APPLYING THE ANTICIPATORY FAILURE DETERMINATION AT A VERY EARLY STAGE OF A SYSTEM'S DEVELOPMENT: OVERVIEW AND CASE STUDY

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Abstract: Anticipatory Failure Determination (AFD) is a tool used in the TRIZ (Theory of Inventive Problem Solving) methodology. This article introduces its concept and describes the process of AFD in different versions of the method. The article presents the application of the AFD method at a very early state of a system's development, i.e. its concept formulation stage, which corresponds to a technology readiness level (TRL) equal to 2. The system under analysis is a set of devices used to reduce displacement ship hull resistance. The system was modelled using functional analysis. An analysis of system resources was then carried out. Possible direct, indirect, and accident-related failures were identified. A multi-criteria analysis of the causes of system failures was conducted from which the top 10 potential failures were selected. Observations were made on the applicability of AFD in respect to systems not yet implemented.

Keywords: complex technical system, anticipatory failure determination – AFD, anticipatory failure analysis – AFA, failure prediction, Theory of Inventing Problem Solving – TRIZ

INTRODUCTION

TRIZ, is the Russian acronym for the Theory of Inventing Problem Solving. It is the life's work of Genrich Altshuller, his associates and the successors of his ideas for developing ARIZ (Algorithm for Inventive Problem Solving) (Mayer, 2017; Oxford Creativity, 2017). TRIZ is a complex methodology comprising a range of tools for proper definition and modelling of a problem situation (inventive task), structured problem solution finding, and evaluation and selection of the most effective solutions (Howard et al., 2009).

There are a range of methods to simulate the process of failure prediction in complex technical systems including: Failure Modes and Effects Analysis (FMEA), Hazard and Operability Analysis (HAZOP), Preliminary Hazards Analysis (PHA), Risk Assessment, Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). TRIZ also provides tools for solving inventive problems in terms of the identification of causes and consequences of the occurrence of undesirable situations such as failures, errors, environmental impact, and intentional and unintentional effects of human action. Anticipatory Failure Determination (AFD) (Kaplan et al., 1999), also called Anticipatory Failure Analysis (AFA) (Souchkov, 2016), is one such tool. This method is based on a previous tool called subversion analysis, also known as sabotage analysis, which used concepts named the opposite experiment which were method for solving R&D problems developed by Voluslav Mitrofanov, a founder of the Leningrad University of Technical Creativity (Chybowski et al., 2018). Subversion Analysis method was originated by Mitrofanov's student Boris Zlotin in 1977. Later it were developed in 1984 jointly with Alla Zusman (Zlotin and Zusman, 1991) and finally by Svetlana Visnepolchi (2008). Subversion analysis allows for identifying hypotheses regarding the explanation of causes of a given effect and also helps to choose the most likely hypotheses. The tool is very useful in the identification of causes of given phenomena and events (faults, errors, negative impact), especially in situations where causes cannot be easily determined (Chybowski et al. 2018). Subversion Analysis is concerned with prediction and evaluation of consequences of potential undesirable effects, which makes it applicable to already existing, as well as newly developed products and technologies, including single units or units belonging to small product families (nuclear power plants, space ships, lunar vehicles, specialized marine vessels, etc.). The method was transferred to USA and renamed to the AFD. It is based on the inversion of the original question of ‘What to do to make a system work correctly?’ to the question of ‘How to make a given failure occur?’

METHODOLOGY

AFD is a method aimed at finding possible unexpected and undesirable events that risk disrupting the normal operation of a technical system, with the use of existing resources (Fig. 1). This tool was created in the 1980’s (Altshuller et al., 1989; Ungvari, 1999; Zlotin and Zusman, 1991) by Boris Zlotin and Alla Zusman (Kaplan, 1997; Proseanic et al, 2000). This method was computerised by Ideation International Inc. in Detroit, MI, USA (Ungvari, 1999), and is available in the form of two products: Ideation Failure Analysis^{TM} and Ideation Failure Prediction^{TM} (Zusman and Smith, 1991). The two main algorithms are AFD-1 and AFD-2, further described in (Kaplan et al., 1999). AFD has also seen other modifications including AFD-3, integrated AFD, and the xTRIZ Anticipatory Failure Analysis.

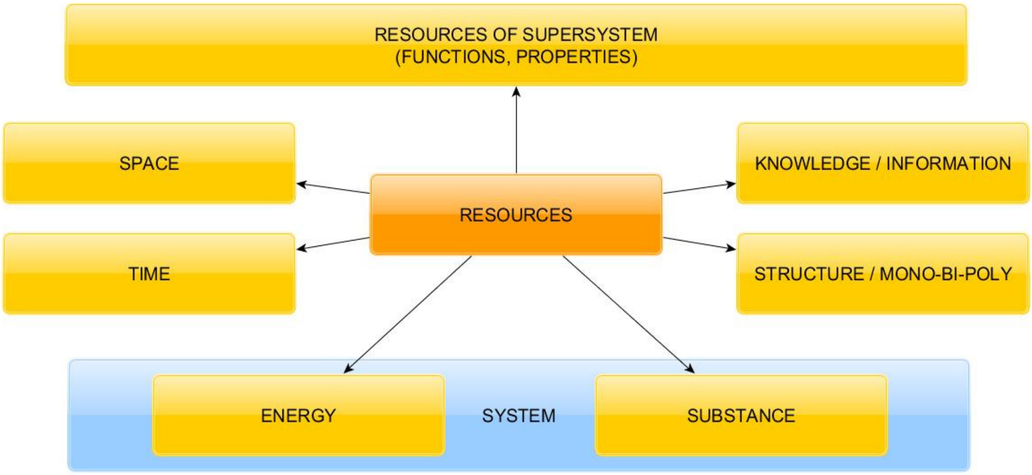

Fig. 1. Categories of resources in terms of type and place of availability

Source: (Chybowski et al., 2018).

Potential failure is a result of unforeseen and undesired negative factors resulting from a combination of the function performed within the system, and the resources available in given conditions.

Failure Analysis (AFD-1)

The AFD-1 algorithm is used to identify the causes of failure that has already occurred. It has been described in detail in (Kaplan et al., 1999). The individual steps in the process are:

1. Formulating the original problem.
2. Identifying a success scenario.
3. Locating failure.
4. Formulating and amplifying the inverted problem.

5. Searching for solutions.
    5.1. Searching for apparent or obvious solutions.
    5.2. Identifying resources.
    5.3. Utilising resources and searching for needed effects.
    5.4. Applying “ARIZ for AFD”
        5.4.1. Recapping the problem
        5.4.2. Formulating the secondary problem(s).
        5.4.3. Formulating the ideal solution of the secondary problem.
        5.4.4. Searching for ways to achieve the ideal solution.
6. Formulating hypotheses and designing tests to verify them.
7. Correcting failure.

Failure Prediction (AFD-2)

The AFD-2 algorithm is used for the prediction and identification of failure that has not yet occurred. It has been described in detail in (Kaplan et al., 1999). The individual steps in the process are:

1. Formulating the original problem.
2. Identifying the success scenario.
3. Formulating the inverted problem.
4. Searching for obvious possible failures.
5. Identifying available resources.
6. Utilising the knowledge base.
7. Inventing new solutions by applying “ARIZ for failure prediction”.
    7.1. Formulating a general way to produce the desired effect and the secondary problem.
    7.2. Formulating the ideal conditions for realising the harmful effect.
    7.3. Searching for ways to achieve the ideal conditions.
    7.4. Searching for the way to change the system.
8. Intensifying and masking harmful effects.
9. Analysing relevant harmful effects.
7. Preventing and eliminating harmful effects.

Human Factor Analysis (AFD-3)

The AFD-3 method was presented in (Sunday, 2014) as a response to potential limitations of AFD-1 and AFD-2 in terms of prediction of failure associated with human errors, organizational errors, bad ergonomic design, and other manufacturing defects. The AFD-3 method is a continuation of AFD-1 and consists of the following steps:

1. Formulating the original problem.
2. Identifying the success scenario.
3. Locating failure.
    3.1. Mapping system dependency to design structure matrix (DSM).
    3.2. Identifying failure.
4. Formulating the problem at the subsystem’s level.
5. Stating the success scenario at the subsystem’s level.
6. Locating failure at the component level.
7. Gathering the required information.
    7.1. Consulting the design documentation.
    7.1. Mapping design matrix (DM) information to DSM.
8. Locating failure at the design parameter (DP) level.
9. Locating the DP failure at the process domain.
10. Formulating, inverting, and amplifying the problem.
11. Searching for a solution.
    11.1. Searching for an apparent solution.

  11.1. Identifying resources in the manufacturing process.
  11.1. Utilising the identified resources to produce the DP problem.
  11.1. Applying ARIZ.
12. Formulating and verifying hypotheses.
13. Implementing a solution to the problem.

Integrated AFD Method

Andreas Jensen and Terje Aven at the University of Stavanger proposed a modification of the AFD-1 method, that consisted of a generalization of the stages of solution finding (AFD-1, point 5), i.e. the use of an alternative creative method (Jensen and Aven, 2015a; Jensen and Aven 2015b). Hence, in addition to/instead of the application of ARIZ, they offered the use of brainstorming (the Osborne-Parnes model) or De Bono lateral thinking, as well as other inventive methods (Howard et al., 2009).

xTRIZ Anticipatory Failure Analysis

In (Souchkov, 2016) the approach to AFD was modified by the introduction of combinations between functions and resources which, under certain conditions, lead to the occurrence of failure. Failure, seen within the framework of a system's function model, can be divided into:

1. Direct Potential Failure – directly related to the failure factor (failure mode) associated with a given function (relation) that exists between two system components.
2. Indirect Potential Failure – related to the failure mode associated with the impact between two components which are not directly linked functionally, but do interact through an intermediary.
3. Accident-Related Failure – related to an unexpected and unplanned change in the operating conditions of the system, or a change in its environment (supersystem).

Here, the basic element is the functional modelling of the system. This approach is also significant thanks to the introduction of the evaluation stage of individual identified causes of failure, in terms of severity. Individual steps of the algorithm are:

1. Selecting a system to analyse.
2. Defining the stage of a system’s operation / stage of the life cycle.
3. Building a function model of the system and the supersystem.
   3.1. Defining subsystems and supersystem of the analysed system.
   3.2. Defining functions between components of subsystems and the supersystem.
4. Creating the list of functions.
5. Identifying available resources.
6. Checking how combinations of functions and resources can create failures (it is important since not each combination can create failure).
7. Estimating indirect and environmental impacts.
8. Searching for generic causes of failures not indicated at previous stages.
9. Ranking potential failures and accidents.
   9.1. Bringing all the failures on a single list.
   9.2. Defining a list of potential top 10 most critical failures.
   9.3. Ranking the probability of each potential failure and degree of its impact.

APPLICATION OF AFD IN A SYSTEM IN ITS CONCEPTUAL DEVELOPMENT STAGE

System Description

AFD was used as the example in the evaluation of the failure tolerance of systems of low technology readiness level (NASA, 2017). In this case study, the method of proceeding described in section 3.3 was applied, due to the fact that it embraces elements of all the previously presented approaches. The object of the analysis was a newly developed system for the minimization of hull resistance and removal of lichen covering displacement vessels that is the subject of a patent application (Chybowski, 2017a). The general view of the system is shown in Figure 2. The essence of the solution applied in the invention is based on the fact that the hull plating, 1, has integrated heaters below the waterline, 3, that generate gas particles, 6. The heaters are connected to the control system, 4 (by means of feedback in the form of the heater temperature signal), and the actuating system, 5 (providing power for the heaters), while the hull was covered with a cavitation and heat resistant coating.

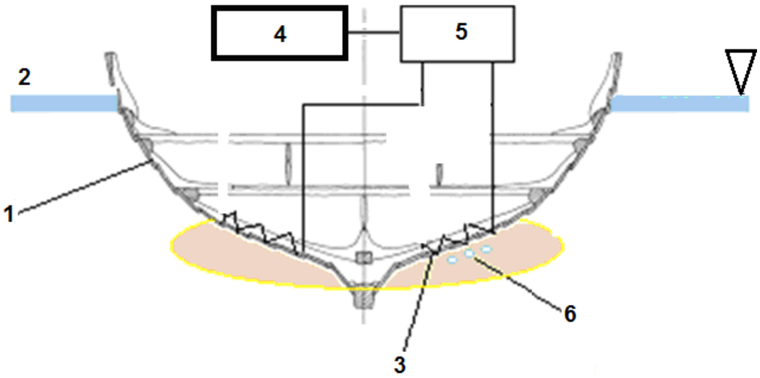

Fig. 2. General view of the analysed system (description in text)

The number of gas particles generated by the steam or electric heaters depended on the heating temperature specified by the control system, on the basis of information about the heater temperature and/or the outboard water temperature and/or vessel draft and/or vessel speed and/or depth of water area and/or swimming area, describing water salinity and the possibility for growth of living organisms as defined by the operator. The solution employs thermal energy provided by the heaters to generate steam using sea water, and extract air contained in the sea water in order to remove the lichen covering the hull, and to form a layer of gas (bubbles of steam and air) encircling the hull. By reducing hull resistance it is possible to obtain higher speeds in displacement ships, while reducing the amount of fuel used which, consequently, leads to a reduction in the amount of polluting substances produced as a result of fuel combustion and emitted by ships: CO_2, NO_X and SO_X. (Midor et al., 2018).

Function Modelling and Resources analysis

Analysis can be conducted for different stages of the life cycle, including in particular: production of raw materials, manufacturing of the system, transportation of the system, storage of the system, starting the system, operation of the system, system's maintenance by ship's crew, system's maintenance by divers, system's maintenance by shipyard in the dry dock, utilisation of the system, and recycling materials. This analysis was conducted for the system operation phase.

For the analysed system a function model was built, which is presented in Figure 3.

For the purpose of system modelling the following hierarchy of components was adopted:

1. The supersystem level of the analysed system:
   - "supersystem product" – ship's hull (including cavitation and temperature protective layer),
   - other supersystem components: operator, water, steam bubbles.
2. The analysed system: steam bubbles generator.
3. The subsystem level: control unit, supply unit, heaters.

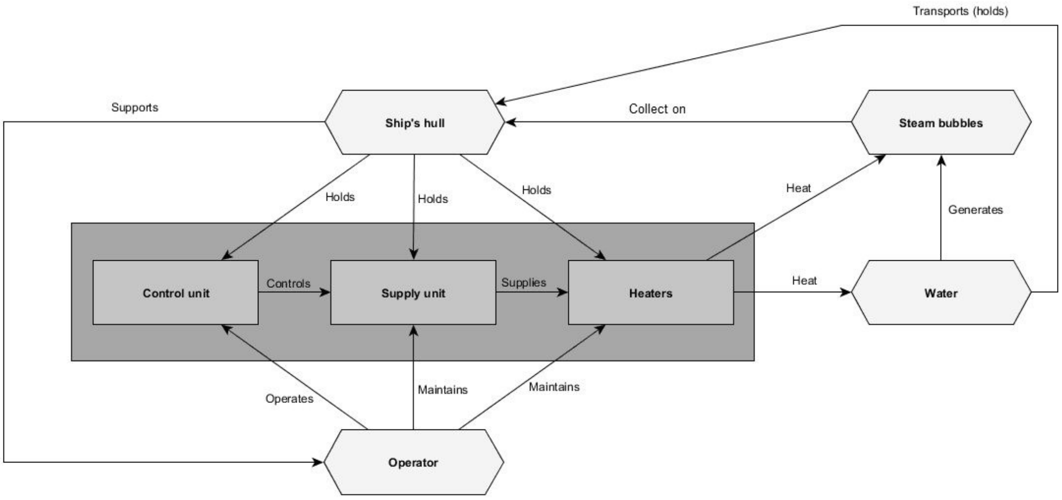

Fig. 3. Function model of the analysed system

For the analysed system, an analysis of resources, set out in Table 1, was conducted and the supersystem components were selected at the modelling stage.

Table 1
Function specific resources

Number	Category	Specific resources
1	Time	Operation time of heaters (life time) Intervals between bubbling Time from last maintenance Time to next maintenance Short operation time (voyage/trip time)
2	Space	Effective heat exchanging area of heaters Volume of steam bubbles zone Volume of machinery compartments Total hull volume
3	Substance / Materials	Metal Water (liquid) Water (steam bubbles) Semiconductors Plastics Air Hull coating
4	Energy	Electrical Thermal (heat) Mechanical (hull drag) Mechanical (propeller thrust) Mechanical (thrust deduction) Mechanical (water inertia) Mechanical (ship inertia) Mechanical (buoyancy) Mechanical (cavitation) Mechanical / acoustic (noise and vibrations) Gravity
5	Information	Heaters operational data (temperature, hull fouling etc.) Overboard water characteristics (density, temperature, air content etc.) Navigational information (water depth, drought, sheep speed etc.)
6	Additional functional	Human operations (maintenance)

Failures Identification

A list of potential direct failures, summarized in Table 2, was created for identified resources and system functions. In the next stage, potential indirect failures and accident-related failures, presented respectively in Tables 3 and 4, were sought.

Table 2
Identifying direct potential failures (function + resources)

Number	Function	Potential failures
1	Hull holds control unit	Heaters burned (overheated) Heaters heated only partly Heaters are out of control
2	Hull holds supply unit	
3	Hull holds heaters	Heater is lost
4	Control unit controls supply unit	Insufficient steam generation Over-generation of steam bubbles
5	Supply unit supplies heaters	Heaters are off Heaters burned (overheated)
6	Operator operates control unit	Operator shocked by electricity Heaters are out of control
7	Operator maintains supply unit	Operator shocked by electricity Heaters are out of control
8	Operator maintains heaters	Operator shocked by electricity Operator burned by heater Heaters are out of control
9	Heaters heat water	Heater is cracked (by thermal overloading)
10	Heaters heat steam bubbles	
11	Water generates steam bubbles	Bubbles damage hull due to cavitation
12	Steam bubbles collect on the hull	Bubbles generate wave effects which increases friction Bubbles generate wave effects which increases noise
13	Water transports (holds) the hull	Water floods into internal compartments of the hull
14	Hull supports operator	Loss of system supervision by the operator

Table 3
Identifying indirect potential failures

Number	Failure function	Potential failures
1	Ship's power plant failures (black-out)	System is temporarily out of service
2	Animals or humans enters the steam bubbles zone in the water	Death of human or animal in the water
3	Operator made mistakes while operating the system due to external circumstances	Operator shocked by electricity Operator burned by heater

Table 4
Identifying accident-related failures

Number	Non-planed change	Potential failures / accidents
1	Ship grounding	Serious mechanical damage of heaters (system down) Water floods into internal compartments of the hull

The results obtained are summarised in the final list of potential failures:

1. Heaters burned (overheated)
2. Heater is cracked (by thermal overloading)
3. Heaters heated only partly
4. Heaters are out of control
5. Heater is lost
6. Insufficient steam generation
7. Over-generation of steam bubbles
8. Operator shocked by electricity

9. Operator burned by heater
10. Bubbles damage hull due to cavitation
11. Bubbles generate wave effects which increases friction
12. Bubbles generate wave effects which increases noise
13. Water floods into internal compartments of the hull
14. Loss of system supervision by the operator
15. Death of human or animal in the water
16. Serious mechanical damage of heaters (system down)
17. System is temporarily out of service
18. Heaters are off

DISCUSION

Identified potential failure was evaluated by means of a multi-criteria analysis. Each type of failure was assessed on a scale from 0 to 1, in terms of 8 criteria which were the following:
C1 – Degree of probability
C2 – Degree of disrupting a process (process severity)
C3 – Degree of damage to humans
C4 – Degree of damage to a technical system (product severity)
C5 – Degree of damage to supersystem (except humans)
C6 – Degree of damage to environment
C7 – Relative total cost failure
C8 – Degree of reoccurrence under the same conditions
A comparison of the assessment results is presented in Table 5.

Table 5 Multi-criteria evaluation of identified failures

Failure / accident	C1	C2	C3	C4	C5	C6	C7	C8	Sum
Heaters burned (overheated)	0.5	0.8	0.0	1.0	0.0	0.0	0.6	0.8	**3.7**
Heater is cracked (by thermal overloading)	0.2	1.0	0.0	1.0	0.0	0.0	0.6	0.6	**3.4**
Heaters heated only partly	0.8	0.5	0.0	0.5	0.0	0.0	0.4	0.5	**2.7**
Heaters are out of control	0.5	0.5	0.0	1.0	0.0	0.0	0.2	0.5	**2.7**
Heater is lost	0.1	1.0	0.0	1.0	1.0	0.0	1.0	0.2	**4.3**
Insufficient steam generation	0.5	0.5	0.0	0.0	1.0	0.0	0.2	0.5	**2.7**
Over-generation of steam bubbles	0.1	0.0	0.0	0.0	1.0	0.0	0.0	0.2	**1.3**
Operator shocked by electricity	0.2	0.0	1.0	0.0	1.0	0.0	1.0	0.9	**4.1**
Operator burned by heater	0.1	0.0	1.0	0.0	1.0	0.0	1.0	0.8	**3.9**
Bubbles damage hull due to cavitation	0.8	0.0	0.0	0.0	1.0	0.0	0.8	1.0	**3.6**
Bubbles generate wave effects which increases friction	0.5	0.0	0.0	0.0	1.0	0.0	0.1	0.5	**2.1**
Bubbles generate wave effects which increases noise	1.0	0.0	0.2	0.0	1.0	1.0	0.1	0.8	**4.1**
Water floods into internal compartments of the hull	0.1	1.0	1.0	1.0	1.0	1.0	1.0	0.5	**6.6**
Loss of system supervision by the operator	0.9	0.5	1.0	0.5	1.0	0.5	0.6	0.9	**5.9**
Death of human or animal in the water	0.1	0.0	0.0	0.0	1.0	1.0	1.0	0.9	**4.0**
Serious mechanical damage of heaters (system down)	0.3	1.0	0.0	1.0	1.0	0.0	0.6	0.9	**4.8**
System is temporarily out of service	0.8	1.0	0.0	0.0	0.1	0.0	0.1	1.0	**3.0**
Heaters are off	0.5	1.0	0.0	0.0	0.1	0.0	0.1	1.0	**2.7**

The overall score-based assessment of fulfilment of the criteria C1-C8 allowed for the creation of a top 10 ranking of potential failures which are:

1. Water floods into internal compartments of the hull.
2. The system is not supervised by the operator.
3. There is serious mechanical damage of heaters (system down).

4. The heater is lost.
5. The operator is shocked by electricity.
6. Bubbles generate wave effects which increases noise.
7. Humans or animals die in the water.
8. The operator is burned by heater.
9. Heaters burned (overheated)
10. Bubbles damage hull due to cavitation.

CONCLUSION

The source literature features case studies describing the use of AFD for such systems as, among others, an automotive engine (Proseanic et al., 2000; Smith and Phadke, 2005), a cable (Zihui and Rong, 2010), a mountain expedition (Jensen and Aven, 2015a; Jensen and Aven, 2015b), a production platform (Jensen and Aven, 2015c), and an optical system (Sunday, 2014). In the conducted analysis, an evaluation was made of a system not yet in operation (a system in its conceptual phase). This approach can be applied to other systems with a low technology readiness level (Chybowski and Kuźniewski, 2016).

For the analysis of system failure tolerance, the xTRIZ algorithm described in section 3.3 was used, as it included all the previously mentioned elements. These elements include direct and indirect failure search (which was the basis for AFD-1 and AFD-2), as well as accident-related failures (which constitutes the main objective of the AFD-3 method). The xTRIZ approach combines system modelling, resource analysis, potential failure search and multi-criteria evaluation of the obtained results.

It should be noted that the presented approach is not limited to the use of one or other inventive methods (TRIZ methods of solving inventive problems and non-TRIZ methods), which means that it shares common elements with the integrated AFD. Various methods can be applied for this purpose (Derlukiewicz et al., 2016; Zusman and Smith, 2016). The analysis presented is part of a larger project, and the system under evaluation is the result of the application of ARIZ for finding methods of reducing fuel consumption in ships.

Searching for potential failure can be supported by means of specialised software such as the aforementioned Ideation Failure Analysis™ and Ideation Failure Prediction™ (Kaplan et al., 1999), as well as on the basis of different physical chemical, biological, geometrical, and even psychological effects (AULIVE, 2017; Bejger and Gawdzińska, 2011; Boratyńska-Sala, 2016; Oxford Creativity 2017; Pajor et al., 1999; Zaplata and Pajor, 2016; Zolkiewski 2013).

The ranking of the identified failures can also be made using various methods, including in addition to the aforementioned assessment matrix, a weighted average as well as methods based on direct comparisons of failure-related values of individual assessments, and the importance of individual evaluation criteria. Particularly useful here is the Analytical Hierarchy Process (AHP) method, which was successfully applied as a tool supporting TRIZ (Chybowski et al. 2017).

The direction of further development for AFD seems to be its use in the assessment of the quality of products and the structure of advanced materials, as a supplement to methods currently used (Biały 2014; Cempel, 2013; Chybowski, 2017b; Gawdzińska et al., 2016).

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