Proceedings of the World Congress on Engineering 2018 Vol II
WCE 2018, July 4-6, 2018, London, U.K.

A FMECA-Based Analysis of the Complex Plant Controlling a Variable Pitch Propeller

Lorenzo Damiani, Pietro Giribone, Roberto Revetria, M*ember, IAENG*

***Abstract*— The object of this paper is a method that allows to determine the criticality of a system. As a case study, it is considered a Variable Pitch Propeller (VPP) Plant: at first it is studied to understand its characteristics and operating logics and, subsequently, four possible Operating Modes were identified. For each Operating Mode a fault tree is modelled in TARAS, a software that allows calculating the MTBF (Mean Time Between Failures) of the plant. Subsequently, the results are validated using a block diagram.**

Finally, a FMECA (Failure Mode, Effects, and Criticality Analysis) is carried out: it includes both an analysis aimed at highlighting which are the possible failure modes and their consequences on the operation of the VPP Plant and a criticality analysis aimed at identifying which items are more critical than others for the specific Operating Mode and which Operating Mode is more critical than other..

***Index Terms*— Complex systems, FMECA Analysis, Failure Analysis, Simulation.**

I. Introduction

Each item, plant and in general each system is able to operate correctly for a limited time period, which is interrupted by a failure: the causes of this failure can be multiple and the industry is more and more interested in knowing, studying and preventing them. According to this vision there are the engineering activities that study the reliability of a system and that include the predictive analysis, the failure and effects analysis and the criticality analysis of the system.

In this paper, the Authors applied the failure analysis [1-4] to a complex device, namely a variable pitch propeller (VPP). The Variable Pitch Propeller plant allows rotating the propeller blades of a ship around their long axis, in order to regulate the thrust by changing the fluid impingement angle.

The VPP system was simulated by the TARAS software [1], able to obtain as result the availability of the system and other quantities related to failure behavior of a complex mechanical plant [5], such as the Failure Mode Criticality Number (Cm) that is referred to the single failure mode and the Item Criticality Number (Cr) that is referred to the item object of the analysis.

For the failure analysis, four scenarios were considered, each linked to a specific state and situation in which a ship is required to operate. In particular:

- Scenario 1: maximum ship performance required
- Scenario 2: ship cruise.
- Scenario 3: ship cruise with VPP Primary Control Unit out of order.
- Scenario 4: ship cruise with VPP Emergency Control Unit out of order.

II. The VPP system

The Variable Pitch Propeller Plant allows rotating the propeller blades of a ship around their long axis. In a ship there are two VPP Plants, one for each propeller, that usually are identical: for this reason the report now presented is referred only to one plant.

The VPP Plant is consisting of the following subsystems:

- Hub & Propellers: it is the mechanism contained in the hub that allows rotating the propeller blades.
- Pitch Controller: it is the mechanism that controls the state of the propeller blades.
- Oil Tubes: these are the tubes that transport oil from the Pitch Controller to the Hub & Propellers subsystem.
- Tank: it is the tank in which the oil for the pitch variation and the lubrication is stored.
- Primary Control Unit: it is the hydraulic circuit that sends the oil to the Pitch Controller. Among the other items, the Primary Control Unit has two Pumping Lines (A and B) and two Starters (A and B), which can work in parallel or alternately depending on the required rotation speed of the blades. It has also two distributors, one for the normal operation and one in stand-by that it is used in case of failure of the Primary Distributor and which has limited functionality.
- Emergency Control Unit: it is the circuit that sends the oil to the Pitch Controller in case of failure at the Primary Control Unit. The Emergency Control Unit works in a degraded way.
- Primary Control Panel: it is the panel that controls the VPP Plant.
- Emergency Control Panel: it is the panel that controls the VPP Plant in case of failure at the Primary Control Panel. The Emergency Control Panel works in a degraded way.

Based on the type of mission, the plant works in different conditions and is admitted or not the failure of different subsystems and items: therefore this subsystems and items

Lorenzo Damiani Author is with Genoa University, Via Opera Pia 15, 16145 Genoa, IT (e-mail: Lorenzo.Damiani@unige.it).

Pietro Giribone Author is with the University of Genoa, Department of Mechanical Engineering, Via Opera Pia 15 16132 Genoa IT (e-mail: Piero@itim.unige.it).

Roberto Revetria Author is with the University of Genoa, Department of Mechanical Engineering, Via Opera Pia 15 16132 Genoa IT (Phone Number: +393339874234; e-mail: Roberto.Revetria@unige.it).

ISBN: 978-988-14048-9-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

are related with appropriate logics.

III. Simulation of the VPP Operational Modes

There are four different Operating Modes, called Scenarios.

In the first Scenario (Case 1) the ship has the imminent need to move from the point A to the point B, so at the VPP Plant is required to operate ensuring maximum performance. It follows that full availability of all its subsystems is required, with the exception of the Emergency Control Unit and the Emergency Control Panel. With this model we want to simulate the conditions for which it is possible to navigate at full speed, and take advantage of the maximum speed of rotation of the blades, using both the Pumping Lines (and, in consequence, both the Starters) and the other systems of the Primary Control Unit.

In the second Scenario (Case 2), the ship doesn't have an imminent need and must only reach the point B without a time limit, so at the VPP Plant it is required only to rotate the propeller blades and it does not matter the way this is done: therefore, it is possible to perform the mission using the Primary Control Unit (it is sufficient to use one of the Pumping Lines with the relative Starter and indifferently the Primary Control Panel or the Emergency Control Panel) or using the Emergency Control Unit.

In the third Scenario (Case 3), we suppose that the Emergency Control Unit is not available, so at the VPP Plant it is required to rotate the propeller blades using the Primary Control Unit: also in this Scenario it is sufficient to use one of the Pumping Lines with the relative Starter and indifferently the Primary Control Panel or the Emergency Control Panel, but it is not possible to rotate the propeller blades using the Emergency Control Unit.

In the fourth Scenario (Case 4) we suppose that the Primary Control Unit is not available, so at the VPP Plant it is required to rotate the propeller blades using the Emergency Control Unit.

For each of this Scenarios, correspond a Fault Tree which is different to the others because of:

- the Boolean logic gates AND (in which all the inputs must to be 1 to obtain the output 1) and OR (in which is sufficient that only one input is 1 to obtain the output 1) relate the subsystems and the items in different ways
- some subsystems or items are excluded.

The symbols used for the logic gates are illustrated in Fig. 1.

Figure 1: Logical gates symbols.

In Fig. 2, 3, 4 and 5, are illustrated all the Fault Trees for the different Scenarios: a null failure rate is assigned to elements that do not contribute to the Top Event.

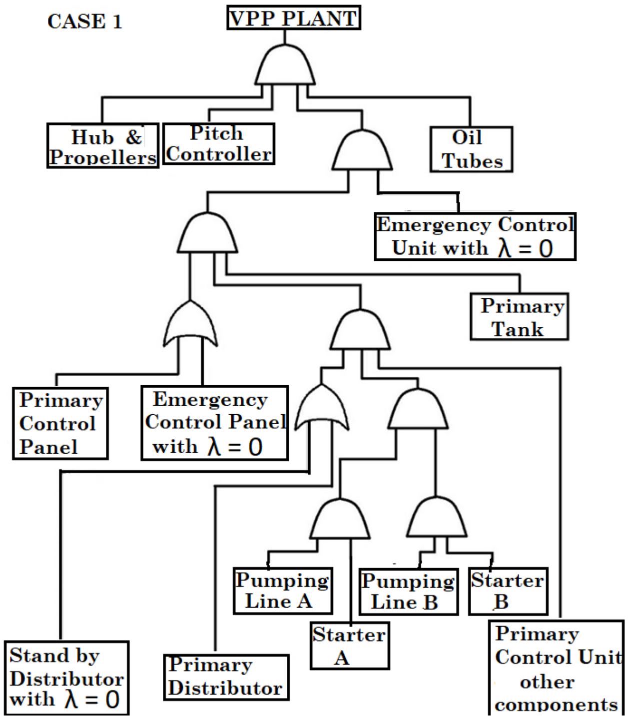

Figure 2: Logical scheme of operational mode 1.

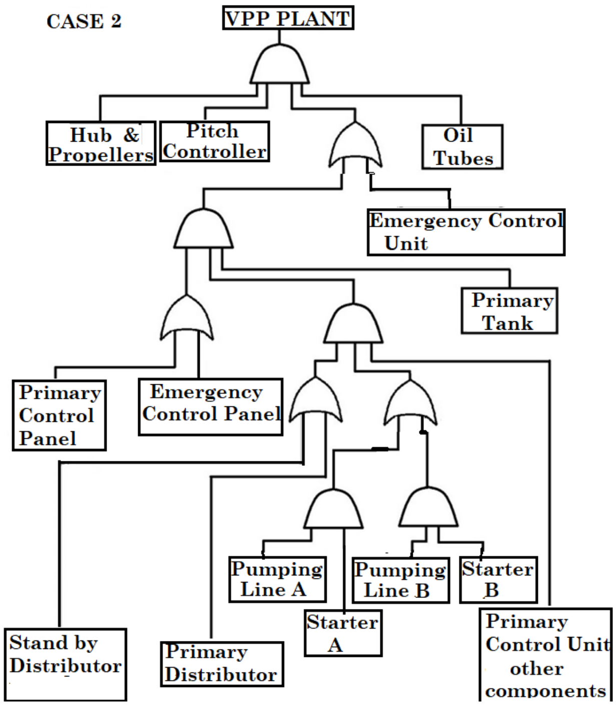

Figure 3: Logical scheme of operational mode 2.

ISBN: 978-988-14048-9-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

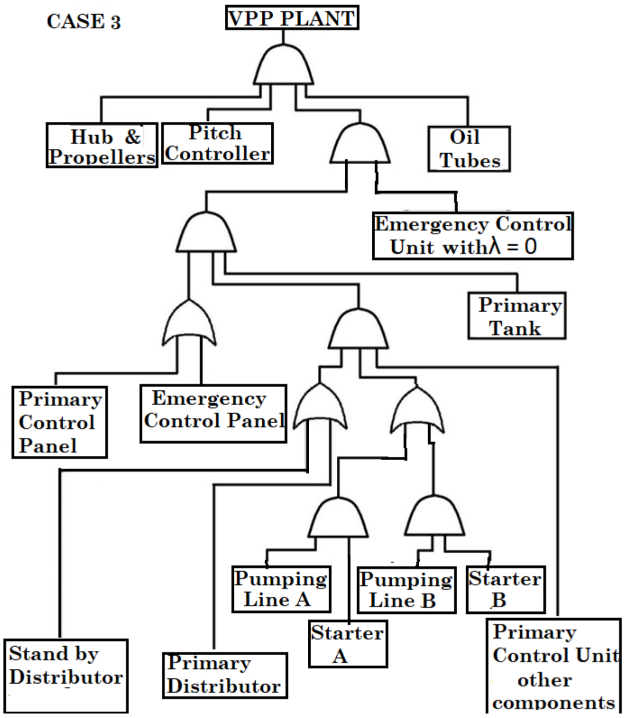

Figure 4: Logical scheme of operational mode 3.

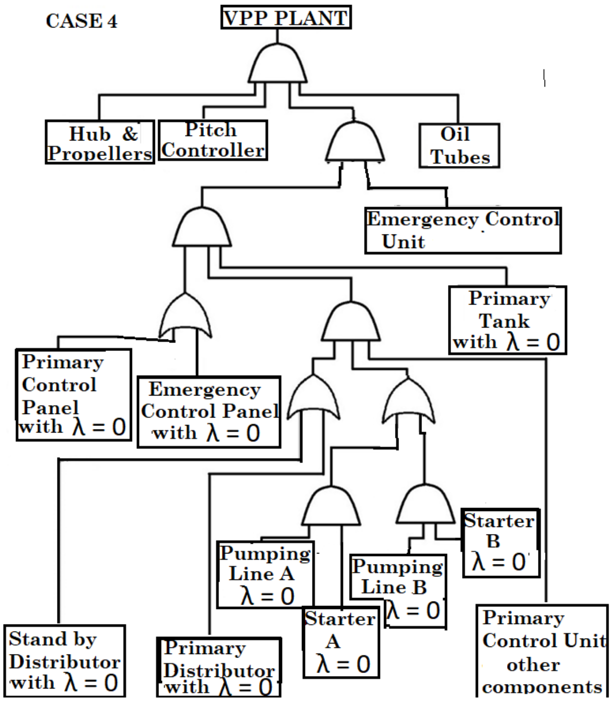

Figure 5: Logical scheme of operational mode 4.

IV. Generation of Block Diagrams by TARAS

TARAS is a software able to simulate the probable failures of a plant and determine, among the other results, its Mean Time Between Failure (MTBF). Each Scenario is modelled in TARAS: the Fault Tree is realized assigning to each item/subsystem of the plant a relation with the other items/subsystems and a failure rate. The subsystems (with the exception of electronic subsystems like the Control Panels and the Starters) are decomposed into their constituting items to ensure that their calculated failures rate will be realistic, indeed for each item a failure rate was found from databases or from calculation methods provided by technical texts [6,7]. In TARAS it is possible to model only single parts of a Fault Tree and, subsequently, to nest them in a new Scenario relative to the whole system.

The fault tree analysis is developed by determining for each item of the Fault Tree, taken into consideration for the specific Scenario, a state that can be:

- 1, if the item is available at the time considered
- 0, if the item is not available at the time considered

The states of two or more elements that are at a lower level converge into a node, which is represented with logical gates. The inputs of the logic gates can also be the outputs of other logic gates that are always at a lower level.

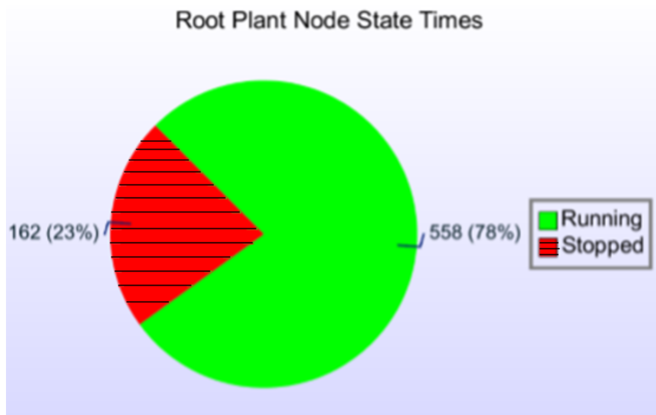

Figure 6: Availability pie chart reported by TARAS.

In order to attribute a state to each item, TARAS uses the Monte Carlo simulation[8-11]: it generates a random number between 0 and 1 for each item of the Scenario, compares this random number with the failure rate of the item and assigns to it the state 1 if the random number is higher than the failure rate else assign to it the state 0 that means a failure occurred. To evaluate the consequences of a failure on the plant, TARAS verify if a failure that occurred in an item propagates into the Fault Tree and produce or not the “Top Event” (Plant shutdown); in positive case, TARAS reports it in order to calculate the MTBF of the plant. TARAS runs several simulations based on the number of simulated hours set. In TARAS it’s also possible to make several replication of the same Scenario: in our case each Scenario is replicated five times and for each replication are simulated 8760 hours of operation. At the end of each replication TARAS provides the results. In Fig.6 there is an example of pie chart shown by TARAS, representing the availability of the plant at the end of one replication for Case 1.

It is possible to collect the results of all the replications in a spread sheet and analyze them: in Tab.1 are reported the MTBF and the failure rate (expressed in failures per million hours) calculated for each Scenario based on the five replications.

Evaluating the results obtained with TARAS it is possible to say, basing on the experience, that they are realistic: indeed the expected MTBF for this kind of plants is about 1000 hours.

With the aim of validating the results obtained simulating the VPP Plant with TARAS, a Block Diagram is realized for

ISBN: 978-988-14048-9-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

each Scenario: each block diagram reflects the Fault Tree of the Scenario it represents. In the Block Diagram all the blocks contains the failure rate of the item that represent it or contains the failure rate calculated according to the probability that a failure occurs for two or more elements in series or parallel. In the root block is found the failure rate of the VPP Plant.

Table 1: MTBF and Failure Rates for the 4 cases

Scenario	MTBF [h]	Failure rate [Fails/Mh]
# 1	749	1335
# 2	2343	427
# 3	1149	870
# 4	1357	737

In Fig.7 is represented the Block Diagram concerning Case 3.

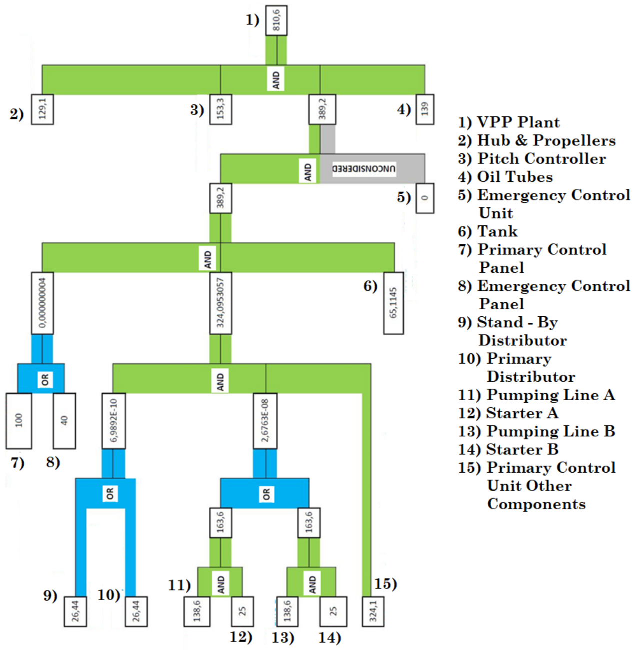

Figure 7: Block Diagram for case 3.

For the other cases the Block Diagram is not represented but the calculated MTBF and failure rates are reported in Tab.2.

Comparing the results obtained with the Block Diagrams to the results obtained with TARAS, it is possible to understand that the mutual pair of numbers are very similar, so it is possible to conclude that the results are verified.

V. FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

The Failure Mode, Effects and Criticality Analysis (FMECA) has the goal to identify and classify all the probable failures in a system and determines its criticality. The FMECA is the result of two activities:

- FMEA (Failure Mode and Effects Analysis) that makes use of Worksheets and classify the failures and evaluate their consequences on the system

Table 2: MTBF and Failure Rates for the 4 cases

Scenario	MTBF [h]	Failure rate [Fails/Mh]
# 1	776	1289
# 2	2386	419
# 3	1233	811
# 4	1511	662

- CA (Criticality Analysis) that classify the failures based on their criticality. At the end it is possible to calculate two Criticality Numbers, the Failure Mode Criticality Number (Cm) that is referred to the single failure mode and the Item Criticality Number (Cr) that is referred to the item object of the analysis.

For the VPP Plant, a FMECA is developed for each Scenario and relative to the whole Plant, so the Item Criticality Number is referred to the whole Plant.

The advantages takes from this analysis method is that it is possible identify which are the items that cause the failures more critics and that it is possible to compare different configurations of the same system in terms of criticality to understand which (and how much) is more critical than others.

In the FMECA it is necessary to assign to each failure mode a Severity Class that identifies the criticality level of the failure mode and a Failure Mode Ratio representing the fraction of the failure rate relative to the item taken into consideration. Assign a Failure Mode Ratio using the results obtained with TARAS isn't possible because the number of events relative to each subsystems and relative to each Scenario are insufficient to determine a realistic value, so the Failure Mode Ratio is obtained from the Block Diagram. It is calculated considering, for each level of blocks, the ratio that its failure rate has on the upper block: using this method is sure that the sum of the contributions relating to all the blocks not further broken down is 1. Subsequently, the Failure Mode Ratio relative to items contained in blocks not further broken down is obtained calculating the ratio that the item failure rate has on the block not further broken down.

In the Tab.3 below are reported the Item Criticality Numbers Cr relative to the VPP Plant and are divided on the base of the Severity Class.

Table 3: Item Criticality Numbers Cr

Scenario	C_r for S. Class 1	C_r for S. Class 2	C_r for S. Class 3	C_r for S. Class 4
# 1	0	763,4	474,5	96,1
# 2	0	323,4	103,3	1,2E-08
# 3	0	488,4	315,4	66,6
# 4	0	533,7	200,1	3,4

ISBN: 978-988-14048-9-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

For the Severity Class 1, all the Cr are null because no failures cause death of people or loss of the system. The Criticality Numbers for the Severity Class 4 (that represent failures that not cause delay for the mission) are variable in function of which are the subsystems that are excluded from the Scenario and is the least important parameter among those considered.

The Item Criticality Numbers Cr that are most interesting to comment are those relating to Severity Class 2 and 3. As expected, Case 1 has the Cr of Class 2 and 3 higher, having to ensure the operation of the most of the items that compose the Scenario while Case 2 has the lowest ones, since many of the subsystems that allows it to work are redundant, so they have a very low Failure Mode Ratio. Regarding Case 3 and 4, observing the Cr relative to the Severity Class 2, it is immediately evident that Cr Case 4 is higher than Cr Case 3 and the reason lies in the fact that many of the items with Severity Class 2 (pumps, electric motors, distributors) of the Primary Control Unit are redundant, so they have a very low (approximately zero) Failure Mode Ratio, while in the Emergency Control Unit they are not redundant.

Regarding to Severity Class 3, Case 3 has an higher Cr than Case 4, as expected, motivated by the fact that the Severity Class 3 items are not redundant either in Case 3 or in Case 4.

VI. Conclusion

In conclusion, it is possible to say that TARAS is a valid software to analyse complex systems (also thanks to the possibility of nesting different Scenarios, which makes the fault tree modelling very simple) and the Monte Carlo method is equally valid for solving this kind of problems. Furthermore, from the results obtained, it is possible to understand how the same plant has different failure rates and Criticality Numbers depending on its configuration and on the conditions in which, at the plant, it is request to operate.

Note that this same type of analysis, which in this report refers to the VPP Plant, can be developed also for other systems, of more or less complexity. It is possible to develop it for different constructive solutions (rather than develop it for the same constructive solution in different operational modes as is done for the VPP Plant) in order to evaluate which is the best constructive solution in terms of criticality or failure rate, and make decisions about it..

References

[1] L. Damiani, P. Giribone, R. Revetria, A. Testa, An innovative model for supporting FMEA/FMECA analysis on complex coal-fired power plants, Proceedings of the IASTED International Conference Modelling, Identification and Control (MIC 2014), 2014 Innsbruck, Austria..

[2] R. Revetria, A.G. Bruzzone, Reliability Analysis by Using Simulation for Complex Automated Plants International Journal of Simulation Series 34 (4), 1999, 115-119.

[3] A.G. Bruzzone, R. Revetria, Reliability Analysis by using Simulation for Complex Automated Plants, Proc. of ASTC2002, Business and Industry Symposium, 34 (4) San Diego, 2002.

[4] E. Briano, C. Caballini, P. Giribone, R. Revetria, Two methodologies to support gas turbine power plant availability estimation: design of experiment and Montecarlo simulation, 2010WSEAS Transactions of Systems 9 (9), 2010, 1109-2777.

[5] L. Damiani, R. Revetria, K. Mzoughi, P. Giribone, A Hybrid Simulation Model for Evaluating Risk Related to Complex Plants in Hospitals, Proceedings of the World Congress on Engineering and Computer Science 2016 Vol II WCECS 2016, October 19-21, 2016, San Francisco, USA.

[6] Handbook of Reliability Prediction Procedures for Mechanical Equipment – Logistic Technology Support, May 2011, Carderockdiv, NSWC-11.

[7] Military Handbook Reliability Prediction of Electronic Equipment MIL-HDBK-217F, December 1991.

[8] Cassettari, L., Mosca, R.,Revetria, R., Experimental error measurement in monte carlo simulation, Handbook of Research on Discrete Event Simulation Environments: Technologies and Applications, pp. 92-142.

[9] Bendato, I., Cassettari, L., Giribone, P.G., Mosca, R. Monte carlo method for pricing complex financial derivatives: An innovative approach to the control of convergence(2015) Applied Mathematical Sciences, 9 (124), pp. 6167-6188.

[10] I. Bendato, L. Cassettari, F. Rolando, M. Mosca, R. Mosca, Stochastic techno-economic assessment based on a Monte Carlo simulation and the response surface methodology: The case of an innovative linear Fresnel CSP system, Energy, (2016) Energy, 101, pp. 309–324.

[11] Damiani L., Giribone P., Guizzi G., Revetria R., Romano E., Different approaches for studying interruptible industrial processes: Application of two different simulation techniques, Handbook of Research on Computational Simulation and Modeling in Engineering, 2015.

ISBN: 978-988-14048-9-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)