Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2017, 52 (124), 137–144
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/255

Received: *20.10.2017*
Accepted: *04.12.2017*
Published: *15.12.2017*

Selected issues regarding achievements in component importance analysis for complex technical systems

Leszek Chybowski✉**, Katarzyna Gawdzińska**

Maritime University of Szczecin, Faculty of Marine Engineering
1-2 Wały Chrobrego St., 70-500 Szczecin, Poland
e-mail: {l.chybowski, k.gawdzinska}@am.szczecin.pl
✉ corresponding author

Key words: importance analysis, complex system, human-machine interfaces, machinery, quality criteria, multi-criteria analysis

Abstract

Selected issues of component importance analysis for complex technical systems have been presented in this paper. A generic example of a complex technical system and selected statistics of operating losses have been described. A description and diagrams of both qualitative and quantitative importance analysis have also been included. The most significant problems facing complex technical system modelling have been pointed out. A multi-criteria system component importance analysis and the basic criteria for a system component quality evaluation have also been introduced. Some factors influencing the importance of the technical system's components have also been described. Finally, the necessity of further developing importance analysis methods for machinery operation has been highlighted.

Introduction

The main goal of this paper was to demonstrate the present state-of-the-art and also new developments in terms of applying the multi-criteria analysis of component importance to evaluate the operation of complex technical systems (CTS) under risk and uncertainty. The system's operating characteristics have been introduced and the system's interactions with the environment have been described. The proposed methods will enable the selection of important criteria that will be made at the very beginning of the system analysis (Chybowski & Gawdzińska, 2016a; 2016b).

A chain, which is only as reliable as its weakest link, is the symbol of reliability and safety for a technical system consisting of many elements/subsystems. This model, however, is seldom true for today's machinery where elements that compose a whole are not connected in series, but make up a complex multifunctional structure (Andrews, 2008; Sun et al., 2008; Żurek, Zieja & Smalko, 2012). Moreover, it is all too often the case that the "weak links", that different evaluation criteria reveal, are not always the most important element in regard to sustaining the proper quality of the operational process. Good reliability of technical systems is certainly a precondition for their safe and effective exploitation (Espiritu, Coit & Prakash, 2007; Bajkowski & Zalewski, 2014; Goerlandt & Montewka, 2016).

There is often a need to increase the reliability of a system, which can be achieved by modifying the system structure, or improving the reliability of selected components (Grzebieniak & Chybowski, 2006b; Reliasoft, 2007; Chybowski, 2009; Derlukiewicz, Ptak & Koziołek, 2016). Reliability theory concentrates on intact system operation, and allows for the estimation of measured values that describe the absence of susceptibility to damage, availability, and exploitation safety (Woropay, 1983; Żółkiewski, 2011; Kuo & Zhu, 1012). With regard to a system, basic dependability measures are important information for intact system operation.

However, these measures only give very general information about the vulnerability of system components and, except for a series reliability structure, are unable to describe the impact of a component on the whole system. A component's impact on the system (i.e. the system's tolerance for component failure) is connected with both the component's dependability characteristics and with the system's structure of where a particular component is located during a given operational state (Chybowski & Gawdzińska, 2016b; Gawdzińska et al., 2016).

For example, in waterborne transport, applying modern technical solutions to improve exploitation safety (e.g. by introducing so called unmanned engine rooms) has resulted in increased construction complexity of a power plant, but has also resulted in its greater reliability and durability. Additionally, progress in materials science and engineering (Gawdzińska, Chybowski & Przetakiewicz, 2015; Gawdzińska et al., 2016) has given rise to new methods for technical diagnostics, and improved maintenance procedures have greatly contributed to greater ship reliability and durability and have reduced idle time in a ship's operation (mean time to repair). This, in turn, has extended the mean time between failures and decreased the overall costs of spare parts during a ship's operation.

Importance criteria

Criteria relevance refers to the selection of importance criteria and determining their weight coefficients in order to calculate a given importance measure. This approach is useful in the first stage of importance evaluation for a system's components (Karanta, 2011). Considering the process quality factor, the characteristics connected with criteria relevance (from (Kolman, 1994)) have been pointed out in Table 1.

Reliability importance analysis is aimed at determining which system component is the most important for the system's operation, considering an optimal value of a given reliability measure (e.g. which component most affects the system availability, expected time-to-failure, or which component will most likely bring about the system breakdown).

If $\Phi(f)$ is a numerical function of the system state which represents a given number for every function f of function space, then checking if the value of $\Phi(f)$ is within the arranged interval $[a,b]$ of the allowed variables is considered an importance evaluation criterion (Woropay, 1983):

$$a \le \Phi(f) \le b \tag{1}$$

Table 1. A set of universal importance criteria (Kolman, 1994)

No.	Name	The criterion informs on:
1	Safety	Protection of or threat to life or health
2	Benefit	Gained benefits or achieved effects
3	Cost	Incurred costs
4	Reliability	Reliability, susceptibility to breakdown, or absence of operation efficiency
5	Novelty	Novelty, fashion, or time factors
6	Effectiveness	Proper task fulfilment
7	Exactness	Purpose and compatibility of application
8	Usability	Durability, running hours, and operation time
9	Faultiness	Flaws, faults, and fidelity
10	Appearance	Shape harmony, colour, aesthetic impressions

The term *importance* is closely connected with *sensitivity* and sometimes they are used interchangeably in the professional literature. In (Karanta, 2011), sensitivity is defined as a partial derivative of the reliability function R with respect to the reliability r_i of the *i-th* system component. This definition is called Birnbaum's reliability importance measure:

$$P_i^D = \frac{\partial R}{\partial r_i} \tag{2}$$

According to this relation, a component's importance is dependent on two basic factors:

- the system components' reliability characteristics;
- the system reliability structure.

In the presented approach, the more important the component is, the less susceptible it is to damage, and the more its location in the reliability structure resembles an independent component in the series reliability structure. This thesis has not been confirmed because, as stated at the beginning, in order to comprehensively evaluate the components' importance it is necessary to determine the consequences of their failure. For instance, the crankshaft of a combustion engine has very good reliability, but when it fails the engine is put out of use for a reasonably long time, which qualifies this component as very important. Hence, a CTS components' importance depends on (Chybowski, 2012; Chybowski, 2014):

- the reliability characteristics of system components;
- the system's reliability structure;
- the results of system components' failure.

Sensitivity analysis

The system sensitivity analysis (failure tolerance of the system), including component importance analysis in the structure of complex technical systems, is interdisciplinary and is part of fundamental research, more precisely – system theory. It is also tackled by reliability theory, safety theory, exploitation theory, and economics (Chybowski, 2004; Rausand & Høyland, 2004; Zanoli, Astolfi & Marczyk, 2012).

Component importance analysis is strictly connected to system sensitivity evaluation consisting of (Ziemba, Jarominek & Staniszewski, 1980):

- separating the parameters (factors) for which a small change of the value results in a big change of the value for external characteristics;
- studying the influence of sensitive parameters on the system effectiveness, by verifying the influence of these parameters on the system characteristics;
- forced modification of harmful sensitivity influence and exposing useful sensitivity by changing the system structure.

A general index of system quality *I*, described by elements of set *W* in time *T* can be expressed by (Ziemba, Jarominek & Staniszewski, 1980):

$$\begin{aligned} I(\overline{W},T) = & \int_0^T \rho_1(\overline{W},\theta)[\Delta f_1(\overline{W},\theta,t)]^{\chi_1}\,\mathrm{d}t + \\ & + \int_0^T \rho_2(\overline{W},\theta)[\Delta f_2(\overline{W},\theta,t)]^{\chi_2}\,\mathrm{d}t + \ldots + \\ & + \int_0^T \rho_m(\overline{W},\theta)[\Delta f_m(\overline{W},\theta,t)]^{\chi_m}\,\mathrm{d}t \end{aligned} \tag{3}$$

where:

t – short time, understood as an independent variable of the system's operation dynamics;

θ – long time, understood as an independent variable of the system's development process.

Note that:

$$\begin{aligned} &\Delta f_1(\overline{W},\theta,t) = f_{01}(\overline{W},\theta,t) - f_1(\overline{W},\theta,t), \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ &\Delta f_m(\overline{W},\theta,t) = f_{0m}(\overline{W},\theta,t) - f_m(\overline{W},\theta,t), \end{aligned}$$

There are many kinds of sensitivity, including parameter, structural, structural and parameter, exploitation, and dynamic sensitivity. Structural and parameter sensitivity describes the influence of the size and quantity of components on system characteristics. The index (1) can be written as:

$$\begin{aligned} I(\overline{W},\theta,t) = & \sum_{i=1}^{i=n_1}\int_0^T \rho_1(\overline{W},t)[\Delta f_i(\overline{W},\theta,t)]^{\chi_i}\,\mathrm{d}t + \\ & + \sum_{i=1}^{i=n_2}\int_0^T \rho_1(\overline{W},t)[\Delta f_i(\overline{W},\theta,t)]^{\chi_i}\,\mathrm{d}t + \\ & + \sum_{i=1}^{i=n_3}\int_0^T \rho_1(\overline{W},t)[\Delta f_i(\overline{W},\theta,t)]^{\chi_i}\,\mathrm{d}t \end{aligned} \tag{4}$$

The particular summands of the formula (3) successively describe the quality of system components, the relations of quality between components, and the sum of the integrals expressing the quality of the components and the relations between them.

The present state-of-the-art of component importance analysis for complex technical systems has been shown in the following sections. Additionally, the necessity of further development of importance analysis methods for machinery operation has been presented.

Problems in importance analysis

The system reliability structure depends on (Chybowski, 2014):

- the system composition level assumed for the analysis and the method of its division into elements;
- the functional relations between system components;
- the criteria taken to assume that a given component or system technical condition is in a down state;
- the function performed by the system.

Every reliability structure could be represented by means of sets of characteristic system components, referred to as minimal cut-sets (system failure oriented analysis) or minimal path-sets (system intact oriented analysis). Some structures are not useful for the CTS analysis, because of the existence of the so-called *passive components* (i.e. the ones that do not affect the reliability system state). The structures containing passive components might be reduced because, for the description of the system components state and the whole system state, the function of the argument number that is lesser than the total number of components is sufficient (Woropay, 1983).

Among the reduction-resistant structures, we can indicate the ones where component restoration might cause system failure or system restoration. Such structures, known as "incoherent" in the published literature (Gomes & Awruch, 2002; Grzebieniak & Chybowski, 2005; 2006a; Chybowski, 2014), hardly ever exist and are not applied to a prevailing number of technical objects. For that reason, in the following work only coherent structures have been considered.

CTSs, such as a marine power plant, are difficult to describe because:

- they are renewable or partly renewable;
- their functional and reliability structure is time-dependent;
- they are complex, have a hierarchical structure, and have multilevel feedback;
- their failures are partly or totally dependent on each other;
- their response to a determined range and character of inputs and disturbances is known;
- they have many kinds of reservation (redundancy relations are unknown and form overlapping sets);
- their reliability structure is often completely or mostly unknown, despite the existence of known and selected basic functional components.

System importance measures have been introduced to describe the influence that the change of the system component reliability state has on the whole system reliability state (Espiritu, Coit & Prakash, 2007; Kuo & Zhu, 2012). During the analysis of the technical system reliability, an analyst usually concentrates on identifying the most sensitive components whose reliability must be improved to optimally increase the reliability of the whole system (component importance measures). The measures may be determined depending on:

- the system structure (Figure 1a) – qualitative measures (e.g. minimal cut set order, Birnbaum's structural importance measure);
- the system structure and system components reliability characteristics (Figure 1b) – quantitative measures (e.g. Birnbaum, Bergman, Lambert, Natvig, Barlow-Proshan or Vessely-Fussell reliability measures etc.).

As depicted in the presented chart of the technical system analysis (Figure 1), the reliability structure and reliability models of the components of the system (which together form the reliability model of the system) are acquired through the process of identification and system modelling. The next step is the selection of quantitative importance measures and their application to the system model, as well as qualitative importance measures and their application to the system structure model. Information on the reliability features of the components and the consequences of the damage is acquired through a reliability database search and experts' knowledge. As a result of the analysis, estimates of selected importance measures as well as a ranking of system component importance for each importance measure can be determined. Based on the acquired results, conclusions are then drawn on the construction of the analysed technical system and the effectiveness of the system operating procedures.

Analogically, the minimal cut-set importance is considered (local importance measures). It relates to searching for the so called "weak links" in the system (i.e. the most unreliable components and components groups), which is called importance analysis. Importance measures express the reliability criterion as fundamental, so they do not directly express failure consequences for exploitation safety and maintenance costs (searching for "weak links" (Woropay, 1983; Borgonovo & Apostoloakis, 2001; Borgonovo et al., 2003). The authors' scientific interests have been concentrated on component importance analysis and simultaneous evaluation of failure consequence for selected criteria.

Although reliability theory goes back a hundred years, the concept of reliability (in terms of its quality) has accompanied human civilization for a very long time. It has resulted from the fact that it is very important to determine if the activities undertaken were successful or not (Chybowski, 2014). In this sense, reliable operation of CTS, such as a marine power plant and its subsystems, is a priority. Modern ships must meet the growing demands of the goods market. Meeting the demands more efficiently means that larger quantities of goods can be transported over longer distances in shorter periods of time, with the possibility of shorter ship loading and unloading periods. Simultaneously, the necessity to minimize ship maintenance costs has resulted in the reduction of ship's crews which has in turn brought about the necessity to implement additional automated systems, ensuring the continuity and safety of the ship exploitation process.

Due to the limited applicability of reliability importance measures and the earlier specified characteristics of complex technical systems, it has been necessary to develop methods to single out a set of important components in the system for selected importance criteria.

One of the methods of acquiring knowledge about the system is the utilization of expert methods, including the application of subjective probability. Publications, which have taken an interest in the importance evaluation as a subject of research, used simple theoretical systems containing independent events and introduced elementary interactions with the environment.

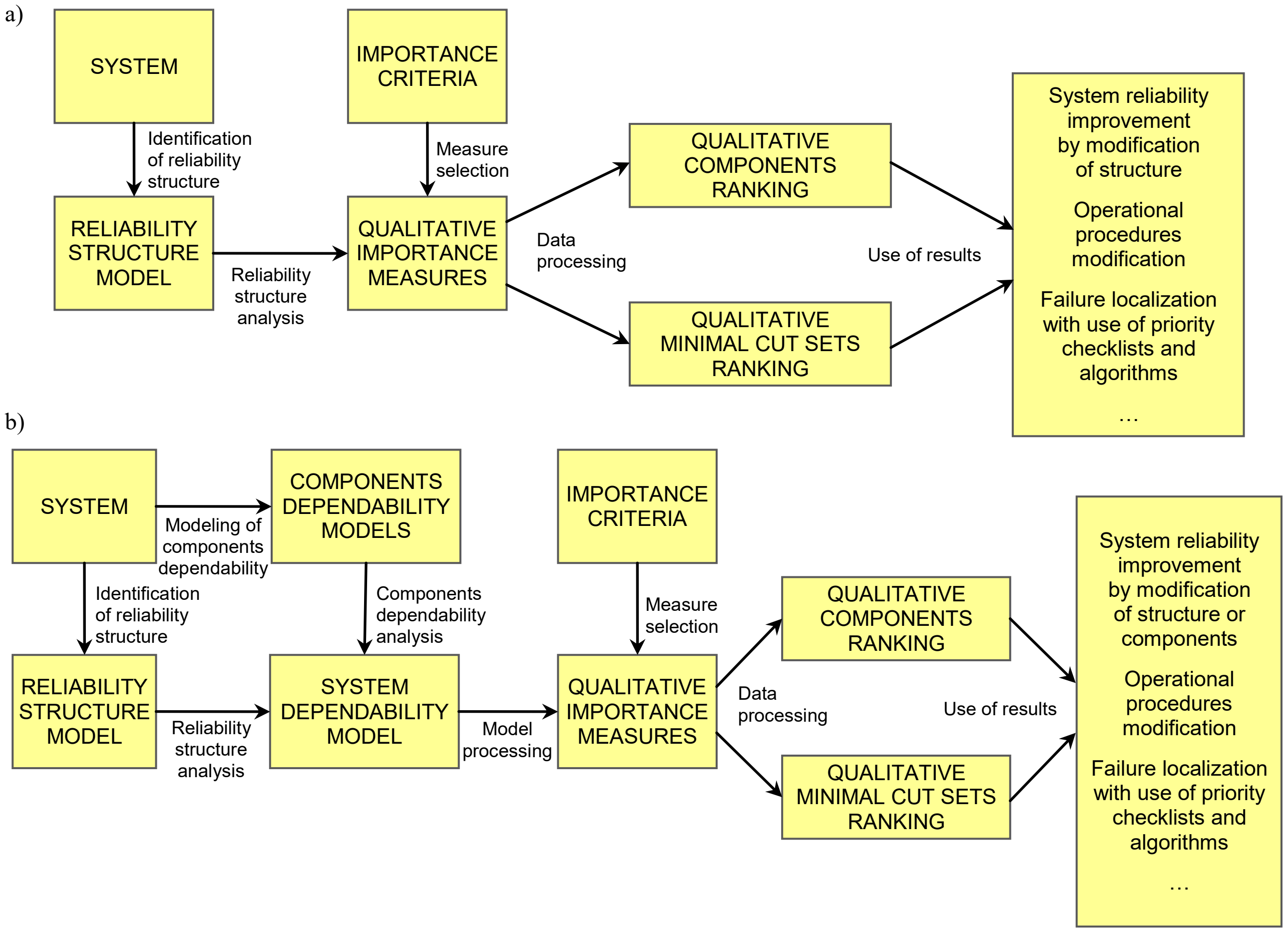

Figure 1. Process of the component importance, and component group, evaluation in the system reliability structure (Chybowski, 2014): a) qualitative analysis, b) quantitative analysis

The results of the initial tests shown in the work (Chybowski & Gawdzińska, 2016a) have demonstrated the lack of a sufficiently accurate importance evaluation of components and groups of components in CTS reliability structure, with exclusive use of either a quantitative or qualitative method. This research was initiated with the purpose of developing applied methods, which would allow a far more effective analysis of CTS component importance than the methods that have been applied so far (Chybowski & Gawdzińska, 2016b). Without the information about the durability of the components and the consequences of the damage, it is possible to acquire the missing data on the system exploitation by surveying experts (Figure 2).

In the proposed scheme, the experts' knowledge serves to determine the relative importance of the importance evaluation criteria as well as to determine the importance of the system components for the assigned criteria (Belton & Gear, 1983; Belton, 1986; Satty, 1990; 1994; Belton & Goodwin, 1996). The analyst's task in the process is to indicate the criteria of the analysis and to draw

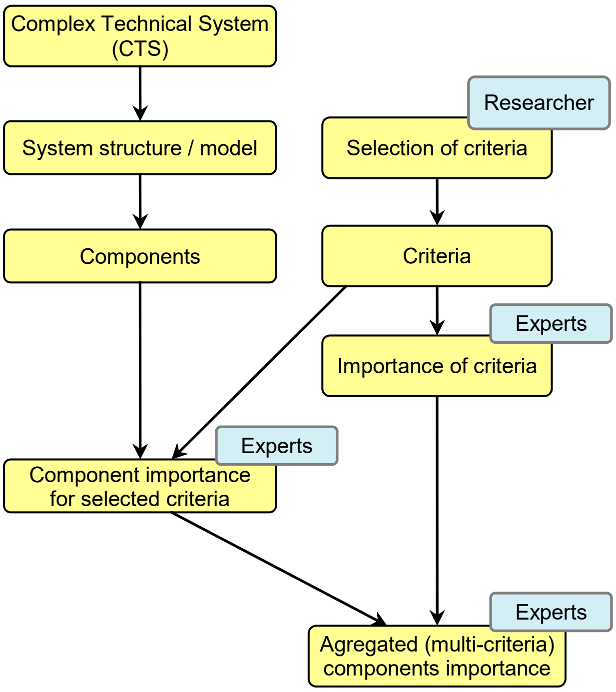

Figure 2. Multiple-criteria of the component importance evaluation process with incomplete information about the system (Chybowski, 2014)

final conclusions from the component importance evaluation.

Conclusions

The methods presented here can be used in the process of designing new systems, as well as modifying operating procedures for existing systems (technical condition assessment of the system as well as developing maintenance procedures to increase reliability). The subject of the system component importance analysis has many aspects and the authors believe that it is necessary to continue research in this field. Further efforts should provide for the development of new, more accurate and more effective evaluation of the effects of the seamless functioning of system components on the broadly defined environment (Ogryczak, 2004; Peng et al., 2011).

It has been assumed that the fundamental character of the issues elucidated in this publication allows for extrapolation of the presented methods to other branches of industry. In terms of CTS (including marine propulsion systems), the developed measures and methods generate utilitarian results by:

- supporting CTS management staff in evaluating the new implemented equipment review schedules as well developing new, more efficient schedules;
- supporting CTS operators with diagrams, charts, priority checklists, and exploitation procedures that were created based on the evaluation results of the component importance in the system reliability structure.

The research that has been conducted has facilitated data acquisition for component damage of the analysed systems, as well as reliability estimation, and engine system preparedness. Rankings have also been created through various methods and for different system importance criteria. The analyses were conducted with the use of specialist software (Synthesis 9 by ReliaSoft: Reliability Workshop 10 and IsoLib by Isograph; CARA Fault Tree 4.1. Academic Version by Sydvest Software), owned by the Institute of Marine Propulsion Plants Operation, Department of Mechanics at the Maritime University of Szczecin. Moreover, special software programs were used; “Ważność” (importance) and AHP, which were specifically designed for the needs of this project. Comparative analyses carried out during the research were conducted with the use of an MS Excel spreadsheet file. The collected material allowed for the creation of a special system that supported decision-making in CTS exploitation; however, a more detailed analysis is needed, which would use a larger number of criteria, including the criteria of reliability, safety, cost-effectiveness, energy efficiency, and maintainability (availability of spare parts and servicing staff).

The focus of this work was extremely wide and has left sufficient room for further research. The methodology developed and presented in (Chybowski, 2014) should be further enriched by the application of different methods identified through the decision-making theory (Dyer, 1990; Downowicz et al., 2000; Cebeci & Ruan, 2007; Dehghanian et al., 2012; Chang & Wang, 2016). The analysis can also be further extended by the application of a larger number of importance criteria. The methods of multiple-criteria importance analysis constitute a helpful tool in processing a large amount of operation data produced by modern CTSs, which are increasingly automated and better equipped with sensors. It can also prove useful to apply modern technological achievements of engineering and systems theories, like the theory of complexity, hybrid optimization methods (Rosenberg & Twardochleb, 2010; Pietruszkiewicz, Twardochleb & Roszkowski, 2011), and modern machine diagnostics systems (Krile & Kos, 2001; Żółkiewski, 2010; Zalewski & Szmidt, 2014; Ptak & Konarzewski, 2015; Wiśniewski & Dyrda, 2016).

The direction of the research in this field should therefore now turn to the use of the previously described methods for a multiple-criteria CTS component importance evaluation in the reliability structure of these systems, as well inclusion of a human factor as an element of the Complex Technical Systems.

Acknowledgments

The research presented in this article was carried out under the Grant NCN 2011/01/D/ST8/07827: “Importance analysis of components in the reliability structure of complex technical systems illustrated by a marine power plant.” The publication was financed through a research grant from the Ministry of Science and Higher Education of Poland 1/S/IESO/17: “Increasing operational effectiveness of complex technical systems by systematic development and implementation of innovations using novel materials and modifying the object’s structure”.

References

1. Andrews, J.D. (2008) Birnbaum and criticality measures of component contribution to the failure of phased missions. *Reliability Engineering and System Safety* 93, pp. 1861–1966.

2. Bajkowski, J.M. & Zalewski, R. (2014) Transient response analysis of a steel beam with vacuum packed particles. *Mechanics Research Communications* 60, pp. 1–6.
3. Belton, V. & Gear, T. (1983) On a short-coming of Saaty's method of analytic hierarchies. *Omega* 11, pp. 228–230.
4. Belton, V. (1986) A comparison of the analytic hierarchy process and a simple multi-attribute value function. *European Journal of Operational Research* 26, pp. 7–21.
5. Belton, V. & Goodwin, P. (1996) Remarks on the application of the analytic hierarchy process to judgmental forecasting. *International Journal of Forecasting* 12, pp. 155–161.
6. Borgonovo, E. & Apostolakis, G.E. (2001) A New importance measure for risk-informed decision making. *Reliability Engineering and System Safety* 72, pp. 193–212.
7. Borgonovo, E., Apostolakis, G.E., Tarantola, S. & Saltelli, A. (2003) Comparison of global sensitivity analysis techniques and importance measures in PSA. *Reliability Engineering and System Safety* 79, pp. 175–185.
8. Chang, T.-C. & Wang, H. (2016) A self-testing cloud model for multi-criteria group decision making. *Engineering Computations* 33, 6, pp. 1767–1783.
9. Cebeci, U. & Ruan, D. (2007) A multi-attribute comparison of Turkish quality consultants by fuzzy AHP. *Int. J. Info. Tech. Dec. Mak.* 06, 01, pp. 191–207.
10. Chybowski, L. (2004) *Szacowanie niegotowości wybranych systemów siłowni okrętowej obiektów pływających specjalnego przeznaczenia*. Materiały XXV Sympozjum Siłowni Okrętowych SymSO 2004. WOiO Politechnika Gdańska, Gdańsk, pp. 5–18.
11. Chybowski, L. (2009) Application of External Events Vectors for Defining Reliability Structure of Fishing Vessels power, Propulsion and Technological Plant. *PJoES* 18, 2A, pp. 45–50.
12. Chybowski, L. (2012) *Example of Comprehensive Qualitative-Quantitative Reliability Importance Analysis of Complex Technical Systems on a Marine Propulsion Plant*. IARS 2012, Symposium Proceedings, Reliasoft Corporation, Warszawa, book session 7/track 2 + CD ROM.
13. Chybowski, L. (2014) *Ważność elementów w strukturze złożonych systemów technicznych*. Radom – Szczecin: ITE-PIB.
14. Chybowski, L. & Gawdzińska, K. (2016a) On the Present State-of-the-Art of a Component Importance Analysis for Complex Technical Systems. *Advances in Intelligent Systems and Computing* 445, pp. 691–700.
15. Chybowski, L. & Gawdzińska, K. (2016b) On the Possibilities of Applying the AHP Method to a Multi-criteria Component Importance Analysis of Complex Technical Objects. *Advances in Intelligent Systems and Computing* 445, pp. 701–710.
16. Dehghanian, P. et al. (2012) Critical Component Identification in Reliability Centered Asset Management of Power Distribution Systems Via Fuzzy AHP. *IEEE Systems Journal* 4, pp. 593–602.
17. Derlukiewicz, D., Ptak, M. & Koziołek, S. (2016) Proactive failure prevention by human-machine interface in remote-controlled demolition robots. *New Contributions in Information Systems and Technologies: Advances in Intelligent Systems and Computing* 445, pp. 711–720.
18. Downowicz, O., Krause, J., Sikorski, M. & Stachowski, W. (2000) Application of AHP Method for Evaluation and Safety Control of a Complex Technical System. In: Downorowicz O. (Ed.) *Wybrane metody ergonomii i nauki o ekspoloatacji*. Gdańsk: Politechnika Gdańska, pp. 7–42 (in Polish).
19. Dyer, J.S. (1990) Remarks on the analytic hierarchy process. Management Science 36, pp. 249-258.
20. Espiritu, J.F., Coit, D.W. & Prakash, U. (2007) Component criticality importance measures for the power industry. *Electric Power Systems Research* 77, pp. 407–420.
21. Gawdzińska, K., Chybowski, L. & Przetakiewicz, W. (2015) Proper matrix-reinforcement bonding in cast metal matrix composites as a factor of their good quality. *Archives of Civil and Mechanical Engineering* 16(3), pp. 553–563.
22. Gawdzińska, K., Chybowski, L., Bejger, A. & Krile, S. (2016) Determination of technological parameters of saturated composites based on sic by means of a model liquid. *Metalurgija* 55, 4, pp. 659–662.
23. Goerlandt, F. & Montewka, J. (2014) *Review of risk concepts and perspectives in risk assessment of maritime transportation*. Proceedings of The European Safety And Reliability Conference (ESREL), Wrocław, pp. 1547––1554.
24. Gomes, H.M. & Awruch, A.M. (2002) Reliability of reinforced concrete structures using stochastic finite elements. *Engineering Computations* 19, 7, pp. 764–786.
25. Grzebieniak, R. & Chybowski, L. (2005) Testy diagnostyczne, grafy wiązań i równania stanu jako narzędzia oceny stanu technicznego urządzeń. *Scientific Journals of the Maritime University of Szczecin, Zeszyty Naukowe Akademii Morskiej w Szczecinie* 5 (77), pp. 247–255.
26. Grzebieniak, R. & Chybowski, L. (2006a) Wykorzystanie testów diagnostycznych zbudowanych metodą macierzy booleowskich do oceny stanu technicznego systemu smarowania silnika głównego. *Zeszyty Niezawodność i Efektywność Systemów Technicznych*. KGTU, Kaliningrad, pp. 79–85.
27. Grzebieniak, R. & Chybowski, L. (2006b) Opis wybranego systemu siłowni okrętowej grafami wiązań. *Zeszyty Niezawodność i Efektywność Systemów Technicznych*. KGTU, Kaliningrad, pp. 86-90.
28. Karanta, I. (2011) *Importance measures for the dynamic flowgraph methodology. CHARISMA Project*. Research report VTT-R-00525-11, Helsinki.
29. Kolman, R. (1994) *Sterowanie jakością wytwarzania*. Gdańsk: Politechnika Gdańska.
30. Krile, S. & Kos, M. (2001) *A heuristic approach to satellite link capacity planning applied in mobile networks*. ITI 2001: Proceedings of the 23rd International Conference on Information Technology Interfaces, Pula, pp. 331–338.
31. Kuo, W. & Zhu, X. (2012) *Importance measures in reliability, risk, and optimization. Principles and application*. John Wiley & Sons, Ltd.
32. Ogryczak, W. (2004) *Decision making under risk.* Monograph course, textbook, Warsaw University.
33. Peng, Y. et al (2011) Ensemble of software defect predictors: an AHP-based evaluation method. *Int. J. Info. Tech. Dec. Mak.* 10, 01, pp. 187–206.
34. Pietruszkiewicz, W., Twardochleb, M. & Roszkowski, M. (2011) Hybrid approach to the computational support of decision making in business. *Control and Cybernetics* 40, 1.
35. Ptak, M. & Konarzewski, K. (2015) Numerical Technologies for Vulnerable Road User Safety Enhancement. *New Contributions in Information Systems and Technologies: Advances in Intelligent Systems and Computing* 354, pp. 355–364.
36. Rausand, M. & Høyland, A. (2004) *System Reliability Theory: Models, Statistical Methods, and Applications*. John Wiley & Sons.

37. Rozenberg, L. & Twardochleb, M. (2010) Hybrid optimization approach for effective quasi-optimization solutions. *Methods of Optimisation and Data Analysis*. University of Szczecin, Faculty of Economics and Management, Szczecin, pp. 31–43.
38. Saaty, T.L. (1990) How to Make a Decision: The Analytic Hierarchy Process. *European Journal of Operational Research* 48, pp. 9–26.
39. Saaty, T.L. (1994) *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*. Pittsburgh: RWS Publications.
40. Sun, Y. et al. (2008) Safety risk identification and assessment for Beijing Olympic venues construction. *Journal of Management in Engineering* 24(1), pp. 40–47.
41. RELIASOFT (2007) *System Analysis Reference. System Reliability, Maitainability, Availability, Throughput and Optimization Analysis*. Tucson.
42. Wiśnicki, B. & Dyrda, A. (2016) Analysis of the Intermodal Transport Efficiency in the Central and Eastern Europe. *OUR SEA: International Journal of Maritime Science & Technology* 63, pp. 43–47.
43. Woropay, M. (1983) *Metoda budowy wielopoziomowych systemów do badania niezawodności z elementów o wyznaczonej a piori istotności*. Rozprawy nr 18. Bydgoszcz: ATR.
44. Zalewski, R. & Szmidt, T. (2014) Application of Special Granular Structures for semi-active damping of lateral beam vibrations. Engineering Structures 65, pp. 13–20.
45. Zanoli, S.M., Astolfi, G.J. & Marczyk, J. (2012) Complexity-based methodology for Fault Diagnosis: application on a centrifugal machine. *Analysis and Control of Chaotic Systems* 3, Part 1. Cancún.
46. Ziemba, S., Jarominek, W. & Staniszewski, R. (1980) *Problemy teorii systemów*. Wrocław: Ossolineum.
47. Żółkiewski, S. (2010) Dynamic Flexibility of Complex Damped Systems Vibrating Transversally in Transportation. *Solid State Phenomena* 164, pp. 339–342.
48. Żółkiewski, S. (2011) Damped Vibrations Problem of Beams Fixed on the Rotational Disk. *International Journal of Bifurcation and Chaos* 21, 10, pp. 3033–3041.
49. Żurek, J., Zieja, M. & Smalko, Z. (2010) *The Reliability Estimation of Structural Components with Some Selected Failure Model*. PSAM11 & ESREL, Helsinki.