THE CHARACTERISTICS OF SEISMIC TIME SERIES AND FORECAST OF MONTHLY ENERGY RELEASED AND EARTHQUAKE NUMBERS IN TAIWAN

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ABSTRACT

In this paper, the author scrutinized the time series of a number of earthquakes and energy released by them in each month for the whole of Taiwan. The data obtained from January 1995 to April 2019, that is, totally 292 months were used in this paper. Both labeled and unlabeled earthquakes recorded in the Central Weather Bureau (CWB) were analyzed to realize the characteristics of these time series. The time series of the number of earthquakes of each month, either total (labeled plus unlabeled) or labeled, were stationary by the check of Augmented Dickey-Fuller (ADF) unit root test. The time series of energy released by the earthquakes in each month, either total or labeled, were also stationary. The ARIMA (Autoregressive Integrated Moving Average) model were used to identify the time series patterns of either monthly earthquakes or energy. The author found that ARIMA (3,0,0) and ARIMA (1,0,0) were suitable to the time series of the total (labeled plus unlabeled) and labeled number of earthquakes per month, respectively. Whereas, ARIMA (1,0,0) was suitable for energy released by both total and labeled earthquakes in each month. The energy released by earthquakes in each month was huge, hence it was normalized by the energy generated by the atomic bomb dropped at Hiroshima, Japan. The ARIMA (1,0,0) model was used to forecast the energy released in each month in the year 2019. In each month, there will 2.8 atomic bombs equivalent energy be released for the total earthquakes and 2.7 for the labeled ones. The relationship between number of earthquakes and energy released was obtained by the regression equation. The adjusted coefficient of determination R_{adj}^2 can be as high as 25.43%, which explained the relationship between the energy released and number of the labeled earthquakes. Since the stationarity of each time series had been checked, the regression equation was not spurious, which usually occurred when two nonstationary time series were used in regression.

Key Words: Spurious, Stationarity, ARIMA

1. Introduction

Taiwan locates on the Circum-Pacific seismic zone, people experience tremor of earthquakes from time to time. To understand rather than ignore seismic characteristics is important for the people living there. Using statistics to study the seismic properties, such the magnitude, intensity, return period, depth, etc. was one of the good ways. However, using time series, which collected important data of earthquakes, gained more attention recently. Originally, time series applied to financial and macroeconomics, but the records of seismic can be expressed as time series. This was the background why the author gained the idea of the application time series to study the

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characteristics of earthquakes. Hope such kind of research can find some hidden secrets of earthquakes and reduce the damage and casualty to the minimum if a strong quake occurs.

In this study, the author adopted the public archive of the Central Weather Bureau (CWB) of Taiwan [1], and then extracted the total (labeled plus unlabeled) and labeled number of earthquakes and their magnitude from January 1995 to April 2019. Totally, 292 months of data were collected. The magnitude of an earthquake represents its energy released, and the equation proposed by Gutenberg and Richter [2,3] was used to calculate the energy issued by each earthquake. Since the energy was usually huge, it was "normalized" by the energy of the atomic bomb which was dropped on Hiroshima, Japan. The atomic bomb with code-named Little Boy [5] produced 6.3E+20 ergs of energy when detonated on Hiroshima, Japan.

The stationarity of a time series is not explosive, nor trending, and nor wandering aimlessly without returning to its mean [6,7]. Whether the time series of a monthly number of earthquakes and their energy released is stationary or not will be checked carefully by the augmented Dickey-Fuller (ADF) unit root test [7]. The stationarity evaluation for each time series was done by Stata and double checked by Eviews. All the graphs were plotted by Minitab. Two types of earthquakes, labeled and unlabeled were recorded in the CWB archive [1]. The labeled one was magnitude larger than 4.0, and the unlabeled one released less energy and affected only locally [1]. Both the time series of the total (labeled plus unlabeled) and labeled earthquakes were scrutinized for the whole of Taiwan. The monthly energy released and earthquake numbers were shown in Appendix A.

2. Time Series of Number of earthquakes per month in Taiwan

2.1 Total (labeled plus unlabeled) earthquakes per month in Taiwan

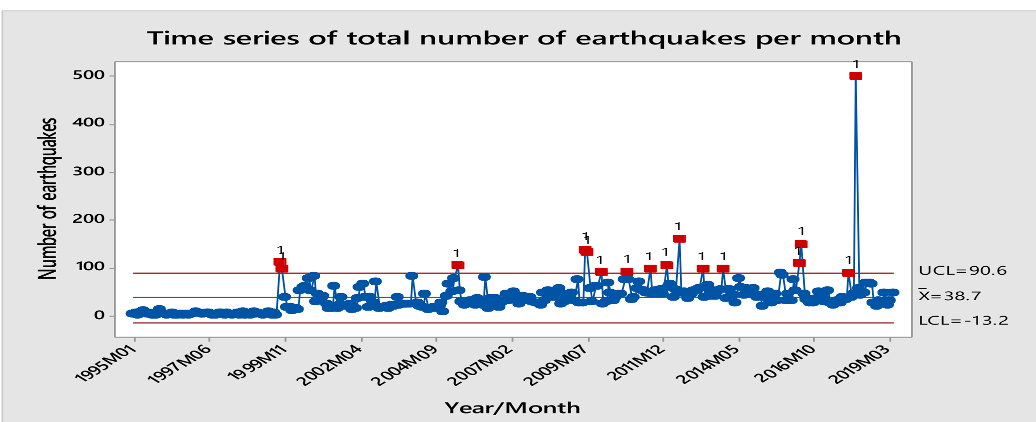

Figure 1: Total earthquakes per month from January 1995 to April 2019

From the figure above, one found that there were 16 months of total earthquake numbers above three standard errors of the mean. One peak point can be observed on the upper right corner, which was astonished 500 earthquakes in February 2018.

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2.1.1 Stationarity check of a number of total earthquakes per month

The Augmented Dickey-Fuller (ADF) unit root test was used to check the stationarity of the time series of the total number of earthquakes per month. The test result was as follows:

$$\Delta MonTotal_t = 27.016 - 0.6951 MonTotal_{t-1} \quad (1)$$
$$(\tau(t)) \quad (8.85) \quad (-12.42)$$

Where

$\Delta MonTotal_t$ = Difference of total number of earthquakes per month at time t

$MonTotal_{t-1}$ = Total number of earthquakes per month at time $t-1$

Table 1: The critical values and Dickey-Fuller unit root test for monthly total earthquakes from January 1995 to April 2019 for the entire Taiwan

$\tau(t)$ Test statistic	1% Critical value	5% Critical value	10% Critical value
-12.42	-3.43	-2.86	-2.57
MacKinnon approximate p-value for $\tau(t)$ = 0.0000			

The null hypothesis H_0: nonstationary was rejected at 5% level of significance. In other words, the time series of the total number of earthquakes per month was stationary.

2.1.2 Pattern identification

The autoregressive integrated moving average ARIMA(p,q,r) method was used in identifying the suitable pattern to simulate and forecast the numbers and energy of earthquakes. The detailed procedures of ARIMA(p,q,r) can be referred to Appendix C.

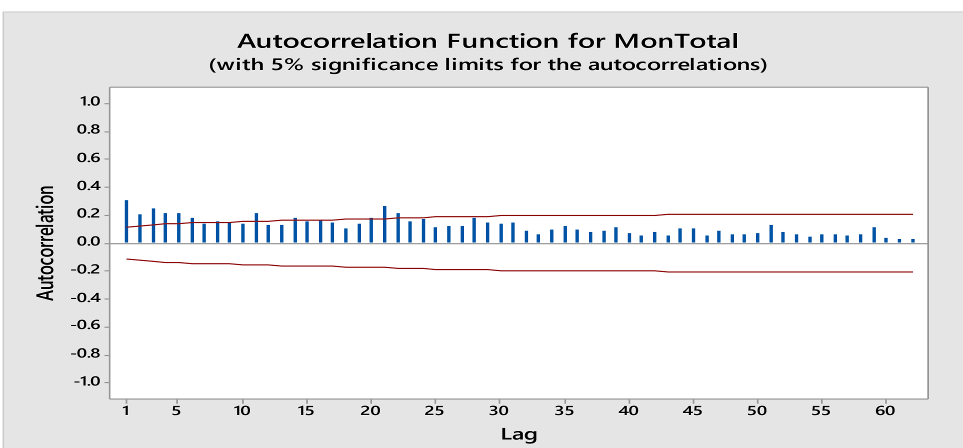

Figure 2: Autocorrelation function (ACF) of the time series of the total number of earthquakes per month

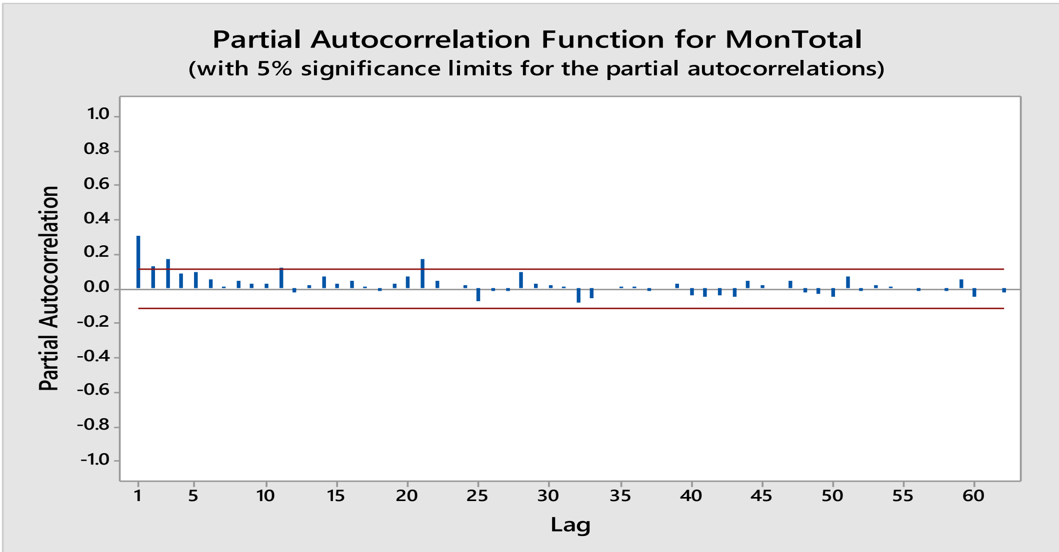

Figure 3: Partial autocorrelation function (PACF) of the total number of earthquakes per month

By trial and errors, one finds that ARIMA(3,0,0) was suitable to be the pattern of the total earthquakes per month, and the autocorrelation function (ACF) of the residuals was as follows:

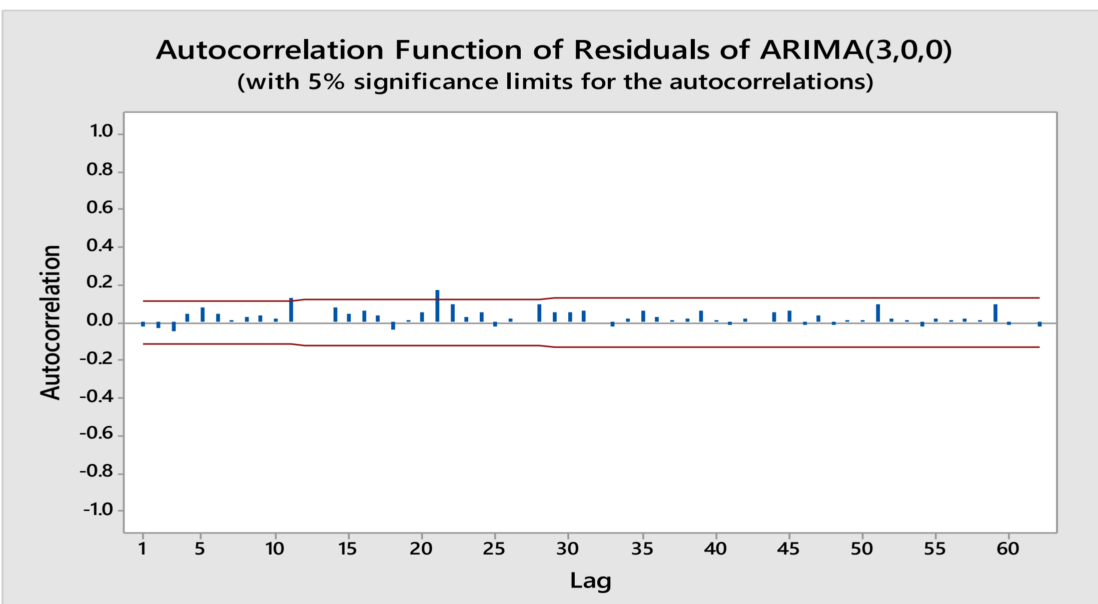

Figure 4: Autocorrelation function (ACF) of the residuals of ARIMA(3,0,0)

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From the above figure, one found that the autocorrelation function of residuals of ARIMA(3,0,0) was within two standard errors of the mean (between two red-line). It means no autocorrelation between the residuals, and ARIMA(3,0,0) might be a suitable model for forecasting the total number of earthquakes in every month. The error analysis of ARIMA(3,0,0) was given in the next subsection.

2.1.3 Error analysis

The purpose of error analysis was to check the accuracy of the proposed model, ARIMA(3,0,0). By using the data from January 1995 to December 2014 to forecast the total number of earthquakes for the next 12 months in 2015. Comparing observed and those predicted by ARIMA(3,0,0), and found the average error numbers in each month of 2015. This procedure repeated from 2015 to 2018, the average error per month can be obtained. The mean absolute deviation (MAD) method [6] was used to check the deviation of the forecasted observed data. The calculation of MAD method was shown in Appendix B. The average error in the number of earthquakes for each month was shown in the following table:

Table 2: Average error in the number of total earthquakes per month from 2015 to 2018

Year	2015	2016	2017	2018	Average error
Average error of number of total earthquakes per month	15	24	11	14	16

The average number of earthquakes per month from the years 2015 to 2018 was 16. This double-digits error may have a space to be improved.

2.1.4 Forecast number of total earthquakes per month

Using ARIMA (3,0,0) model to forecast the total number of the 12 months in 2019 was as follows:

Table 3: The forecast for the total number of earthquakes per month in 2019

Month	1	2	3	4	5	6	7	8	9	10	11	12
Number of total earthquakes	32	35	35	36	37	37	38	38	38	38	38	38

2.2 Labeled earthquakes per month in Taiwan

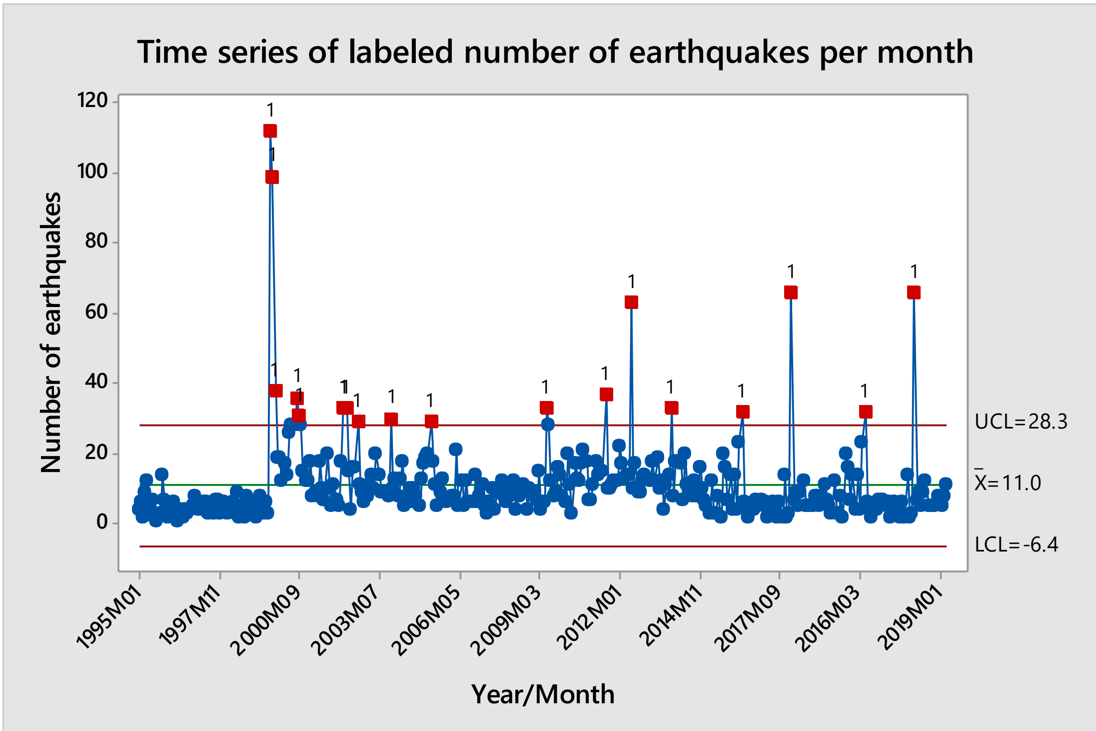

Figure 5: Labeled earthquakes per month from January 1995 to April 2019

The mean value of the labeled number of earthquakes per month from January 1995 to April 2019 (292 months) was 11. There were 17 months with the labeled number of earthquakes above three standard errors of the mean. On September 1999, one magnitude 7.3 earthquakes occurred, which induced 112 labeled earthquakes in that month.

2.2.1 Stationarity check of the labeled earthquakes per month

The stationarity of the time series of the labeled earthquakes was checked in this subsection. The Augmented Dickey-Fuller (ADF) unit-root test [7] was used to check the stationarity of the time series of the labeled number of earthquakes per month. The test result was as follows:

$$\Delta MonLabel_t = 6.427 - 0.5616 MonLabel_{t-1} \quad (2)$$

$$(\tau(t)) \quad (7.51) \quad (-10.63)$$

where

$\Delta MonLabel_t$ = Difference of labeled number of earthquakes per month at time t

$MonLabel_{t-1}$ = Labeled number of earthquakes per month at time t-1

Table 4: The critical values and Augmented Dickey-Fuller unit root test for monthly labeled earthquakes from January 1995 to April 2019 for the entire Taiwan

$\tau(t)$ Test statistic	1% Critical value	5% Critical value	10% Critical value
-10.63	-3.43	-2.86	-2.57
MacKinnon approximate p-value for $\tau(t)$ = 0.0000			

The null hypothesis H_0: nonstationary was rejected at 5% level of significance. In other words, the time series of the total number of earthquakes per month was stationary.

2.2.2 Pattern identification

The versatile ARIMA (p,q,r) [6,7] method was used to identify the time series pattern of the labeled number of earthquakes per month. Two graphs, autocorrelation function (ACF) and partial autocorrelation function (PACF) can be used to guess the suitable values of arguments (p,q,r) of the ARIMA model. As long as a suitable model was selected and use it to simulate the time series, the autocorrelation of the residuals will fall between two standard errors of the mean [6,7].

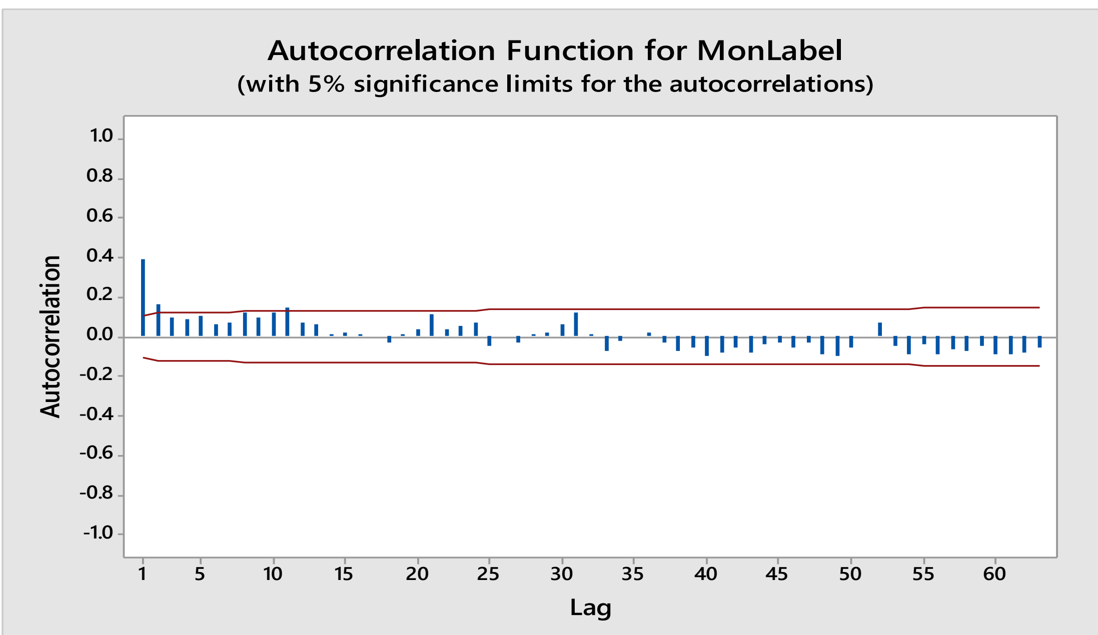

Figure 6: Autocorrelation function of the labeled number of earthquakes from January 1995 to April 2019

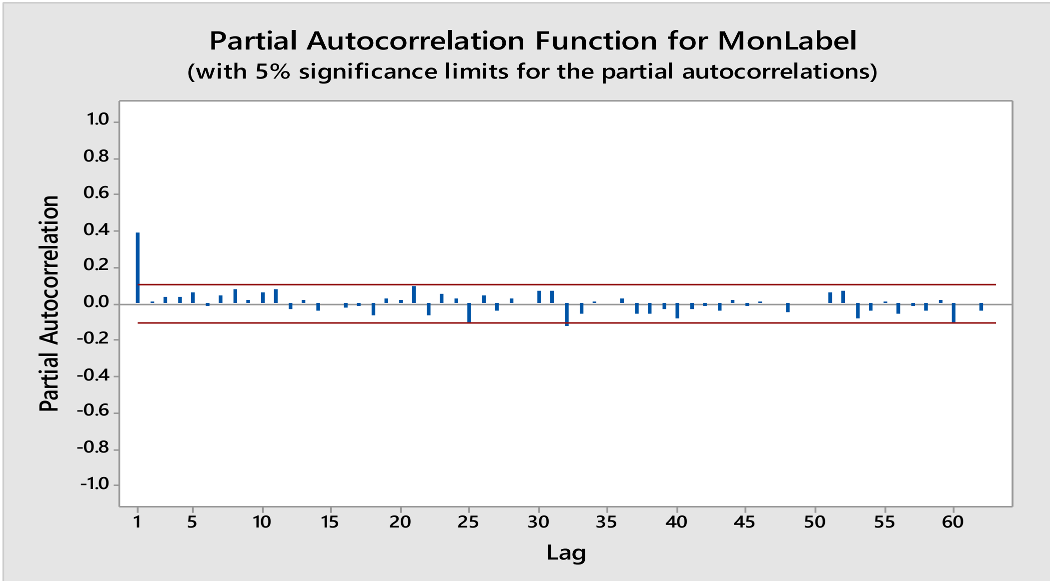

Figure 7: Partial autocorrelation function of the labeled number of earthquakes from January 1995 to April 2019

From the above two graphs, one can identify the ARIMA(1,0,0) might be a suitable one[6]. Using ARIMA(1,0,0) to run the time series, and run the autocorrelation function of the residuals, as follows:

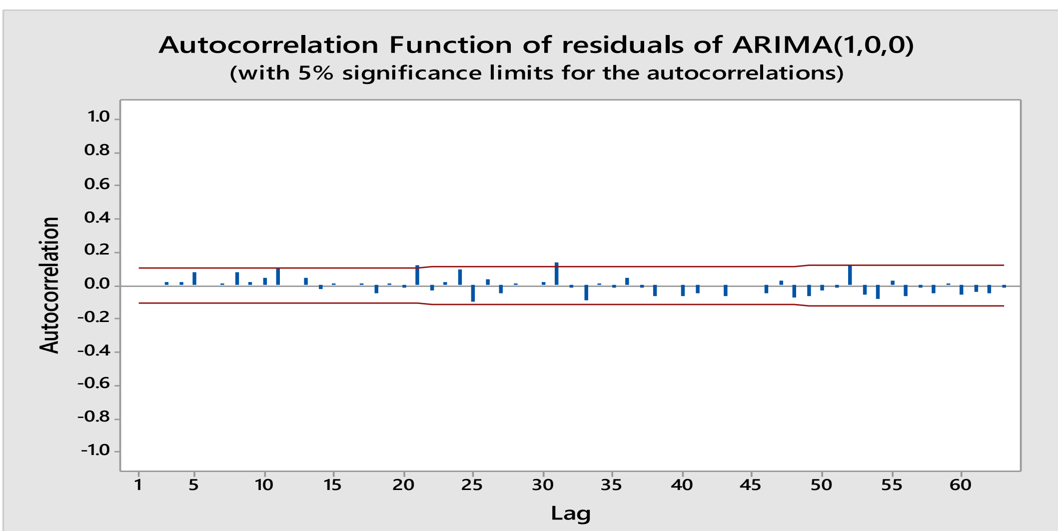

Figure 8: Autocorrelation function of the residuals of ARIMA(1,0,0)

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The autocorrelation functions (ACF) of the residuals were between two standard error of the mean, means the ARIMA(1,0,0) model was suitable for the simulate the time series of the labeled earthquakes per month.

2.2.3 Error analysis

The purpose of error analysis was to check the accuracy of the proposed model, ARIMA(1,0,0). By using the data from January 1995 to December 2014 to forecast the labeled number of earthquakes for the next 12 months in 2015. Comparing observed and those predicted by ARIMA(1,0,0), and found the average error numbers in each month of 2015. This procedure repeated from 2015 to 2018, the average error per month can be obtained. The result was shown in the following table:

Table 5: Average error number of labeled earthquakes per month from 2015 to 2018

Year	2015	2016	2017	2018	Average error
Average error of number of labeled earthquakes per month	6	8	7	4	6

The average error number of labeled earthquakes per month from the years 2015 to 2018 was 6. This single-digit error may be acceptable, although still has a space to be improved.

2.2.4 Forecast number of labeled earthquakes per month

The forecast of the labeled number of earthquakes of the 12 months in 2019 by using ARIMA (1,0,0) model was as follows:

Table 6: The forecast for the labeled number of earthquakes per month in 2019

Month	1	2	3	4	5	6	7	8	9	10	11	12
Number of labeled earthquakes	10	11	11	11	11	11	11	11	11	11	11	11

3. Time series of energy released in Taiwan

3.1 The energy released of total earthquakes per month in Taiwan

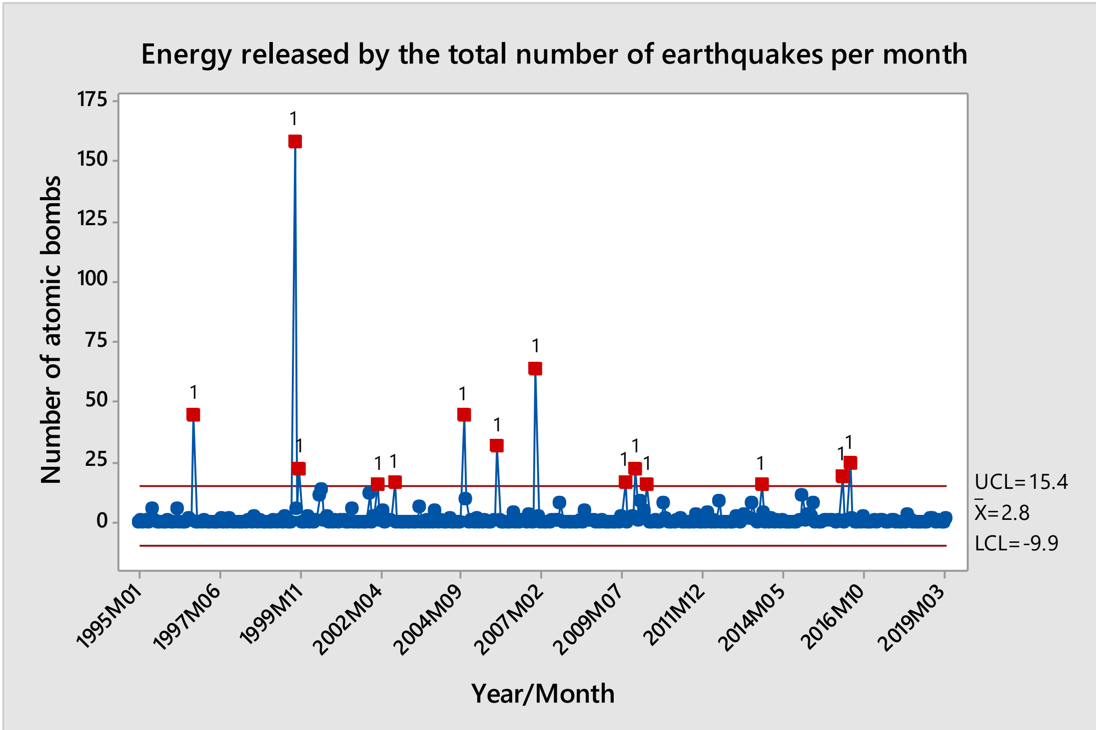

Figure 9: Energy released by the total number of earthquakes per month by the atomic bombs

The mean value of the energy released per month was equivalent to 2.8 atomic bombs dropped in Hiroshima, Japan. There were 14 times in the past 292 months over three standard errors above the mean. They were abnormally large. The largest month was September 1999, the energy released equivalent to 158.56 atomic bombs.

3.1.1 Stationarity check of energy released by the total number of earthquakes per month

The stationarity of the time series of the energy released by the total earthquakes per month is checked in this subsection. The Augmented Dickey-Fuller (ADF) unit root test was used to check the stationarity of the time series of the total number of earthquakes per month. The test result is as follows:

$$\Delta BomTotal_t = 2.779 - 0.9934 BomTotal_{t-1} \qquad (3)$$

$$(\tau(t)) \quad (4.07) \quad (-16.89)$$

Where

$\Delta BomTotal_t$ = Difference of atomic bomb numbers generated by the energy released by the total number of earthquakes per month at time *t*

$BomTotal_{t-1}$ = Atomic bomb numbers generated by the energy released by the total

number of earthquakes per month at time *t-1*

Table 7: The critical values and Augmented Dickey-Fuller unit root test [7] for monthly labeled earthquakes from January 1995 to April 2019 for the entire Taiwan

$\tau(t)$ Test statistic	1% Critical value	5% Critical value	10% Critical value
-16.890	-3.43	-2.86	-2.57
MacKinnon approximate *p*-value for $\tau(t)$ = 0.0000			

The null hypothesis H_0: nonstationary was rejected at 5% level of significance. In other words, the time series of the total number of earthquakes per month was stationary.

3.1.2 Pattern identification of the energy generated by the total number of earthquakes per month

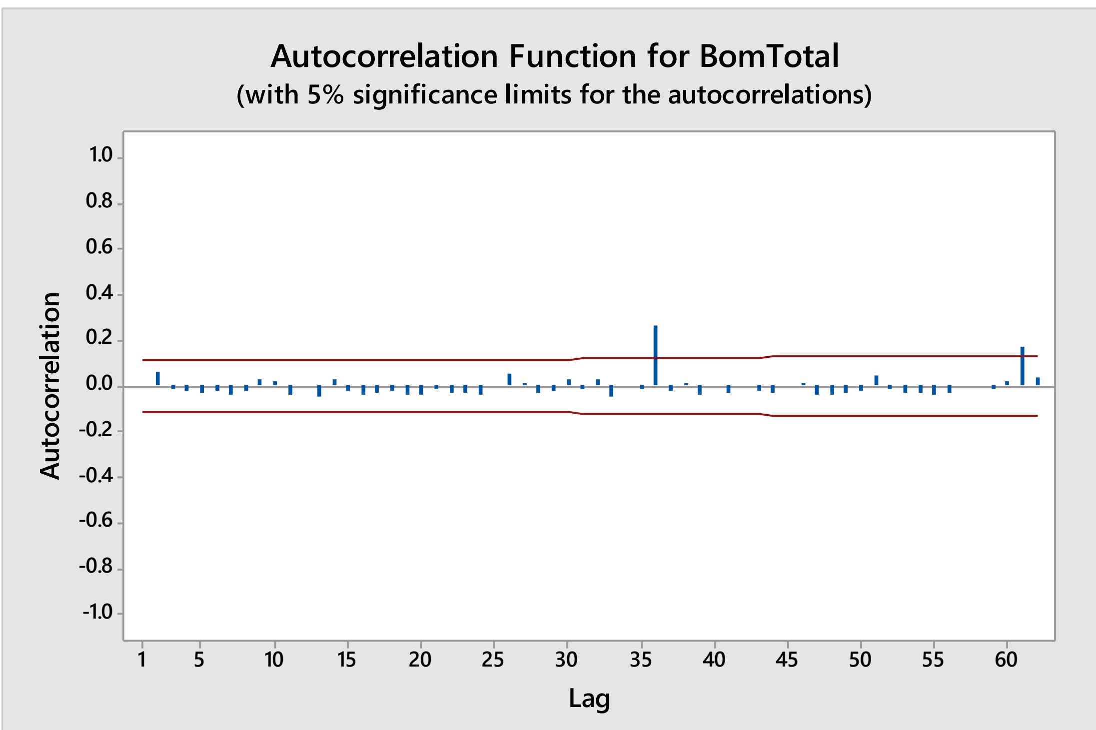

Figure 10: Autocorrelation function (ACF) of energy released by the total number of earthquakes per month

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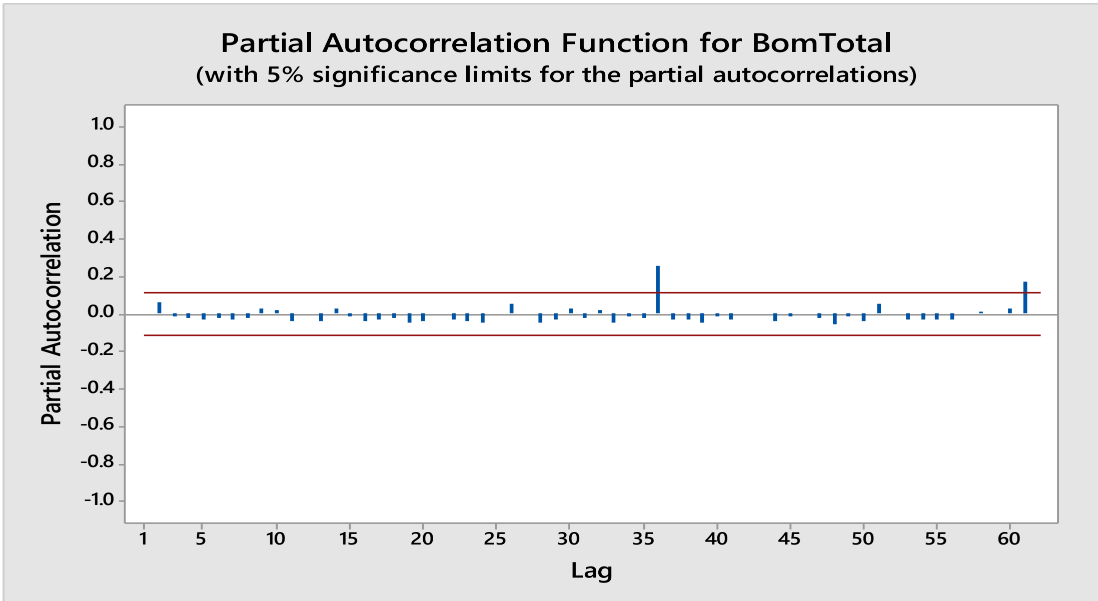

Figure 11: Partial autocorrelation function (PACF) of the energy released by the total number of earthquakes per month

The patterns of the ACF and PACF shown no autocorrelation of the time series. ARIMA(1,0,0) can be a candidate.

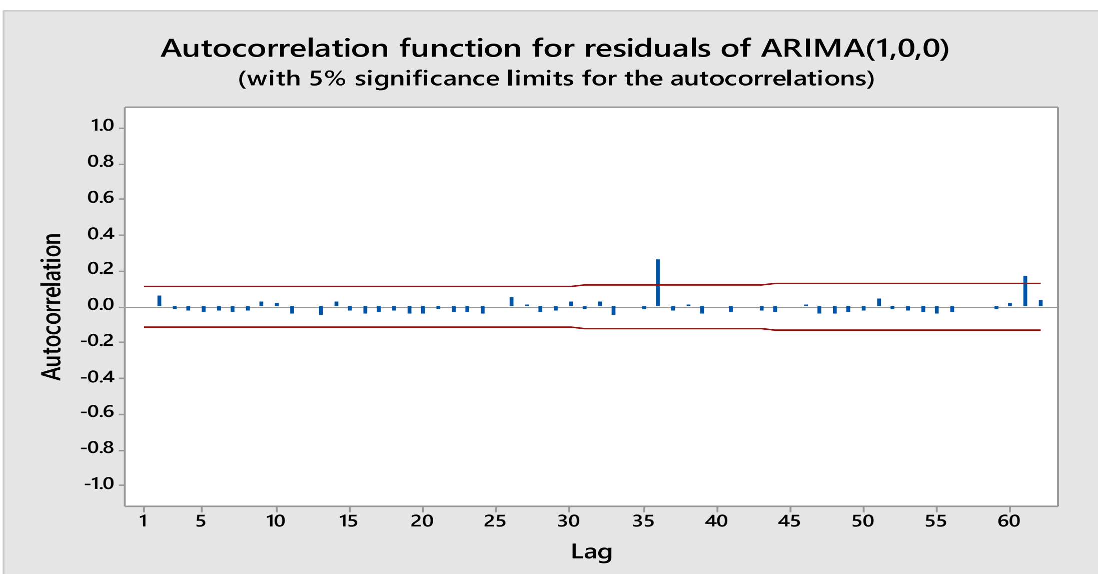

Figure 12: Autocorrelation function of ARIMA(1,0,0)

3.1.3 Error analysis

The purpose of error analysis is to check the accuracy of the proposed model, ARIMA(1,0,0). By using the data from January 1995 to December 2014 to forecast the energy released by the total number of earthquakes for the next 12 months in 2015. Comparing observed and those predicted by ARIMA(1,0,0) and found the average error of energy in each month of 2015. This procedure repeated from 2015 to 2018, the average error per month can be obtained. The result was shown in the following table:

Table 8: Average energy error in terms of atomic bombs of total earthquakes per month from 2015 to 2018

Year	2015	2016	2017	2018	Average error
Average error of atomic bomb numbers per month	2.4	5.1	2.6	2.2	3.1

The average error of energy released by the total earthquakes per month from years 2015 to 2018 was 3.1 atomic bombs. This single-digit error may be acceptable, although still has a space to be improved.

3.1.4 Forecast energy released per month by the total earthquakes

The forecast for the total number of atomic bombs of the 12 months in 2019 was as follows:

Table 9: The forecasted energy released atomic bombs by total earthquakes per month in 2019

Month	1	2	3	4	5	6	7	8	9	10	11	12
Number of atomic bombs by the total earthquakes	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8

3.2 The energy released of labeled earthquakes per month in Taiwan

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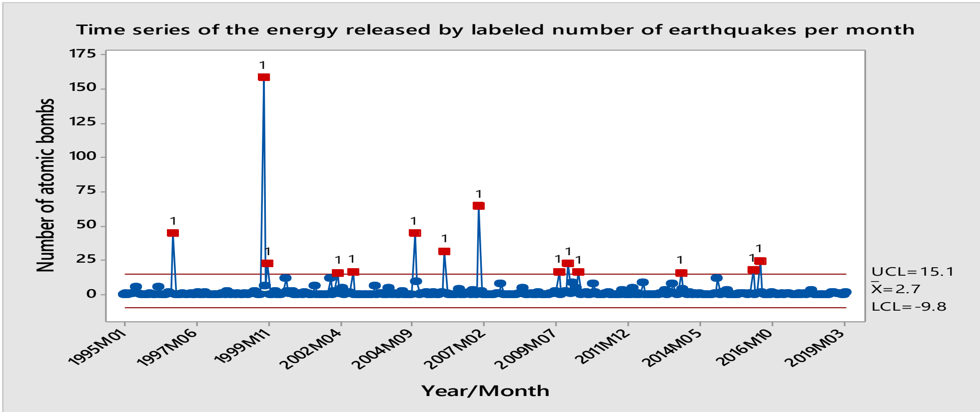

Figure 13: Time series of the energy released by the labeled earthquakes in terms of atomic bombs from January 1995 to April 2019

The mean value of the energy released by the labeled earthquakes equivalent to 2.7 atomic bombs. There was 14 months' energy released above three standards above the mean. The peak value was in September 1999, which was equivalent to 158.56 atomic bombs.

3.2.1 Stationarity check of the labeled earthquakes per month

The stationarity of the time series of the energy released by the labeled earthquakes per month is checked in this subsection. The Augmented Dickey-Fuller (ADF) unit-root test [7] was used to check the stationarity of the time series of the labeled number of earthquakes per month. The test result was as follows:

$$\Delta BomLabel_t = 2.649 - 0.9938 BomLabel_{t-1} \quad (4)$$

$$(\tau(t)) \quad (3.90) \quad (-16.90)$$

Where

$\Delta BomLabel_t$ = Difference of atomic bomb numbers generated by the energy released by the labeled number of earthquakes per month at time *t*

$BomLabel_{t-1}$ = Atomic bomb numbers generated by the energy released by the labeled number of earthquakes per month at time *t-1*

Table 10: The critical values and Dickey-Fuller unit root test for monthly labeled earthquakes from January 1995 to April 2019 for the entire Taiwan

$\tau(t)$ Test statistic	1% Critical value	5% Critical value	10% Critical value
-16.897	-3.43	-2.86	-2.57
MacKinnon approximate *p*-value for $\tau(t)$ = 0.0000			

The null hypothesis H_0: nonstationary was rejected at 5% level of significance. In other words, the time series of the total number of earthquakes per month was stationary.

3.2.2 Pattern identification of energy generated by the labeled number of earthquakes per month

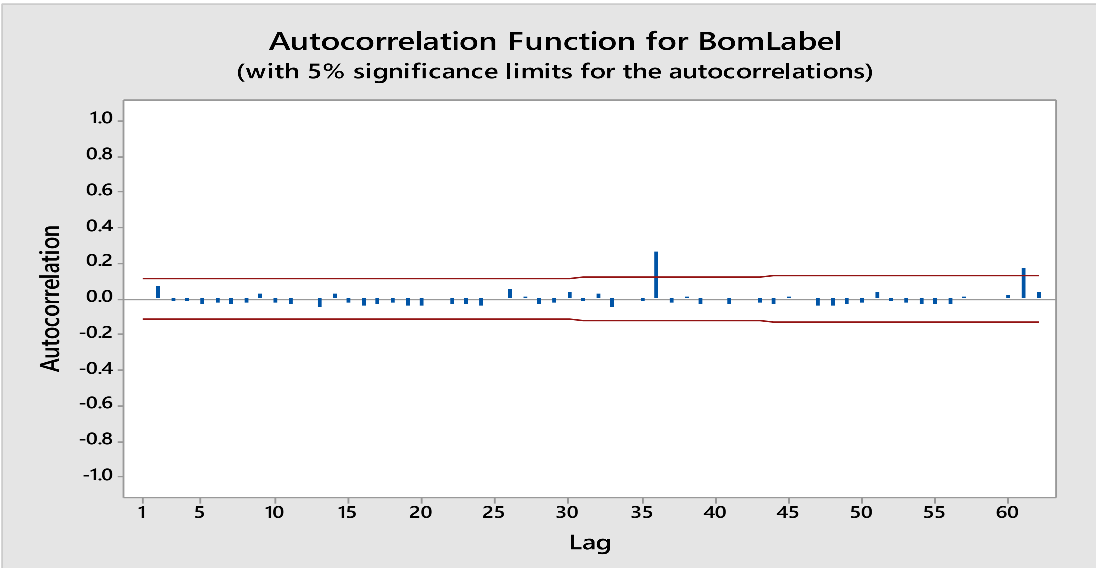

Figure 14: Autocorrelation function of the energy released by the labeled earthquakes in each month

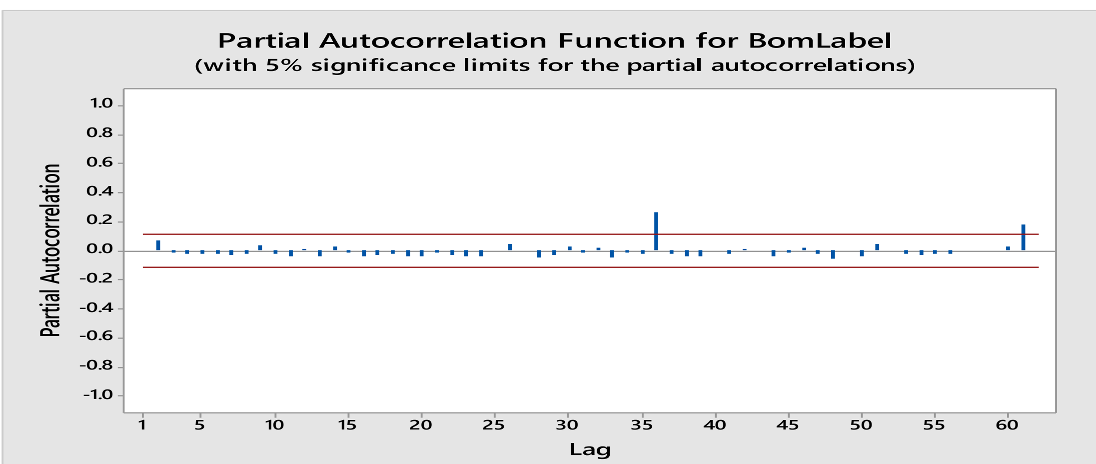

Figure 15: Partial autocorrelation function of the energy released by labeled earthquakes in each month

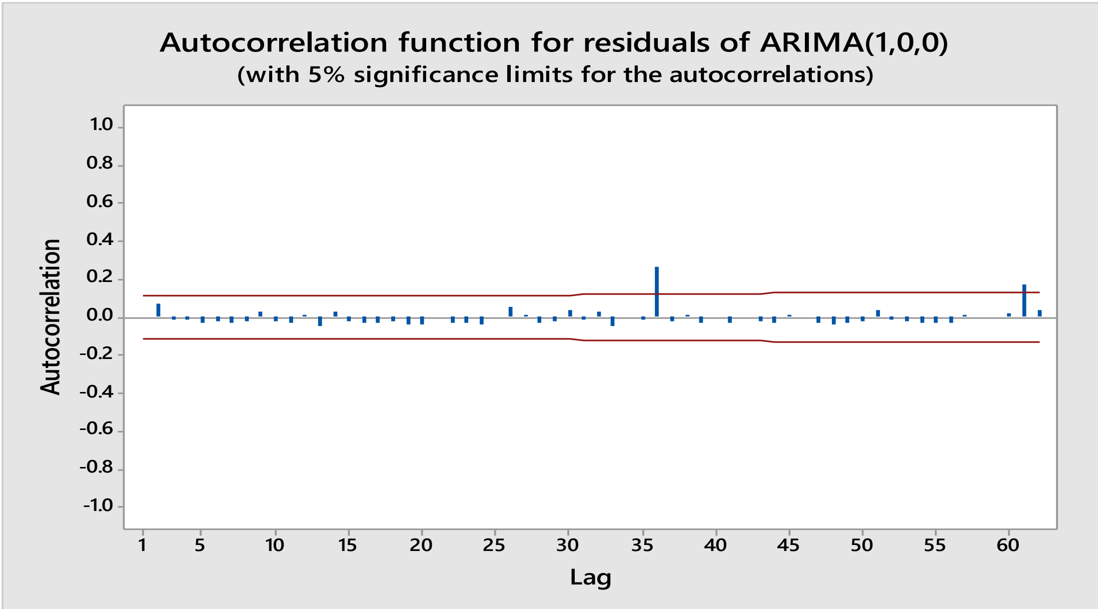

Figure 16: The autocorrelation function of the residuals by ARIMA(1,0,0) model

The ARIMA(1,0,0) of the residuals of the labeled energy in each month was suitable.

3.2.3 Error analysis of energy released by the labeled earthquakes per month

The purpose of error analysis was to check the accuracy of the proposed model, ARIMA(1,0,0). By using the data from January 1995 to December 2014 to forecast the energy released by the labeled earthquakes for the next 12 months in 2015. Comparing observed and those predicted by ARIMA(1,0,0) and found the average error of energy in each month of 2015. This procedure repeated from 2015 to 2018, the average error per month can be obtained. The result was shown in the following table:

Table 11: Average energy error in terms of atomic bombs of labeled earthquakes per month from 2015 to 2018

Year	2015	2016	2017	2018	Average error
Average error of number of atomic bombs per month	2.2	5.0	2.6	2.2	3.0

The average error of energy released by the labeled earthquakes per month from years 2015 to 2018 is 3.0 atomic bombs. This single-digit error may be acceptable, although still has a space to be improved.

3.2.4 Forecast energy released per month by the labeled earthquakes

The forecast for the number of atomic bombs of the 12 months in 2019 was as follows:
Table 12: The forecast of energy equivalent atomic bombs released by the labeled earthquakes per month in 2019

Month	1	2	3	4	5	6	7	8	9	10	11	12
Number of atomic bombs by the labeled total earthquakes	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7

4. Regression analysis

4.1 The energy released by the total number of earthquakes

$$BomTotal = 0.0586MonTotal \;;\; R^2_{adj} = 7.27\% \qquad (5)$$

Where *BomTotal* is energy released by the total earthquakes per month; and *MonTotal* is a number of earthquakes per month. R^2_{adj} is the coefficient of determination adjusted for the appropriate degrees of freedom [6]. R^2_{adj}=7.27% means that the energy released by the total earthquakes can be explained by the total earthquakes per month only 7.27%.

4.2 The energy released by the labeled earthquakes

$$BomLabel = 0.3612MonLabel \;;\; R^2_{adj} = 25.43\% \qquad (6)$$

Where *BomLabel* is energy released by the labeled earthquakes per month; and *MonLabel* is the number of labeled earthquakes per month. R^2_{adj} is the coefficient of determination adjusted for the appropriate degrees of freedom [6]. R^2_{adj}=25.43% means that the energy released by the total earthquakes can be explained by the total earthquakes per month up to 25.43%.

5. Conclusions:

From the calculation of the previous sections, the following conclusions can be obtained:

(1) The time series of a number of earthquakes and energy released per month from January 1995 to April 2019 was stationary by the augmented Dickey-Fuller (ADF) unit root test.

(2) The mean values of the total and labeled number of earthquakes per month were 38.7 and 11.0 respectively. ARIMA(3,0,0) was a suitable model to forecast the total number of earthquakes per month, and ARIMA(1,0,0) was appropriate for the labeled number of earthquakes. The forecasted numbers for total and labeled number of earthquakes per month in the next 12 months closed to the mean values, they were 38 times for total earthquakes, and 11 times for labeled earthquakes.

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(3) The mean values of the energy released by the total and labeled number of earthquakes per month equivalent to 2.8 and 2.7 atomic bombs, respectively. ARIMA(1,0,0) was a suitable model to forecast the energy released by the total number of earthquakes per month, and ARIMA(1,0,0) was appropriate for the energy released by the labeled number of earthquakes. The forecasted energy released by the total and labeled number of earthquakes per month in the next 12 months closed to the mean values, they were 2.8 atomic bombs for the total earthquakes, and 2.7 for the labeled earthquakes.

(4) The regression equations between the energy released and a number of earthquakes were obtained. The coefficient of determination adjusted for the appropriate degree of freedom (R^2_{adj}) for the labeled earthquakes was 25.43%, and it means the energy released by the labeled earthquakes can be explained by the proposed regression equation up to 25.43%. Because the time series for a number of earthquakes per month and energy released by them were stationary, hence, no spurious risk will occur.

6. References

[1]. Central Weather Bureau (CWB) of Taiwan. http://www.cwb.gov.tw. Accessed 5 May 2019.

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7. Appendices

7.1 Appendix A: Earthquake numbers and energy released from January 1995 to April 2019

Table A1: Monthly number of total (labeled plus unlabeled), labeled earthquakes, and their energy released in terms of atomic bombs (only partly shown)

Year/Month	MonTotal	MontLabel	BomTotal	BomLabel
1995M01	4	4	0.06	0.06
1995M02	6	6	0.60	0.60

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1995M03	2	2	0.27	0.27
1995M04	9	9	1.02	1.02
1995M05	12	12	0.36	0.36
1995M06	4	4	5.77	5.77
1995M07	7	7	0.65	0.65
1995M08	2	2	0.04	0.04
1995M09	1	1	0.01	0.01
1995M10	3	3	0.05	0.05
1995M11	14	14	0.10	0.10
1995M12	7	7	1.02	1.02
1996M01	4	4	0.06	0.06
1996M02	2	2	0.01	0.01
1996M03	5	5	5.27	5.27
1996M04	6	6	0.04	0.03
1996M05	2	2	0.05	0.05
1996M06	1	1	0.02	0.02
1996M07	4	4	1.51	1.50
1996M08	2	2	0.52	0.52
1996M09	4	4	44.93	44.93
1996M10	3	3	0.02	0.02
1996M11	4	4	0.22	0.22
1996M12	5	5	0.07	0.07
…	…	…	…	…
2018M01	45	3	0.39	0.36

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2018M02	500	66	3.34	3.09
2018M03	58	7	0.89	0.13
2018M04	44	9	0.11	0.04
2018M05	48	5	0.23	0.20
2018M06	69	9	0.15	0.09
2018M07	68	12	0.32	0.05
2018M08	66	5	0.11	0.06
2018M09	28	5	0.02	0.02
2018M10	21	5	1.38	1.37
2018M11	33	5	1.56	1.43
2018M12	27	8	0.34	0.33
2019M01	49	8	0.51	0.50
2019M02	23	5	0.06	0.06
2019M03	33	8	0.23	0.20
2019M04	49	11	1.85	1.82

Note:

(A1) MonTotal: Total of number of earthquakes per month

(A2) MonLabel: Labeled number of earthquakes per month

(A3) BomTotal: Energy generated by the total number of earthquakes per month (equivalent atomic bomb numbers)

(A4) BomLabel: Energy generated by the labeled number of earthquakes per month (equivalent atomic bomb numbers)

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7.2 Appendix B: Deviation check of the observed and forecasted number of earthquakes per month and energy released in terms of atomic bombs

The mean absolute deviation (MAD) method [6] is used to check the deviation of the forecasted number of labeled earthquakes and the observed data. The mean absolute deviation method has the form:

$$\text{MAD} = \frac{1}{n}\sum_{t=1}^{n}\left|Y_t - \hat{Y}_t\right| \qquad \text{(B1)}$$

Where n is the number of observed data, Y_t is the real number of labeled earthquakes at time t, $\hat{Y}_t$ is the number of forecasting labeled earthquakes at time t.

7.3 Appendix C: ARIMA(p,q,r) forecasting procedures

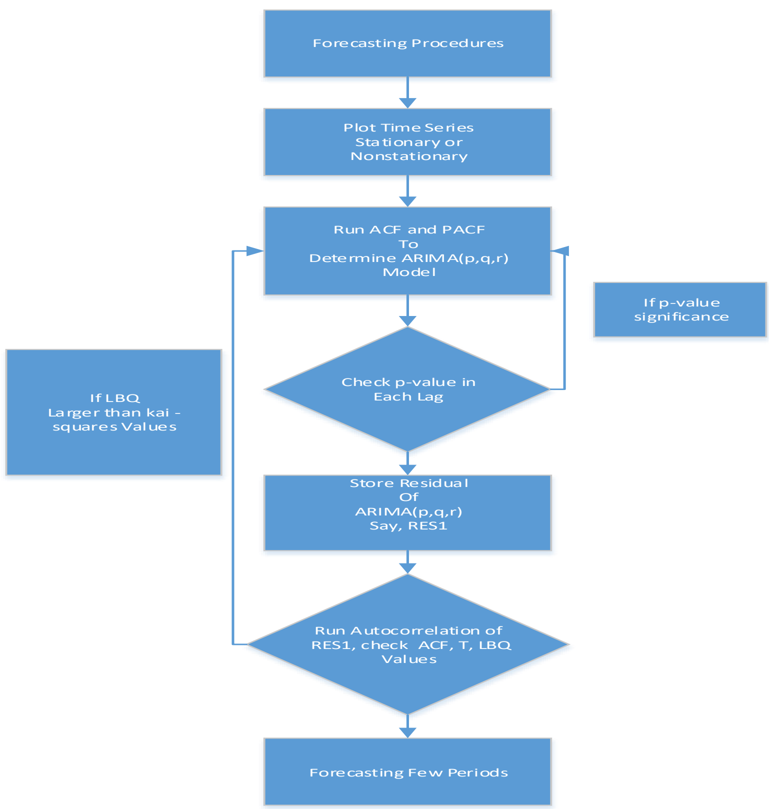

Figure C1: ARIMA(p,q,r) forecasting procedures