Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2022, 72 (144), 77–85
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/536

Received: *19.09.2022*
Accepted: *29.09.2022*
Published: *31.12.2022*

Comparison of selected models useful in ranking the root causes of explosions in marine engine crankcases

Daniel Wiaterek[1], Leszek Chybowski[2]

[1] https://orcid.org/0000-0003-3663-1042
[2] https://orcid.org/0000-0003-0245-3946

[1] Maritime University of Szczecin, Innovation Centre SPV (CIAM Sp. z o.o.)
9/102 Starzyńskiego St., 70-506 Szczecin, Poland
[2] Maritime University of Szczecin, Faculty of Marine Engineering
1-2 Waly Chrobrego St., 70-500 Szczecin, Poland
e-mail: l.chybowski@pm.szczecin.pl
corresponding author

Keywords: marine diesel engine, main engine, prime mover, crankcase explosion, process modelling, root causes

JEL Classification: L62, L90, L92, R41

Dataset: https://zenodo.org/record/6990607 (DOI: 10.5281/zenodo.6990607)

Abstract

This article aims to compile, describe and compare three different models taken from the literature describing the causes of explosions in the crankcases of marine engines. Each of the models has a different level of detail and was prepared with a different purpose. However, the same process, explosions in crankcases, was analyzed in all cases. A statistical evaluation of the frequency of events leading to explosions, a model built using failure mode and effects analysis (FMEA) and a model based on fault tree analysis (FTA) are described in turn. The FTA model drawn from the literature formed the basis for further analysis. Values of important measures of all elementary events of the fault tree were calculated using the Birnbaum reliability measure, Vesely-Fussell measure, Birnbaum structural measure, criticality measure and improvement potential. The percentage importance values of all events determined using these importance measures were compared. The results obtained from the application of each model were evaluated. The results of the models were compared with each other, and an approach using all three models supplemented with diversion analysis was proposed.

Introduction

System analysis methods are divided into inductive and deductive. Inductive methods (bottom-up methods) are based on a detail-to-general approach, i.e. analysis from the bottom (base events) to the top (peak events), while deductive (top-down methods) are based on the opposite approach, i.e. from top to bottom.

Inductive methods are used in determining the states of the system that may exist; they are usually used in the preliminary analysis of system performance. Deductive methods, on the other hand, lead to the development, based on general knowledge, of special cases, to the search for root causes – events whose combinations lead to the occurrence of the postulated situation (state of the system) (Chybowski, 2017).

Deductive methods in relation to problem scenarios are referred to as root cause analysis (RCA) methods, and they help in the in-depth analysis of a problem by leading from the general to the specific, i.e. from the assumed postulated state of a system to the events that may occur during its operation, the combination of which leads to the occurrence of a certain state of the system. An event is defined as any change in the structure or functioning of an object, while a state is the set of all characteristics of an object at a given moment *t*.

RCA methods follow an established workflow that consists of the following steps:

1. Define the problem.
2. Gather data.
3. Identify potential causal factors.
4. Identify the root causes of the problem.
5. Draw conclusions and give recommendations.

Among the most used methods of analysis aimed at assessing hazards and risks during the operation of industrial facilities are the tools shown in Table 1.

The methods listed in Table 1 can provide qualitative evaluation (descriptive characteristics, often derived from the analyst's individual experience and historical data) and/or quantitative evaluation (they use specific measures such as the probability of damage or operator error). Quasi-quantitative methods, on the other hand, use scales to provide quantitative information to rank individual events by importance.

The different methods have their own advantages and disadvantages and a dedicated range of applications, as shown in our selection of three models presented in the literature that can be used to assess the root causes of disasters.

One of the most dangerous events that can occur during the operation of marine engines, an explosion in the crankcase, was chosen as the target of analysis and modelling.

Sequence of events leading to crankcase explosions

For a description of the circumstances leading up to crankcase explosions, see (Chybowski, 2022). A temperature rise is required to initiate an explosion, which can be either general, when the entire crankcase is affected, or local, in the form of a so-called hot spot (Włodarski, 1998). When crank-piston components are damaged, such as by galling of the main bearing, or when contact is made with a heat source located outside the crankcase (a fire in the sub-piston space or in the power plant), vaporization of the oil in contact with the hot spot occurs when the temperature exceeds about 200°C (Valčić, n.d.). Evaporating oil circulates in the crankcase (Burgoyne & Cohen, 1954). As oil vapor enters the cooler areas inside the crankcase, it condenses, forming a so-called white oil mist, with droplets having a diameter in the range of 5–10 μm. As a result of the abovementioned process, the concentration of oil mist increases to the level of the lower explosive limit, which is 47 mg of oil per 1 dm^3 of air (in some studies this level is specified as 50 mg/dm^3). This corresponds to an oil mist concentration of about 13% by weight. The phases of oil mist concentration change are shown in Table 2.

Table 1. A comparison of system analysis methods

Designation	Method of analysis	Deductive (Top-down)	Inductive (Bottom-up)	Quantitative	Quasi--quantitative	Qualitative
5 Whys	5 whys method	+				+
AFD	Anticipatory failure determination	+		+		
ETA	Event tree analysis		+	+		+
FMEA	Failure mode and effects analysis	+ (functional)	+ (hardware)		+	–
FMECA	Failure mode, effects and criticality analysis	+ (functional)	+ (hardware)	+	+	–
FTA	Fault tree analysis	+		+		+
HAZID	Hazard identification	+				+
HAZOP	Hazard and operability study	+				+
What-if?	'What-if?' analysis	+				+
–	Subversion/sabotage analysis	+	+		+	+
–	Ishikawa diagram (Fishbone diagram)	+				+

Table. 2. Phases of development of explosive mixture in the crankcase (prepared on the basis of (Islam, n.d.; Schaller Automation, 2015)

Specification	Phase I	Phase II	Phase III
Phase characteristics	Normal operating condition	Emergency	Lower explosive limit exceeded
Oil mist concentration [mg/dm^3]	< 1.99	1.99–47	> 47

When the oil-air vapor mixture reaches the ignition temperature, combustion is initiated, and an explosion occurs. Studies have shown that ignition can occur at 270–330°C and over 400°C (Islam, n.d.; Piotrowski & Witkowski, 2005).

The flame front travels along the crankcase, causing a pressure wave in front of it. The speed of the gas pressure wave in the initial phase is 0.3 m/s, increasing to about 300 m/s. In the case of long crankcases, it can reach up to 3 km/s (Chybowski, 2022). The maximum pressure in the crankcase during an explosion without detonation reaches about 7 bar (0.7 MPa). A properly designed crankcase should withstand a static pressure of 12 bar (1.2 MPa) without damage (Islam, n.d.).

The process of mixing oil vapor with air is intensified by the turbulence associated with crank-piston components and the operation of the explosion isolation valve (Valčić, n.d.). If, due to the venting of gases through the explosion isolation valves, the pressure in the crankcase is reduced below the pressure in the engine room (Valčić, n.d.), fresh air from the engine's surroundings will be drawn into the crankcase through the open explosion isolation valves (Freeston, Roberts & Thomas, 1956), which in turn can cause a secondary explosion that is more violent than the primary one and can cause further damage to the engine's surroundings.

If the explosion isolation valves do not work, the side hatch flaps in the crankcase wall will be torn out, and there is a risk of a secondary explosion (Rattenbury, 2002). A secondary explosion can also be caused by the failure of components in the crank-piston system (Chybowski, 2022). In this case, it is not preceded by a primary explosion, and is caused by the loss of continuity of the crankcase wall, resulting in a sudden influx of fresh air (BSU, 2018; MAIB, 2018).

Selected models of the causes of explosions in crankcases

A literature review was conducted on attempts to model the causes of explosions in crankcases. The methods employed were based on two main sources of data: statistics on historical damage and errors that could have led to the occurrence of explosions, and expert assessment, which was also based indirectly on information on historical events of a similar nature (Herdzik, 2019). Three of the most reliable techniques, which were based on recognized methods, were selected and analyzed in terms of assessing the causes of disasters and selecting the most likely events that could have led to an explosion. An analysis based on statistical information, a model based on the FMEA method and a model based on FTA are presented. The latter two were supported by expert analysis and the use of fuzzy set theory. The data presented in this article have been posted in the ZENODO repository (Wiaterek & Chybowski, 2022).

Statistical evaluation of the incidence of explosions with a specific cause

By virtue of their design, trunk piston engines are prone to hot gas and fuel blow-by from the combustion chamber into the crankcase in the event of malfunctioning or damaged piston rings, pistons or cylinder liners (Chybowski, 2022). The components separating the crankcase from the combustion chamber are the pistons and sealing rings. Hot gas blow-by into the crankcase can be both the cause of areas of increased oil evaporation and the initiator of ignition. An explosion can also be caused by oil entering the crankcase through a cracked piston bottom (crown). The potential risk of explosion is exacerbated by the possibility of fuel entering the crankcase, for instance from a malfunctioning injection apparatus (Chybowski, 2022). As a substance with a lower flash point than oil (minimum 60°C), fuel can contribute to an explosion that would not have occurred without its presence in the crankcase. To avoid such situations, the engine's circulating oil is subjected to periodic laboratory analysis, especially for viscosity and flash point. Figure 1A shows the root causes of crankcase explosions of unshielded engines according to Rattenburry, developed based on the results of explosions that took place between 1990 and 2001.

In crosshead engines, there is no direct blowing of hot gases from the combustion chamber into the crankcase. Between these locations is the sub-piston space and/or air accumulator and the lower cylinder

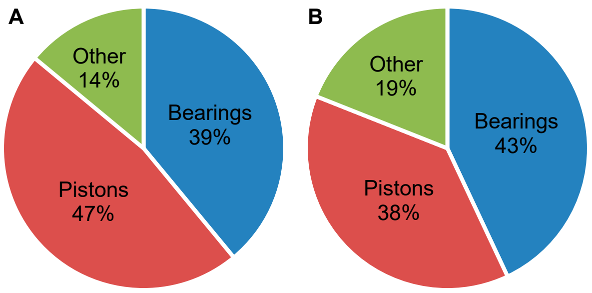

Figure 1. Causes of crankcase explosions according to Rattenbury (Rattenbury, 2002): A – trunk piston engine, B – crosshead engine

block plate (Chybowski, 2022). The piston stems are sealed in the wall with a gland. Figure 1B shows the root causes of crankcase explosions of unshielded engines according to Rattenburry, developed based on the results of explosions that took place between 1990 and 2001.

In a crosshead engine, unburned cylinder oil and combustion residues dripping from the cylinder liners accumulate in the sub-piston spaces (Chybowski, 2022). If the drainage system is not fully serviceable, and if periodic cleaning of the sub-piston spaces and the air reservoir is not implemented, a fire and/or explosion may occur in these spaces because of hot gas blowing from the combustion chambers, on principles analogous to those of trunk piston engines.

Bearing failures can have a variety of causes relating to both improper lubrication (oil flow too low, oil temperature too high or oil contamination), as well as the wear of plain bearing journals and liners, mechanical displacement of half-liners in the seat, and improperly performed repairs (failure to follow repair schedules or the use of non-original replacement parts) (Chybowski, 2022). The specific causes of plain bearing damage can vary depending on the type of engine, operating conditions, liner types used, etc. Examples of damage statistics for marine engine plain bearings are shown in Figure 2.

In crosshead engines, the cause of a crankcase explosion may be an increase in the temperature of one or more piston stems. The reason may be a fire in the sub-piston space, which, if not quickly extinguished, can contribute to a general rise in temperature in the crankcase and/or the formation of hot spots in the gland areas of the piston stems and the piston stems themselves. In addition, leaking piston stem glands provide an additional source of heat in the crankcase in this situation (Chybowski, 2022). A separate risk is a malfunctioning piston stem seal (excessive blowouts on the piston stem gland (Włodarski, 1998) or excessive friction between the piston stem and gland rings (Nowosad, 2009), for example, when non-original rings or springs are used).

FMEA analysis of crankcase explosions

Another model was proposed by Cicek and Celik (Cicek & Celik, 2013), based on the results of an FMEA that was conducted for crankcase explosion events. The purpose of FMEA is to consistently eliminate errors in the construction and operation of a product by recognizing the causes of the errors and applying appropriate ways to prevent them from occurring. In the case of FMEA, after specifying the object of analysis, an analysis of the causes of defectiveness and criticality of errors is carried out for the selected product or process (Herdzik, 2015). Reference (Cicek & Celik, 2013) selected the main root causes of crankcase explosions, defining a Risk Priority Number *(*RPN) as a determinant of the significance of a given event (Gawdzińska et al., 2017):

$$RPN = O \cdot S \cdot D \tag{1}$$

where: O – frequency of occurrence index, S – severity index, D – detectability index.

A summary of the results of the analysis by Cicek and Celik is shown in Table 3. Model inputs are presented in (Cicek & Celik, 2013). This model has been analyzed in detail in, among other publications, (Wang et al., 2017).

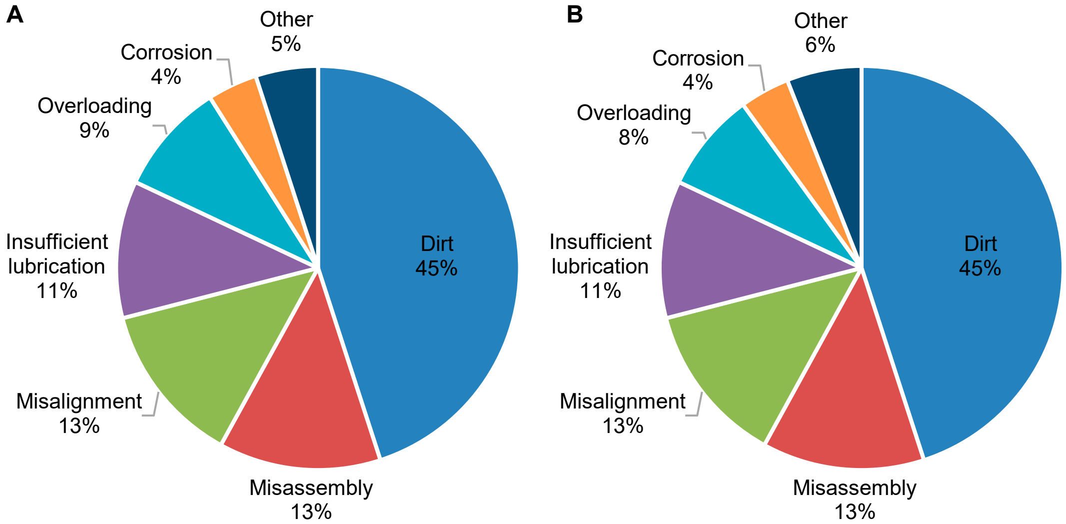

Figure 2. Percentage causes of plain bearing damage of internal combustion engines: A – according to Piaseczny (compiled from (Piaseczny, 1992)), B – according to Mahle (compiled from (Clevite, 2014))

Table 3. FMEA analysis worksheet (compiled from (Cicek & Celik, 2013))

Component	Failure mode	Failure causes	Failure effect	*O*	*S*	*D*	*RPN*
Oil mist detector	Inoperable (FM1)	Wrong calibration of oil mist detector	Oil mist in the crankcase cannot be detected	2	9	10	180
	Inoperable (FM2)	Lack of maintenance		4	9	8	288
Piston	Hole in the piston crown (FM3)	Dripping of fuel valve	Transmission of combustion gases into the crankcase	6	7	8	336
	Excessive wear on piston flame face (FM4)	Fuel impingement from poor atomization	Overheating and excessive pressure in the crankcase	7	8	7	392
Piston ring	Sticking to groove (FM5)	Deposits	Excessive clearance, fire blow	6	6	5	180
Stuffing box	Not functioning correctly (FM6)	Incorrect spring mounted in piston rod stuffing box	Transmission of combustion gas from the combustion chamber into the crankcase	4	10	6	240
	Wearing out of packing rings (FM7)	Loss of sealing	Spark and blow-by	6	7	8	336
Fuel valve	Early opening of fuel valve (FM8)	Service pressure too light	Poor atomization and combustion, timing problems, power balance and temperature variations	6	7	6	252
	Dripping (FM9)	Oversized injection mechanisms	Sticking of piston rings in their grooves, fire blow	7	8	6	336
Engine performance monitoring system	Not fully functional (FM10)	No periodic checking of electronic cards	Unawareness of abnormal condition in combustion process	2	7	5	70
Main bearing	Failing to lubricate (FM11)	Low oil pressure	Friction and excessive heat	3	8	4	96
Crankcase relief valve	Inoperable (FM12)	Not appearing to perform as designed and not seated correctly	Allows air to pass into the crankcase	2	7	9	126

Based on the summary shown in Table 3, it is possible to draw conclusions about the relevance of individual failure modes, the importance of which is represented by the RPN values, that is, in terms of frequency, consequences and the risk of failure to detect the problem for each event. Figure 3 shows the percentage of RPN for the analysis in question, assuming that the sum of all RPN for all failure modes corresponds to a value of 100%.

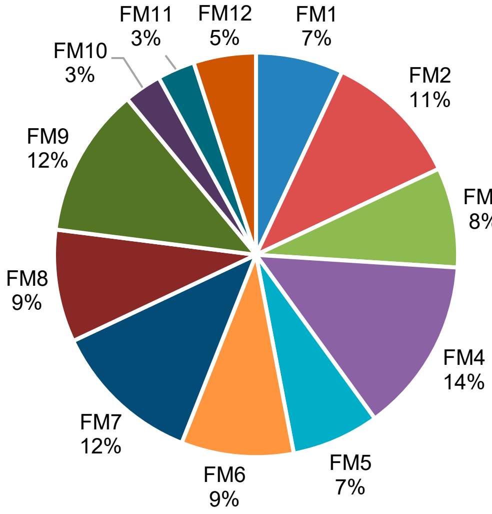

Figure 3. Percentage of individual risk priority numbers for each failure mode (prepared on the basis of (Cicek & Celik, 2013))

The analysis in this case applies to two-stroke engines, but with minor modifications it can be adapted to the specifics of the operation and design of a trunk type engine, so it is evaluated in this material through the prism of the general applicability of the model to the assumed range of applications – that is, in this case, for a trunk type engine.

FTA model of crankcase explosions

FTA is one of the most widely used deductive methods. The method is based on a graphical logical model of the combination of events (component failures, software errors, human errors and environmental impacts) that can occur during the operation of a complex technical system (CTS), the coincidence of which causes a specific undesirable situation modelled through a so-called peak event (Chybowski, 2017) (Figure 4).

In reference (Ünver et al., 2019), this method was used to analyses the root causes of crankcase explosions of a two-stroke, self-ignition trunk

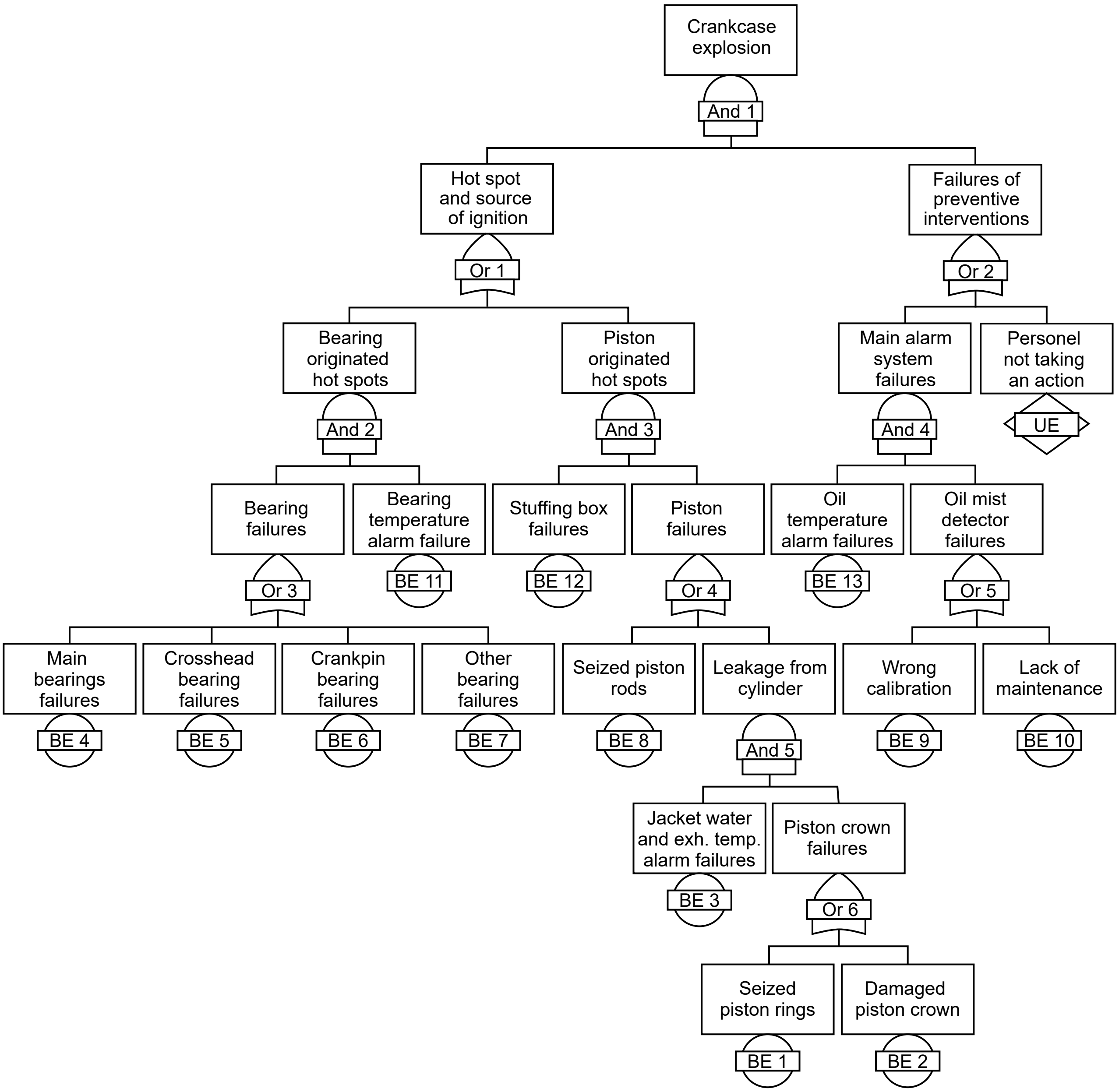

Figure 4. Fault tree for crankcase explosion of a two-stroke, trunk piston marine engine (prepared on the basis of (Ünver et al., 2019))

piston engine, including determining the probability of a peak event, the probabilities and validity of minimum cut sets, and determining general guidelines for preventing such disasters. The analysis in question was carried out in a fuzzy environment. With minor modifications, the fault tree can be adapted to analyses the explosion of crankcases in trunk piston engines. The original model taken from (Ünver et al., 2019) was used for further significance analysis of individual events performed in CARA-FaultTree Application 4.1. academic version (Sydvest, Trondheim, 2000), as shown in Figure 4, while Table 4 summarizes the individual elementary events and the estimated values of their probabilities of occurrence.

The model above can be used to determine the significance of individual events and their impact on the occurrence of a crankcase explosion. For this purpose, the values of the basic importance measures, i.e. Vesely-Fussell measure $I^{V\text{-}F}$, Birnbaum structural measure I^{Bs}, Birnbaum reliability measure I^{B}, criticality measure I^{C} and improvement potential I^{P}, were determined for each of the identified elementary events. Individual definitions of these measures and their detailed description are provided in the subject literature (Chybowski, 2014, 2020; Chybowski, Idziaszczyk & Wiśnicki, 2014). The calculated values of each measure are summarized in Table 5.

To visualize the contribution of each event to the occurrence of the peak event (crankcase explosion)

Table 4. Characteristics of primary events in the analyzed fault tree (prepared on the basis of (Ünver et al., 2019))

Event	Description	Event probability
BE1	Seized piston rings	0.002931
BE2	Damaged piston crown	0.000299
BE3	Jacket water and exhaust gas high temperature alarm failure	0.001858
BE4	Main bearing failure	0.001958
BE5	Crosshead bearing failure	0.001036
BE6	Crankpin bearing failure	0.001137
BE7	Other bearing failure	0.000699
BE8	Seized piston rods	0.000601
BE9	Wrong calibration of the oil mist detector	0.002525
BE10	Lack of maintenance of the oil mist detector	0.003740
BE11	Bearing high temperature alarm failure	0.002239
BE12	Stuffing box failures	0.002239
BE13	Lube oil high temperature alarm failure	0.002972
EU	Staff not taking an appropriate preventative action after an alarm	0.010169

and their mutual comparison, the pie charts shown in Figure 5 were used.

The charts describe the percentage of events due to their importance (the sum of the importance of all events is 100%). Analysis of the values obtained for all measures showed that particularly significant events affecting the occurrence of a peak event were BE 11 (bearing high temperature alarm failure) and UE (personnel not taking an appropriate preventative action after an alarm).

Table 5. Estimated values of the importance of each primary event

Event	I^{B}	$I^{V\text{-}F}$	I^{Bs}	I^{C}	I^{P}
BE11	0.0000498060	0.8897300	0.4229700	0.8895600	0.0000001115
BE8	0.0000228090	0.1091800	0.1141400	0.1093500	0.0000000137
BE4	0.0000227430	0.3557000	0.0281980	0.3552100	0.0000000445
BE6	0.0000227240	0.2065500	0.0281980	0.2061000	0.0000000258
BE5	0.0000227230	0.2004900	0.0281980	0.2000400	0.0000000251
BE7	0.0000227140	0.1269800	0.0281980	0.1266500	0.0000000159
EU	0.0000123050	0.9981700	0.4071000	0.9981700	0.0000001251
BE12	0.0000061836	0.1102700	0.2511000	0.1104400	0.0000000138
BE13	0.0000000762	0.0018277	0.2442600	0.0018064	0.0000000002
BE3	0.0000000736	0.0010902	0.0684810	0.0010910	0.0000000001
BE1	0.0000000423	0.0009893	0.0228270	0.0009900	0.0000000001
BE2	0.0000000422	0.0001009	0.0228270	0.0001007	0.0000000000
BE10	0.0000000361	0.0010911	0.0814210	0.0010773	0.0000000001
BE9	0.0000000361	0.0007366	0.0814210	0.0007264	0.0000000001

Conclusions

Each of the models presented provides different information, due to factors such as different assumptions. The level of decomposition of the explosion process in the engine crankcase leads to different observations on the frequency of participation and importance of individual events on the incident of explosion.

The statistical description is the most general in this case, although individual events could be further examined in more detail (decomposed). However, this model, due to the lack of analysis of the interrelationships between events, reduces the assessment of significance to an analysis of the frequency of individual events (serial reliability structure model). An event is therefore more important the more often it occurs under the operating conditions.

The quality of the FMEA model depends largely on the assumptions made, the available source data and the experience of the experts who are part of the team conducting the analysis.

The FTA model describes the logical relationships between events, so it represents the best of the models described in the article in terms of relationships and process structure. Thus, it can be used to assess the validity of events. It seems that linking the FTA model to statistical data can be a good solution for obtaining meaningful results from statistical analysis. In addition, the results of the validity analysis can be used in the next step to determine the severity index in the FMEA analysis.

It should be noted that all three models described in the article cited from the scientific literature do

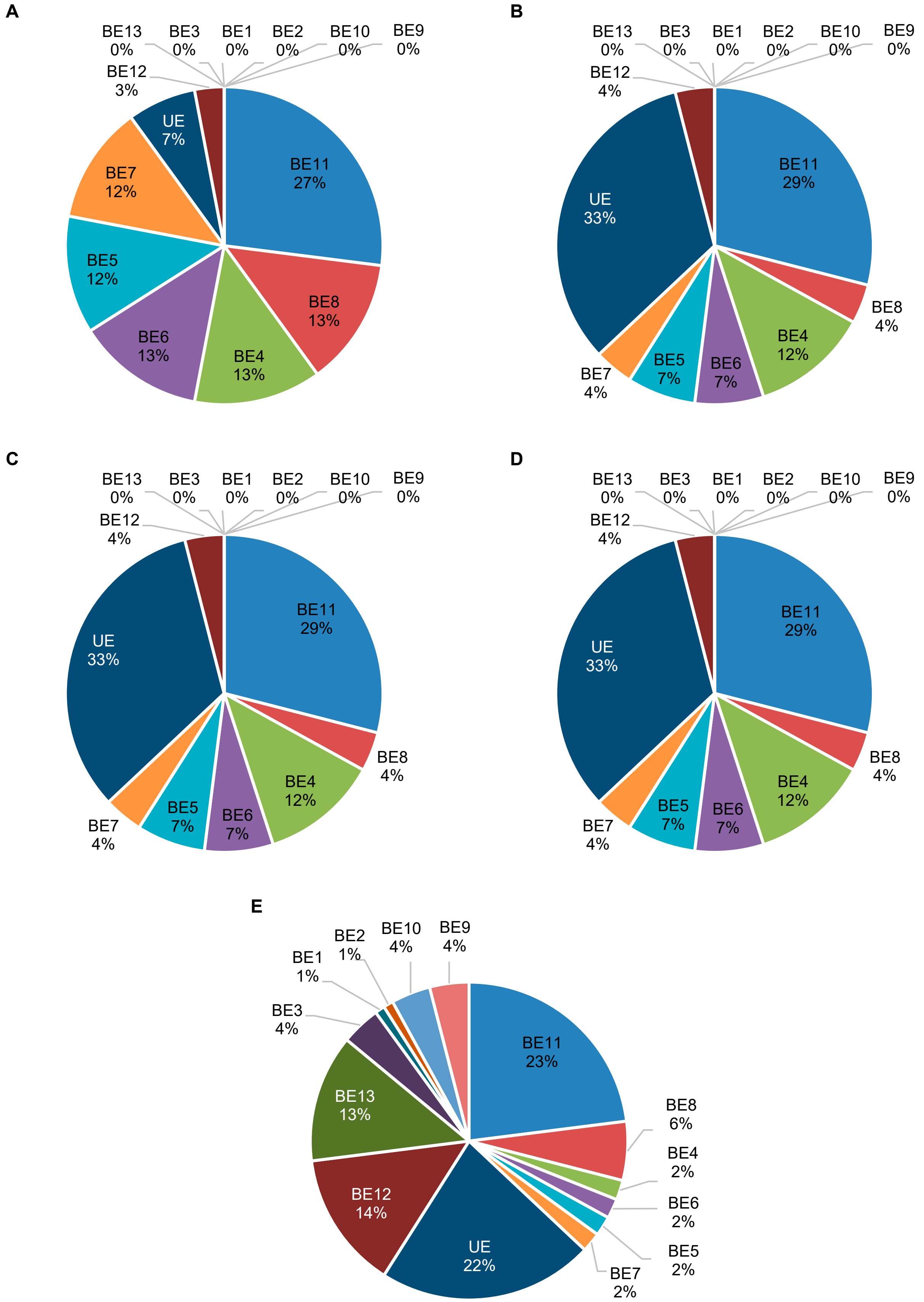

Figure 5. Percentage values of importance measures of events leading to explosions in the crankcase: A – Birnbaum reliability measure, B – improvement potential, C – Vesely-Fussell measure, D – criticality measure, E – Birnbaum structural measure

not capture (or capture only indirectly – by merging several primary events) some events that can lead to explosions in the crankcase, such as a fire in the engine room or a fire in the sub-piston space. To search for root causes in depth and refine the FTA or FMEA model, it is advisable to use tools aimed at finding hidden causes of damage and intentional damage to the system. An example of such a method could be the analysis of diversion (sabotage). The authors believe that linking diversion analysis, statistical data, FTA and FMEA would enable the most objective results possible to be obtained when assessing the risk of operations and planning countermeasures to prevent a disaster from occurring.

Acknowledgements

The research was prepared under Grant 1/S/KPBMIM/22 funded by the Ministry of Science and Higher Education of Poland.

References

1. BSU (2018) *Serious engine damage followed by fire on board the cargo vessel THETIS D on 26 October 2015 in the Kiel Bight*. Hamburg, Germany: BSU (Federal Bureau of Maritime Casualty Investigation).
2. Burgoyne, J. & Cohen, L. (1954) The effect of drop size on flame propagation in liquid aerosols. *Proceedings of the Royal Society A. Mathematical, Physical and Engineering Sciences* 225, 1162, pp. 375–392, doi: 10.1098/rspa.1954.0210.
3. Chybowski, L. (2014) Ważność elementów w strukturze złożonych systemów technicznych. Szczecin, Radom: Wyd. Nauk. Instytutu Technologii Eksploatacji – PIB.
4. Chybowski, L. (2017) *Analiza drzewa niezdatności. Podstawy teoretyczne i zastosowania*. Szczecin: Wyd. Nauk. Akademii Morskiej w Szczecinie.
5. Chybowski, L. (2020) Importance Analysis of Components of a Multi-Operational-State Power System Using Fault Tree Models. *Information* 11, 29, doi: 10.3390/info11010029.
6. Chybowski, L. (2022) *Eksplozje w skrzyniach korbowych silników okrętowych – przyczyny, zapobieganie i minimalizacja skutków*. Szczecin: Akademia Morska w Szczecinie.
7. Chybowski, L., Idziaszczyk, D. & Wiśnicki, B. (2014) A Comparative Components Importance analysis of A Complex Technical System with The Use of Different Importance Measures. In *Systems Supporting Production engineering. Review of Problems and Solutions*. Gliwice: P.A. NOVA.
8. Cicek, K. & Celik, M. (2013) Application of failure modes and effects analysis to main engine crankcase explosion failure on-board ship. *Safety Science* 51, 1, pp. 6–10, doi: 10.1016/j.ssci.2012.06.003.
9. Clevite (2014) *Bearing failures. Major causes of bearing failure*. Stuttgart: MAHLE Aftermarket GmbH.
10. Freeston, H.G., Roberts, J.D. & Thomas, A. (1956) Crankcase Explosions: An Investigation into Some Factors Governing the Selection of Protective Devices. *Proceedings of the Institution of Mechanical Engineers* 170, 1, pp. 811–824, doi: 10.1243/PIME_PROC_1956_170_072_02.
11. Gawdzińska, K., Chybowski, L., Przetakiewicz, W. & Laskowski, R. (2017) Application of FMEA in the Quality Estimation of Metal Matrix Composite Castings Produced by Squeeze Infiltration. *Archives of Metallurgy and Materials* 62(4), pp. 2171–2182, doi: 10.1515/amm-2017-0320.
12. Herdzik, J. (2015) Remarks of the FMEA procedures for ships with dynamic positioning systems. *Zeszyty Naukowe Akademii Morskiej w Gdyni* 91, pp. 47–53.
13. Herdzik, J. (2019) ISM Code on vessels with or without impact on a number of incidents threats. *Journal of KONES* 26(2), pp. 53–59, doi: 10.2478/kones-2019-0032.
14. Islam, S. (n.d.) *Crankcase explosion mechanism*. [Online]. Available from: https://www.slideshare.net/saiful12345660/crankcase-explosion-mechanism [Accessed: March 21, 2021].
15. MAIB (2018) *Catastrophic engine failure, resulting in a fire and serious injuries to the engineer on board Wight Sky, off Yarmouth 12 September 2017*. Accident Report No. 14/2018. London: Marine Accident Investigation Branch.
16. Nowosad, G. (2009) *Zabezpieczenia przeciwwybuchowe* ...