2015 International Nuclear Atlantic Conference - INAC 2015
São Paulo, SP, Brazil, October 4-9, 2015
Associação Brasileira de Energia Nuclear - ABEN
ISBN: 978-85-99141-06-9

IMPORTANCE OF NUCLEAR STATION LOAD FACTOR IN APPLIED TO ENERGY POLICIES

Daniel de Souza Gomes[1]

[1] Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
dsgomes@ipen.br

ABSTRACT

Load factor is the ratio between the energy produced by a station and the energy it would have produced running at maximum power. The Factor intends for all types of commercial reactors. Nuclear plants continuously provide over 11% of the world's electricity. The reactors for which data were available generated 618.7 TWh of electricity in 2014. Typical load factor was around 75% in worldwide during the first quarter of 2015. In this manner, it obtained from an average, three-monthly or yearly. The regular load factor of the reactors in operation was around 56% in 1970. While, in 1980's decade, we have an increase to 63%, the same situation occurred in next the decade and suffering increasing to 73%. Currently, the load factor reaches 78%. Accidents are seasonal factors, with the occurrence of reduction of power generation plants. In 2015 in January, there are over 437 operable commercial reactors in 31 countries, with over 377,728 MWe of full capacity. In Brazil, total capacity is 1901 MWe, with around 2.8% of electricity energy consumed. The primary objective of this study was to find a forecast model that expresses the evolution of the load factor in the next years. In recent years occur an extensive development of pressurized water reactors in Asia. The periodicity of seasonal effects on the performance of nuclear power plants due to aging. However, the impact of plant age depended on new technologies that allow the growth of the performance. The accident of Fukushima was an inflection point for energy policies. The event produced a trend that reduced the load factor in the world.

1. INTRODUCTION

The capacity factor also called load factor (LF) is the ratio measured during a specified time, which is defined by the average power to the maximum demand. The rate represents the energy produced over that period divided by net power capacity. The period can be annual or quarterly. Statistical data followed the yearly average. The reporter included all commercial reactors in operation around of the world. The numbers of the power plant in operation and years of experience accumulated were also investigated. The statistics show the generated power and the operation time of each reactor. LF is one of the major indexes used for analyzing the economic viability of nuclear plants [1]. The objective of this study was determined the best model for forecasting load factor for the next years. The historical series compiled since 1970 decade show a short memory. The series have a variance that goes to zero as the sample size increases. There are additional difficulties associated with the worldwide benchmarks. The primary idea in this investigation was the development a model to forecast the yearly the capacity factor.

The model based on historical series can predict the capacity factor, using concepts such as the autoregressive model coupled with moving average. The small difference can occur on the source of the statistical data. The power reactor information system (PRIS), developed and maintained by the IAEA, for over four decades, was used as the data sources in the investigation. The forecasting with limited information was made the possible by using the autoregressive integrated moving average (ARIMA), time-series approach. The ARIMA methodology shows the flexibility of the trend-cycle and the seasonal behavior.

2. TIME SERIES FORECASTING

In the past developing of nuclear-power generation was a technological competition among several countries. All began immediately following 1945. The pressurized water reactor (PWR) created during army nuclear power program (ANPP) started a technological race. However, strategic knowledge could disappear if operate only to increase profits. The returns arise with the higher capacity factor and better management and time of operation [2]. If a station must be shut down frequently or operate at less than full capacity, the plant will have a cost that exceeds the planned cost. Learning by doing on nuclear stations produces an increase in capacity factor [3]. The lost capacity factor was attributable to scheduled outages, equipment failure, regulatory inspection, and refueling [4].

2.1. Load Factor Nuclear Power Plant

Power plant load factors have been statistically investigated to identify trends or other sources of variation in these data. The systematic measure of this factor began in 1969, with the value of 5.8%, in a single reactor in operation. Already in 1970, we have 29 reactors with an average LF of 64.5%, in the Decade of 1980 the permanence increasing. A little fall occurs near accident events the 1978 and 1979, with 69.3% with 67.3%. In 1979, occurs the Accident at Three-Mile Island (TMI) [5]. The nuclear expansion chose the projections drastically due to accidents as TMI, Chernobyl in 1986, and Fukushima in 2011 [6]. There was substantial in safety. Therefore, the impacts were again more significant in Japan [7].

2.2. Time Series Forecast

Time series are equally time spaced from a set of sample variables observed over a period, called window, and may classify as discrete or continuous, deterministic or stochastic, multivariate or univariate. The time-series behavior may show a probabilistic process, which computes the probability of the past event given the future. The deterministic process is functional relationships prescribed by the physical law. A stochastic time series is described as sets of random variables, x, of the element measured with respect to time.

There are several methods to forecast time series, and most methods consider the observations of a past time to trace a sequence of the historical behavior pattern. There is a decomposition of series in parts such as seasonal, cyclical behaviour, trends, and random variations. The types of the forecasting model split into few parts, and autoregressive bases Box-Jenkins (BJ) methodology. The Holt-Winters is an other model, the stepwise regression models can be used to fit the first portion of the data [8]. These models predict the remainder of the data for various lead times. Historical information from anterior periods used can predict the future, with precision. Often, the data series displays a seasonal behavior.

If the tendency has a repetitive conduct, during constant intervals, it indicates a seasonality. Therefore, the electricity generated by nuclear plants shows a partial seasonality, during the year, due to demand of the commercial calendar.

2.3. Autoregressive Models

The moving average is the model most used to forecast data in a defined interval. The goal of the simple moving average is the medium value, to the variable observed in the particular period. In stochastic processes, the future values are calculated based on weights applied to the historical values of the series. The combination Moving Average (MA) and Autoregressive (AR) models are powerful to predict the next values of the series [9]. The Autoregressive-moving-average (ARMA) model can show oversimplifications [10].

The BJ method of an autoregressive, integrated moving average model, describes both the stationary behavior and non-stationary [11]. Therefore, the design has a powerful flexibility. Once validated, it can create a prediction of future values. The algorithm has three phases: identification, estimation, and validation aiming at building a prediction model. It was initial, developed as a model for series, and through the correlation function; it should reduce the sum of squared errors. In the validation phase, there is a test.

2.4. Box–Jenkins Method

The statistical approach Box-Jenkins (BJ) first published the research on control theory and time-series analysis, in 1960. The BJ methodology uses the model describing the time series produced by the average load factor since 1969 until 2014. The modeling used for historical series of load factors assumes had a stochastic process. At the same time, it tries to find the process data generator with the minimal variables. Through the model based on cycles and trends, the future value of the observed variable can be calculated.

The approach of Box-Jenkins is excellent for short-term forecasting models, with over 60 observations, mostly in the presence of seasonality. The process of determining the variable of integration order is of paramount importance used in the time series models. The misidentification order integration or some unit roots can lead to spurious regression or even statistical tests to present themselves significant, even though they have no meaning.

2.5. Seasonality and Capacity Factor

Seasonality is the similar behaviors with the cycles periodic within time series and sequences involving deviation from trends. In the American commercial reactors, occurred an increase in generating energy took place during the 1970s. However, took place during next decade a capacity lowered. Over three years before the Fukushima event in 2011, the average load factor was 63%. During last years from 2011 to 2014 all, of the 43 reactors were out of services. The risk of investments is real, because of notable variation in the capacity of operation. The effect was short oscillations on the capacity factor around the world or seasonality. The economic effect due to the reduction of the capacity factor by 10% produces a higher cost, about 10%. The conclusion is the better management applied to nuclear units. It gets a growing trend of the LF. In 1980, the average score was 209 reactors in operations, with a yearly average of 67.3%.

In 1989, were in operation 407 reactors, with 72.8% for an annual LF rate. The disaster arose in Ukraine on April 26, 1986; with a violent explosion during a series of experiments at Reactor IV of the Chernobyl was an inflection point in nuclear policies. In the year of 1986, operative a use was 73.5%, with 347 reactors in operation.

3. MATERIALS AND METHODS

Frequently, a constraint exists on the seasonal factor to justify the cyclical behavior but the model support no periodic. ARIMA models are also capable of calculating a broad range of periodic effect. The historical series and all the statistical data having as a data source the IAEA-PRIS, using the ARIMA methodology. In Table 1 and Table 2, the data nuclear reactor distribution around the world is shown and classified by types.

Table 1: Nuclear reactor distribution by region at september 2014

Regions	Reactors	Net Capacity (MWe)	Capacity (%)
Africa	2	1860	0.49
America - Latin	7	4841	1.28
Asia - Middle East and South	25	6913	29.57
Europe - Central and Eastern	69	49657	13.09
Asia - Far East	100	90014	23.73
Europe - Western	117	113837	30.02
America - Northern	118	112139	29.57
Total	438	379261	100.00

Table 2: Nuclear reactor yypes – at september 2014

Reactor Types	Reactors	Net Capacity [MWe]
Pressurized Water Reactor (PWR)	279	261052
Boiling Water Reactor (BWR)	78	74686
Pressurized Heavy-Water Reactor (PHWR)	49	24549
Light-Water Graphite Reactor (LWGR)	15	10219
Gas Graphite Reactor (GCR)	15	8175
Fast Breeder Reactor (FBR)	2	580
Total	438	379261

The approach chosen was the non-seasonal autoregressive. The model ARIMA (p, d, q), where p is the parameter that represents the order of the autoregressive factor, d is the degree of differencing and q is the order of the moving-average model. However, predictions based on the statistical information as the identical method may present a slight variation. The same methodology applied to forecast the global capacity could predict any case, using the historical series. The parameters are equal for any predicting due to the precision. The model used is the ARIMA (2, 2, 1) presented quality results, and is consistent.

In South America, only Brazil and Argentina produce electricity in nuclear plants, but other reactors are under construction. The performance of Brazilian plants is related to the years of operation. Angra-1 is the first plant built in the country and offer a capacity factor of 48.2%. The load factor is preferred model, and adopted to asses the performance of electrical generation of nuclear station. The Increase of operating years and upgrade of the load factor contributes to reducing generation cost. The load factor series of unit Angra 1 is shown in Table 3.

Table 3: Operating history Angra-1

Year	Energy (GWh)	LF (%) Annual	LF (%) cumulative
1982	51.700		
1983	162.500		
1984	1545.480		
1985	3169.380	57.8	57.8
1986	132.360	2.4	30.1
1987	910.560	16.6	25.6
1988	566.640	10.3	21.8
1989	1695.100	30.9	23.6
1990	2055.340	37.5	25.9
1991	1306.350	23.8	25.6
1992	1506.370	27.4	25.8
1993	402.700	7.3	23.8
1994	41.450	0.8	21.5
1995	2333.640	42.6	23.4
1996	2288.840	41.6	24.9
1997	2989.970	54.5	27.2
1998	3093.820	56,4	29.3
1999	3631.680	66.2	31.7
2000	3164.930	57.6	33.4
2001	3164.430	65.9	35.3
2002	3775.190	68.8	37.1
2003	3137.060	57.2	38.2
2004	3890.160	70.8	39.8
2005	3520.380	64.2	41.0
2006	3205.230	58.4	41.8
2007	2553.430	56.1	42.3
2008	3314.530	76.8	43.4
2009	2668.920	50.9	43.7
2010	4076.720	76.4	45.0
2011	4452.480	83.5	46.4
2012	5134.910	96.0	48.2
2013	3734.79	70.0	48.9
2014	4706.85	88.2	50.2

The experience and aging of units were relevant as well as securing expressive period without failures or outages, by taking adequate maintenance action. The maintenance support is necessary to take measures against components or defects due to aging. To ensure the reliability of these units, we must reinforce the cycles of preventive repairs, and shortening the outage duration for refueling. By comparing American nuclear power plants with other countries verified that average cumulative capacity generated, show a little score. Aging plants can reduce the load factor, and few countries have the high capacity as China and India, due to new units. The load factor series of station Angra 2 is shown in Table 4, since 2000.

Table 4: Operating history Angra-2

Year	Energy (GWh)	LF (%) annual	LF (%) cumulative
2000	2421.170		
2001	9904.990	85.7	85.7
2002	9238.240	82.7	84.2
2003	9418.970	84.3	84.2
2004	6919.820	61.8	78.6
2005	5676.660	50.8	73.0
2006	9778.320	87.6	75.4
2007	9096.950	81.4	76.3
2008	9894.030	88.3	77.8
2009	9554.650	85.6	78.7
2010	9697.440	86.8	79.5
2011	10342.440	92.6	80.7
2012	10035.500	89.6	81.4
2013	10045.270	89.9	82.1
2014	9756.540	87.4	82.5

The unit Angra-2 operated 14 years, since 2001 and showed a net power of 1275 MWe until 2014. The capacity factor life measured was 81.4%.

4. QUANTITATIVE FORECASTING

In the last decade of the twentieth century, there were 406 reactors in operation, with 72.6% of LF at the end of 1990. In this epoch, investments began in developing countries, increasing the prospect of nuclear energy. One of the challenges is the extension of fuel burning. New alloys based on Zirconium with 1% niobium are being tested. In 1999, 424 reactors were operated around the world, with an average LF of 82.4%.

4.1. Global Forecasting

During the period, there was an improved performance of nuclear plants. After 1980, for two decades. There was a global average LF of 68%, culminating with 86%. During the past ten years, and noticed a stabilization around 85%, a small reduction is evident. However, in Asian plants LFs record of 95%.

In 2010, the global average was 84.8%. The capacity factor notes that there is variance between the types of reactors and the influence of time operation. However, 67 units were under construction, and 2 stations were in a long-term shutdown. In Figure 1 and 2, show the global results from the ARIMA model applied to the historical series provided by PRIS. Currently, 438 nuclear reactors are in operation with 379,261 MWe of total net installed capacity through the world.

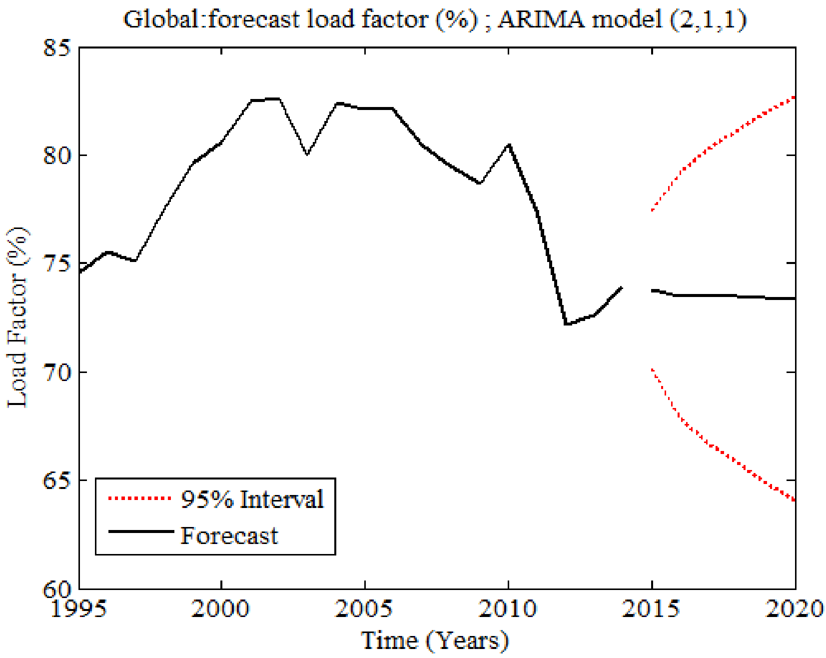

Figure 1: Forecasting global load factor for next five years.

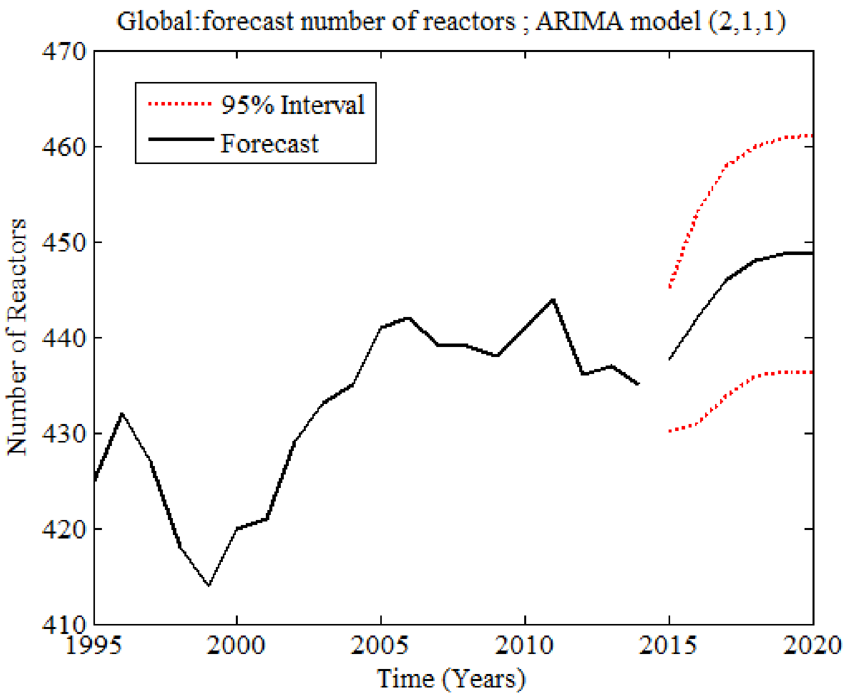

Figure 2: Forecasting a global number of reactors for next five years.

In Table 5, is shown global forecasting for next six years. The numbers of the reactor in operation really must increase in Japan. During last year, 42 units were in maintenance. However, the Japan moves toward returning the service in the second half of 2015. The refueling process, done a month before a reactor restarts.

Table 5: Global forecasting for next six years

Year	Load Factor (%)	Number of Reactors	Total Net Capacity (GW)
2015	73.78	440	376.16
2016	73.52	441	378.94
2017	73.50	442	379.96
2018	73.47	442	382.08
2019	73.42	442	383.52
2020	73.36	443	385.38

4.2. Aging Plants

The mechanism used to expand the maximum power level at which a nuclear unit may produce is called a power uprate. This procedure is practice adopted, firstly, in American units, then in the Belgium, Sweden, Germany, Switzerland, Spain, and Finland in the last decade. This process is standard to enhance the output of units, for over 30 years. Since 1977 to 2011, in the American fleet were reported about hundred power uprates approved with increases as high as 20 %. These power units were renewed, adding 4222 MWe to the grid. The capacity can increase from 1.3% to 20 %.

4.3. Brazilian Plants

In Figures 3 and 4, the results of power plants localized in Brazil are shown.

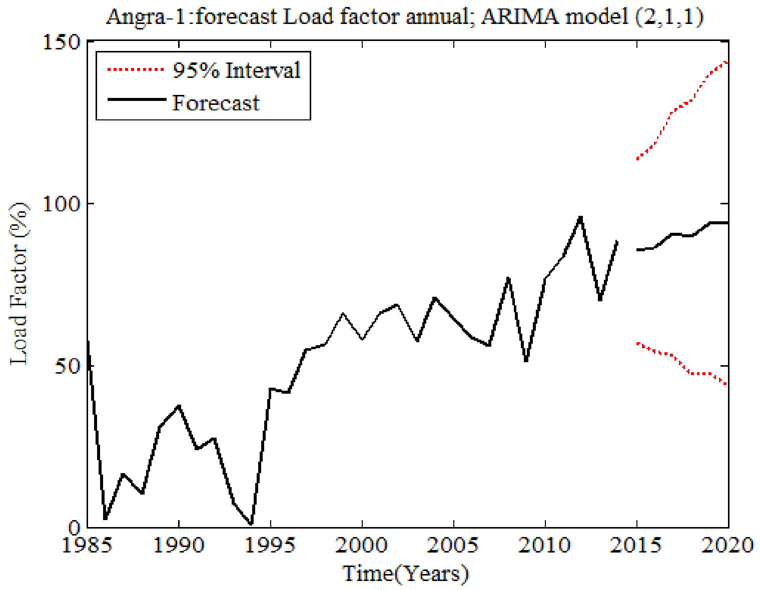

Figure 3: Angra-1 forecasting load factor for next five years.

The results were obtained from the ARIMA model applied to the historical series provided by AIEA, in the PRIS.

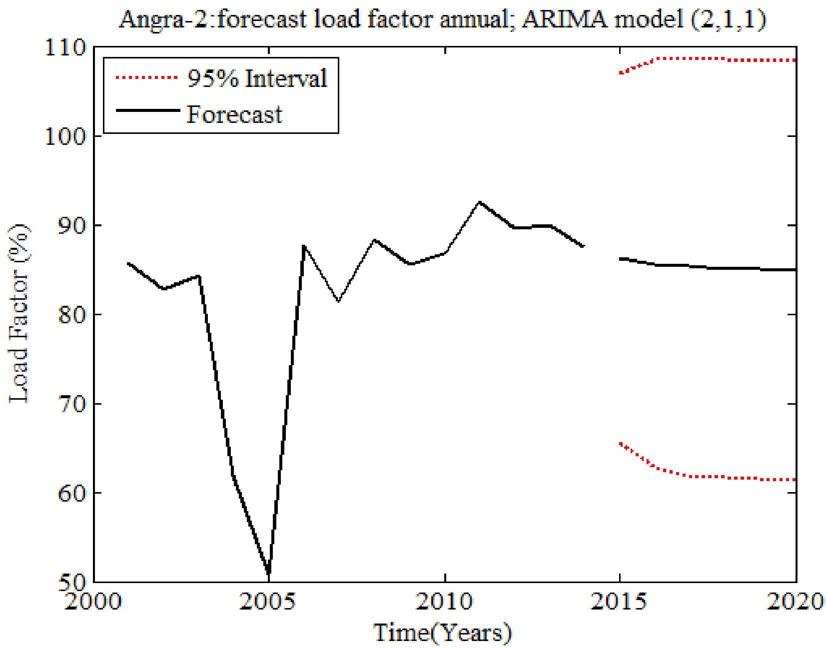

Figure 4: Angra-2 forecasting load factor for next five years.

Nowadays, an extension of a lifespan of nuclear stations built before the turn of the Millennium occurs. After 2010, many station facilities that began operations around 1970 showed the risk of losing their license. Therefore, we have many reactors nearing the end of their licensing period. In 2009, a considerable decrease in investment and a substantial reduction of nuclear investments worldwide was detected. The funds drop in part, because of the financial crisis that began in 2008, with the collapses of banks in America. Analyzes showed nuclear expertise represents actual attractive options for greenhouse gas (GHG) emission reductions, especially in countries with growth projections for energy demand.

5. CONCLUSION

The forecasts developed by using the ARIMA method predict an increase in the number of reactors around the world and at the same time show the aging of existing plants. The load factor is an annual average that was predicted by the ARIMA model for six years. The nuclear units display a scenario of operation reduced, since September 2014 exposes about fifty units, off operation over a year.

In Japan, all units are out of service between September 2011 and the second half of 2015, because of Fukushima accident. These stations undergo a new licensing, after a deep review. The 43 Japanese reactors can begin the job in next year, afterward safety modernization. In Belgium, the units Doel 1, 2, and Tihange-2, these units are offline after forty years of operation. In the worldwide, the station reaches the age limit of operation have been offline. GDF Suez-Electrabel managed to approve its operation for another ten years until 2025.

In Sweden, the operator OKG announced the extension the operation and increased power in the Oskarshamn-2 unit. The station underwent a process of modernization in the security system, between March 2014 and extended to 2017.

In Korea, the Wolsong unit 1 is awaiting the approval of the extension of operation for another seven years. The Korean unit Wolsong-1, start to operate in 1983, but was taken out of service in 2009, for an extended period of the maintenance outage. The uprate included replacement of all its pressure tubes. The unit-1 come off for three years and restart in 2015. These combined factors produce a reduction an annual average load factor by about 1%.

ACKNOWLEDGMENTS

The authors of this investigation gratefully acknowledge the sponsor from Nuclear Energy Research Institute (Instituto de Pesquisas Energéticas e Nucleares); IPEN/CNEN-SP, Brazil.

REFERENCES

1. R. G. Easterling, “Statistical analysis of US power plant capacity factors through 1979.”, *Energy*, Volume. **7,** n. 3, pp. 253-258 (1982).
2. R. Cowan “Nuclear power reactors: a study in technological lock-in.”, *The journal of economic history*, Volume. **50**, n. 03, pp. 541-567 (1990).
3. P. L. Joskow, G. A. Rozanski, “The effects of learning by doing on nuclear plant operating reliability”, *The Review of Economics and Statistics*, pp 161-168 (1979).
4. R. Beck, J. L. Solow, “Forecasting nuclear power supply with Bayesian autoregression”, *Energy Economics*, Volume**. 16**, n. 3, pp. 185-192 (1994).
5. R. F. Chisholm, S.V. KASL, B. Eskenazi, “The nature and predictors of job-related tension in a crisis situation: Reactions of nuclear workers to the Three Mile Island accident”, *Academy of Management Journal*, Volume. **26**, n. 3, pp 385-405 (1983).
6. P. H. Gudiksen, T. F. Harvey, R. Lange, “Chernobyl source term, atmospheric dispersion, and dose estimation”, *Health Physics*, Volume. **57,** n. 5, pp. 697-706 (1989).
7. Y. Du, J. E. Parsons, “Capacity Factor Risk at Nuclear Power Plants”, *Center for Energy and Environmental Policy Research (CEEPR)*, pp. 10-016 (2010).
8. G. EP. Box, G. M. Jenkins, G. C. Reinseil, *Time series analysis: forecasting and control,* John Wiley & Sons, (2011).
9. H. Akaike, “Maximum likelihood identification of Gaussian autoregressive moving average models”, *Biometrika*, Volume. **60**, n. 2, p. 255-265, (1973).
10. J. Beran, “Maximum likelihood estimation of the differencing parameter for invertible short and long memory autoregressive integrated moving average models.”, *Journal of the Royal Statistical Society,* Series B (Methodological), pp 659-672 (1995).
11. G. Rothwell; “Utilization and service: decomposing nuclear reactor capacity factors”, *Resources and Energy*, Volume**. 12**, n. 3, pp. 215-229 (1990).