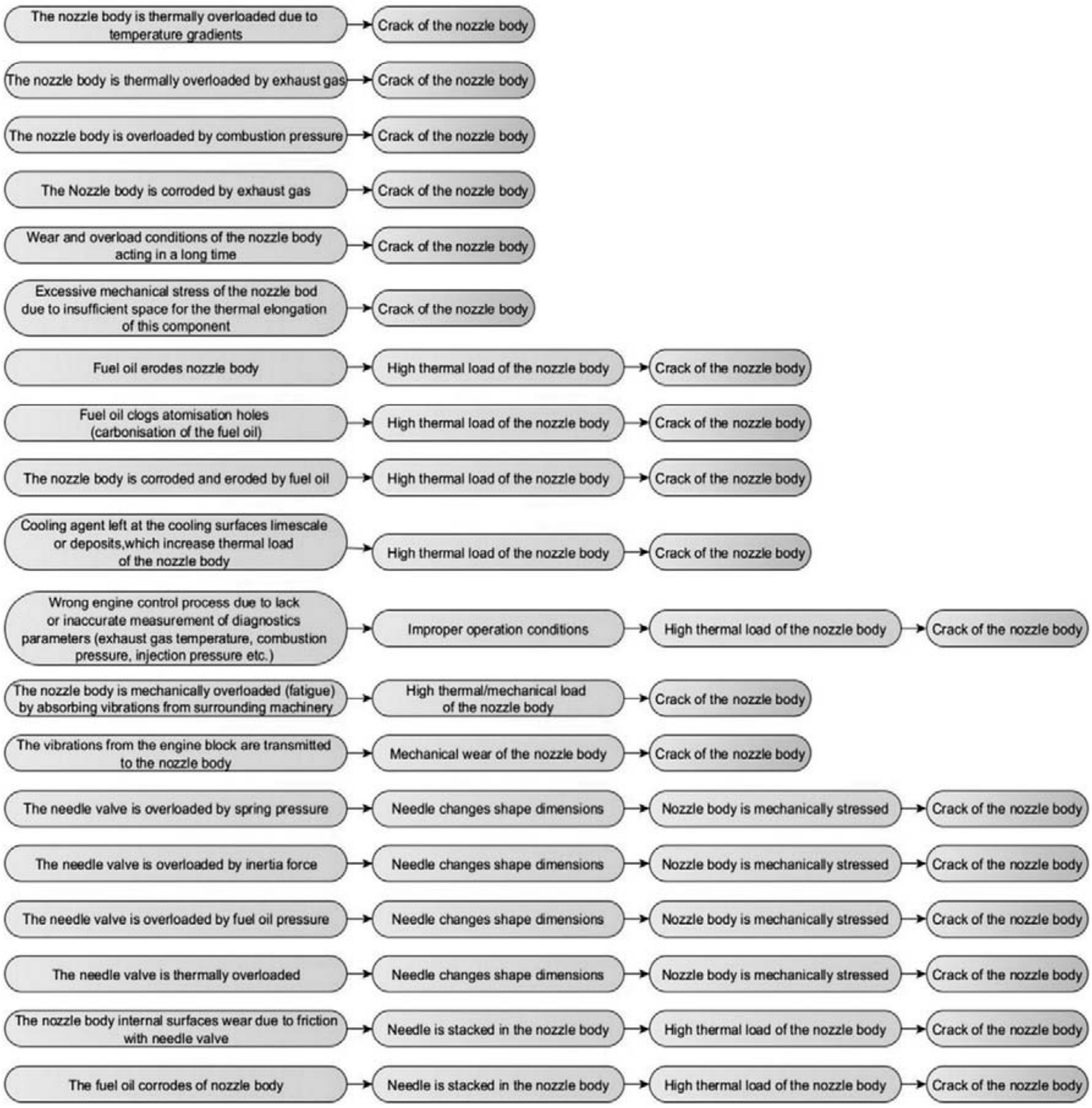

Fig. 6 Cause and effect analysis of the problem

TABLE II
RESOURCE-BASED CAUSES OF THE PROBLEM

No.	Resource	Possible failure / fault
1.	Time	Wear and overload conditions of the nozzle body acting for a long time
2.	Space	Excessive mechanical stress on the nozzle body due to insufficient space for the thermal elongation of this component
3.	Materials	Fuel oil leads to corrosion of the nozzle body; Fuel oil leads to erosion of the nozzle body; Fuel oil carbonising increases friction wear of the nozzle precision pair; Exhaust gas leads to corrosion of the nozzle body; Cooling agent leaves limescale or deposits at the cooling surface which increase thermal load on the nozzle body
4.	Energy	The nozzle body is deformed by heat from the combustion chamber; The nozzle body is thermally overloaded by high combustion chamber temperature (temperature gradients)
5.	Information	Wrong engine control process due to lack of, or inaccurate, measurement of diagnostic parameters (exhaust gas temperature, combustion pressure, injection pressure, etc.)
6.	Functional	The nozzle body is mechanically overloaded (fatigue) by absorbing vibrations from surrounding machinery

TABLE III
RANKING OF CAUSES

Cause	C1	C2	C3	C4	C5	Total
The nozzle body is thermally overloaded due to temperature gradients	1.0	1.0	0.5	1.0	1.0	4.5
The nozzle body is thermally overloaded by exhaust gas	1.0	1.0	0.5	1.0	0.5	4.0
The nozzle body is overloaded by combustion pressure	1.0	1.0	0.5	1.0	1.0	4.5
The nozzle body is corroded by exhaust gas	1.0	1.0	0.5	1.0	0.0	3.5
Wear and overload conditions on the nozzle body acting over a long time	0.5	0.5	0.0	1.0	1.0	3.0
Excessive mechanical stress on the nozzle body due to insufficient space for the thermal elongation of this component	0.0	1.0	0.0	1.0	0.0	2.0
Fuel oil erodes the nozzle body	1.0	1.0	0.5	1.0	1.0	4.5
Fuel oil clogs atomisation holes (carbonisation of the fuel oil)	1.0	1.0	0.5	1.0	1.0	4.5
The nozzle body is corroded and eroded by fuel oil	1.0	0.5	0.5	1.0	1.0	4.0
Cooling agent leaves limescale or deposits at the cooling surfaces which increase thermal load on the nozzle body	0.5	0.0	1.0	0.0	0.0	1.5
Wrong engine control process due to lack of, or inaccurate, measurement of diagnostic parameters (exhaust gas temperature, combustion pressure, injection pressure etc.)	0.5	0.5	1.0	0.5	0.0	2.5
The nozzle body is mechanically overloaded (fatigue) by absorbing vibrations from surrounding machinery	0.5	0.0	1.0	0.0	0.0	1.5
The vibrations from the engine block are transmitted to the nozzle body	1.0	0.0	1.0	0.0	0.0	2.0
The needle valve is overloaded by spring pressure	1.0	0.5	0.5	1.0	1.0	4.0
The needle valve is overloaded by inertia force	1.0	0.5	0.5	1.0	1.0	4.0
The needle valve is overloaded by fuel oil pressure	1.0	0.5	0.5	1.0	1.0	4.0
The needle valve is thermally overloaded	1.0	0.5	0.5	1.0	1.0	4.0
The nozzle body internal surfaces wear due to friction with needle valve	1.0	0.5	1.0	1.0	0.5	4.0

V. RANKING OF CAUSES

The importance of each potential cause of the problem was determined as the sum of the score of the following five criteria:

C1. All necessary resources to produce a cause are available;
C2. A cause does not require introduction of additional conditions;
C3. A cause might change unexpectedly;
C4. A cause does not contain a non-verified statement;
C5. Intuitive probability of a cause is high.

In each criterion, the given cause could have values in the range of ⟨0, 1⟩, where the extreme values mean: 0 – failure to meet the criterion; 1 – meeting the criterion in full. Maximum and potential total weight of a given hypothesis for a listed number of criteria is therefore 5. The results of this ranking analysis are presented in Table III.

As a result of the quantitative analysis of the ranking of potential causes of the problem, possible hypotheses were selected. Among the most likely ones, the top 10 hypotheses are:

1. The nozzle body is thermally overloaded due to temperature gradients;
2. The nozzle body is overloaded by combustion pressure;
3. Fuel oil clogs atomisation holes (carbonisation of the fuel oil);
4. Fuel oil erodes the nozzle body;
5. The needle valve is overloaded by spring pressure;
6. The needle valve is overloaded by fuel oil pressure;
7. The needle valve is overloaded by inertia force;
8. The nozzle body is thermally overloaded by exhaust gas;
9. The needle valve is thermally overloaded; and
10. The nozzle body is corroded and eroded by fuel oil.

VI. FINAL REMARKS

The analysis carried out proves the utility of subversion analysis in the analysis of damage with a complex nature; normally composed of many factors having a degrading effect [30].

Owing to a systematic approach applied to the individual functions performed by the elements of a system and the cooperating elements of the supersystem, together with the analysis of resources, it is possible to avoid mistakes related to an analyst's habits and routine approach, known as the psychological inertia effect.

Due to its in-depth analysis of phenomena, subversion analysis is very well suited to the search for causes of new phenomena, damage to one-off and prototype systems and it enables the analysis of the human factor in a broad sense [3], [4]. This covers the intended and unintended errors related to factors such as the system operator's ignorance, deliberate sabotage and terrorist attacks, and errors related to the lowering of an operator's psychophysical fitness, e.g. due to illness, fatigue or psychoactive substances [4].

The method presented can be a preliminary and complementary element of risk analysis of marine systems and the analysis of shipping safety. The method can be complementarily used with methods such as FMEA, HAZOP, FTA and ETA [21], [31], [32]. Moreover, the ranking analysis of hypotheses can be conducted on the basis of different weights of the individual component criteria, which can be achieved by using a weighted average, or the methods of assisted decision-making process, e.g. AHP [24], [33], [34].

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