Tripartite Analysis of COVID-19's Impact on Stock Prices: A Case of Tesla Supply Chain in Taiwan

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Abstract

In this article, we analyzed the impact of COVID-19 on Tesla supply chain stock prices from three perspectives: modern portfolio theory, event study approach, and interactive seemingly unrelated regression estimation. We investigated the top ten Tesla related stocks in Taiwan. Our observations are summarized as follows. (1) The expected rate of return in the stock market had showed a significant decline in the early stage of the outbreak. The average investment risk 70 days after COVID-19 was announced as Public Health Emergency of International Concern was significantly higher than 70 days prior to the announcement. However, the extent of impact for each stock varied among Tesla related stocks. (2) The day when COVID-19 was declared as a pandemic, negative Cumulative Average Abnormal Returns (CAAR) were immediately observed. In contrast, when Taiwan government announced the lockdown of border and the confirmed cases of navy members on the Dunmu Fleet, Taiwan stock market did not react negatively to the news and for some days CAARs even appeared to be positive. (3) Taiwan's stock market was relatively stable during the pandemic. The reason why COVID-19 had negative impacts on Taiwan stock market in 2020 was mainly due to the disease situation of foreign epidemic.

Keywords: COVID-19, Tesla Supply Chain, Modern Portfolio Theory, Event Study, Interactive Seemingly Unrelated Regression

JEL Classifications: C33, E44, G11, L62

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1. Introduction

The lock down of border to avoid the outbreak of COVID-19 beginning from the end of 2019 has posed a major challenge on global brands which have heavily relied on global partnerships to achieve competitiveness. The disease has become a pressure test of supply chains on how they respond to sudden changes in supply and demand in the period of disruption. While the virus is still an ongoing treat, some economies and regions are restarting their economic activities. Supply chain leaders now are facing a new challenge to reshape their supply chains towards resilience and responsiveness. The American electric vehicle manufacturer, Tesla, has not been immune to the impact. The manufacturing of Tesla vehicles relies heavily on its global parts and component providers including the USA, Canada, France, UK, Japan, China, and Taiwan and the company is currently facing a severe shortage in components and raw materials. Meanwhile, Taiwan government has launched three major investment programs designed to encourage businesses to invest in Taiwan since 2019. As of June 2021, 15 Tesla suppliers have been approved attracting over a hundred billion NT dollars investment according to the Ministry of Economic Affairs. Automotive electronics industry has indeed become a key industry in the nation's development plan. Therefore, this research aims at examining the financial impact on Tesla supply chain when the unprecedent health crisis hard hit global economy.

Figure 1 shows the movement of Taiwan Capitalization Weighted Stock Index (TAIEX) and the stock price of top ten Tesla suppliers in Taiwan before and after the World Health Organization (WHO) declared COVID-19 a Public Health Emergency of International Concern (PHEIC) on January 30, 2020. It is observed that after the outbreak of COVID-19, the benchmark index and Tesla related stocks shed for two months. The TAIEX fell approximately 28 percent from its peak on January 14, 2020 before the announcement to a 42-month low in March 2020. In March 19, Taiwan government announced the lockdown of border and the stock market rebounded, a V-shaped curve in the stock price was formed. While investors regained confidence in Taiwan, most Tesla related stocks, however, underperformed the benchmark index amid the pandemic as seen in Figure 1.

This research aims at investigating the impact of the unforeseen health crisis from three angles including the Modern Portfolio Theory (Markowitz, 1952), the Event Study approach, and the Interactive Seemingly Unrelated Regressions (ISUR). We first compared the risk and expected rate of return of the optimal portfolio before and after COVID-19 was declared as PHEIC for a period of 4.5 months. The event study approach was then applied to evaluate the immediate and short-term reaction of the market in response to major COVID-19 events by cumulative average abnormal returns. Finally, we employed interactive seemingly unrelated regressions to estimate the influence of global disease situation on Taiwan stock market.

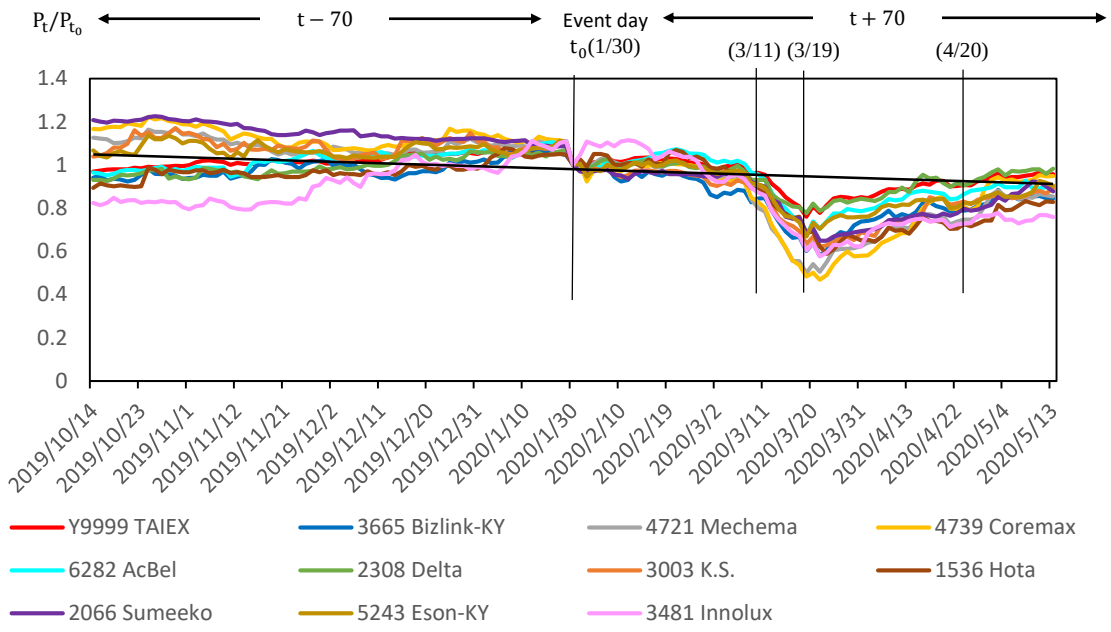

Figure 1 Taiwan Stock Performance 70 Days Before and 70 Days After the PHEIC Announcement on January 30, 2020

2. Literature Overview

This section reviews related literature including studies on the impact of SARS in 2003 and COVID-19 on the stock market, as well as methodologies that will be utilized in the mathematical formulations of this research: the modern portfolio theory and the event study approach.

2.1 Impact of SARS on the Stock Market

Before the recent outbreak of COVID-19, Taiwan had experienced a similar contagious and fatal illness, severe acute respiratory syndrome (SARS), originated in China and spread to Taiwan at the end of 2002. The epidemic of SARS had a disruptive impact on Taiwan, especially on the travel and tourism industry and aviation industry. Biotechnology industry, however, was observed to grow against the tide during the outbreak of SARS. Chen *et al.* (2007) examined the effect of SARS on the movement of stock price in the hotel industry in Taiwan. The authors employed three event study approaches including Generalized Autoregressive Conditional Heteroskedastic model (GARCH) developed by Bollerslev (1986), Threshold GARCH (TGARCH) by Glosten *et al.* (1993), and Exponential GARCH (EGARCH) by Nelson (1991) and showed that negative returns of the stock price were observed 10 days after the outbreak of SARS, and the negative effect was more significant 20 days after the outbreak. Lee (2006) discovered that SARS and the presidential election of 2004 both caused stocks of the transportation, general merchandise, and tourism industry to experience negative cumulative abnormal returns. The financial and economic impact of SARS had severe influences on the

short-term operations in the industry in Taiwan. Chong *et al.* (2010) utilized the event-study to investigate the Chinese stock market 40 days before and after the outbreak of SARS in the pharmaceutical and tourism industry and found that the pharmaceutical industry benefited from the epidemic while the tourism industry suffered for a long time. Chen *et al.* (2009) studied 32 companies in the Taiwan stock market during the outbreak of SARS under the event study approach with GARCH process. Their results suggested that SARS had a negative impact on the stock performance of companies in the tourism, wholesale, and retail industry while it had a positive influence on the biotechnology industry.

2.2 Impact of COVID-19 on the Global Stock Market

Ding *et al.* (2020) examined the financial performance of over 6000 companies around the globe during COVID-19 outbreak in the early 2020. The authors discovered that companies that had the following characteristics prior to the pandemic were less susceptible to the drop in the stock prices: stronger financial performances, operated in regions with less influenced supply chains and customer touch points, engaged with more corporate social responsibility, with a sound management, and with greater non-financial corporate ownership. Onali (2020) investigated the relation between COVID-19 cases and deaths and Dow Jones and S&P 500 by GARCH (1,1). Empirical results of April 2019 to April 2020 suggested that the crisis did not impact the US stock market returns expect for the number of confirmed cases in China. In some countries, there was conditional heteroscedasticity in the stock market returns. The number of reported deaths in Italy and France had a negative impact on stock market returns and a positive impact on the VIX returns. Al-Awadhi *et al.* (2020) used panel data to regress the number of COVID-19 confirmed cases and deaths on the performance of Chinese and Hong Kong stock markets and concluded that the number of confirmed cases had a negative impact on the Shanghai Stock Exchange Composite Index and the Hang Seng Index. Zhang *et al.* (2020) showed that the risk of stock market magnified during the pandemic of COVID-19 and the degree of volatility in the stock market was subject to the severity of the outbreak in each country. The uncertainty and economic loss induced by COVID-19 caused the market to be highly unpredictable. Nonetheless, unprecedent government measures and interventions worsened the stock market and triggered long-run issues in the global market. Most recent literature on COVID-19 have concluded that the disease had distorted economic activities and have a negative impact on the stock market specifically the risk and volatility have increased dramatically.

2.3 Modern Portfolio Theory

One of the most prevailing investment theories in the literature is the modern portfolio theory introduced by Markowitz (1952). The author assembled a variety of assets and assessed the efficiency of the investment mathematically by the portfolio's overall risk and return. The author suggested that the strategy of diversification effectively reduced the risk of an investment

portfolio. Recent application in Taiwan, for example, Liu *et al.* (2018) investigated the first seven public offering ETFs in Taiwan by calculated the efficiency of the portfolio constructed by the modern portfolio theory and their results suggested that the market return of the portfolio was far away from the efficiency frontier. Only FTSE TWSE Taiwan 50 and FB Technology had outperformed the market return.

2.4 Event Study Approach

Yuan and Chen (2018) adopted the event study approach to discuss the impact of US-China trade war on Taiwan stock market. They concluded that the impact on Taiwan's stock prices were enormous especially to those corporations that heavily reply on Chinese supply chains. Chi *et al.* (2018) combined GARCH (1,1) with text mining techniques to evaluate the effect of real time information on Taiwan's Apple related stocks. They discovered that stock prices reacted in advance to the information released on social media but then corrected themselves after the actual event took place. Shieh and Kung (2019) investigated the movement of stock prices before and after corporations received corporate social responsibility awards across industries in Taiwan and found that the announcement of award winners did not have consistent influences on the stock price. High-tech companies were observed to be negatively or not significantly related to award winning. The stock price of some industries had shown negatively related to the information one day before the announcement.

Contributions of our research to the literature lies in (1) utilizing the modern portfolio model to evaluate the risks and expected returns of Tesla related stocks in Taiwan in the early outbreak of COVID-19, (2) employing the event study approach to assess the impact of COVID-19 on the stock market during major event periods, (3) establishing regression models to estimate the effect of the pandemic on Tesla related stocks, and (4) understanding the magnitude of the impact of COVID-19 and providing managerial and political suggestions in response to the current pandemic and future random events.

3. Mathematical Formulation

3.1 Null Hypotheses

This research involves tripartite analysis to evaluate the impact of COVID-19 on Tesla related stocks in Taiwan. We first employed the modern portfolio theory and the event study approach to evaluate and compare the risks and expected returns of the portfolio of Tesla related stocks before and after the outbreak of COVID-19 in 2020. Second, we collected the cumulative number of confirmed cases in the US, China, and Taiwan, stock market values, and major COVID-19 event dates and constructed a regression model to assess their effects on daily returns of Taiwan Stock Exchange and Tesla related stocks. Therefore, four null hypotheses are proposed:

H1: there exists no statistical significance in the movement of risks and expected returns of Tesla related stocks before and after COVID-19 outbreak.

H2: there exists no statistical significance in the cumulative average abnormal return of Tesla related stocks before and after major COVID-19 events.

H3: there exists no statistical significance between the performance of Taiwan stock market and the global disease situation.

H4: there exists no statistical significance in the days of the week effect.

3.2 Modern Portfolio Model

The purpose of the modern portfolio theory is to construct an investment portfolio that aims at maximizing the expected return under a given level of risk or minimizing the risk under a given return. Based on the theory, the expected return of a portfolio of N stocks is calculated by the expected return of each stock multiply by the weight of the stock in the portfolio as shown in Eq. (1).

$$E(R_p) = \sum_{i=1}^{N} W_i E(R_i), \quad (1)$$

where R_p is the return of the portfolio,

R_i is the return on stock i, i=1~N,

W_i is the weight of stock i in the portfolio.

The risk of stock *k* is obtained by the standard deviation of returns on the stock, and the overall risk of a portfolio is derived from the covariance between all pairs of stocks as shown in Eq. (2).

$$\sigma_p = \sqrt{\sum_{i=1}^{k} W_i^2 \sigma_i^2 + \sum_{i=1}^{k} \sum_{j=1}^{k} W_i W_j \sigma_{ij}} \; i \neq j \quad (2)$$

where σ_p is the standard deviation of a portfolio,

σ_i is the standard deviation of returns on stock i,

σ_{ij} is the covariance of returns between stock i and j,

W_i and W_j is the weight of stock i and j in the portfolio respectively.

In the empirical studies, we utilized the statistical software SHAZAM to construct the best portfolio of top ten Tesla related stocks in Taiwan based on their daily stock returns and used one-year certificate of deposit of Chunghwa Post as the risk-free rate of interest. The ten Tesla related stocks are listed in Table 1. The event day in this model was set to be the day on which WHO announced COVID-19 as the Public Health Emergency of International Concern on January 30, 2020 and it was also the day that the first COVID-19 confirmed case was announced in Taiwan.

Table 1 Ten Tesla Related Stocks in Taiwan

Company	Code	Industry	Main Components
BizLink	3665	Other-electronics industry	Harnesses and cables
Mechema	4721	Chemical industry	Cobalt cathode materials
CoreMax	4739	Chemical industry	Cobalt cathode materials
AcBel	6282	Electronics industry	Chargers
Delta Electronics	2308	Electronics industry	Power solutions
K.S. Terminals	3003	Electronics industry	Chargers
Hota	1536	Automobile industry	Reduction gear sets
Sumeeko	2066	Electrical Machinery	Fastener
Eson	5243	Optoelectronics industry	Tooling
InnoLux	3481	Optoelectronics industry	Displays

Source: Taiwan Economic Journal

To test whether there exist differences in the risk and the expected return of the portfolio 70 days before and 70 days after the event day, we conduct the paired-samples t-test. Null hypotheses for the risk and the expected return are as in Eqs. (3-4). $\sigma_1(\sigma_2)$ denotes the standard deviation before (after) COVID-19 pandemic. $\mu_1(\mu_2)$ denotes the mean before (after) COVID-19 pandemic.

$$H_0 : \bar{\sigma}_2 - \bar{\sigma}_1 = 0 \tag{3}$$

$$H_0 : \bar{\mu}_2 - \bar{\mu}_1 = 0 \tag{4}$$

3.3 Event Study Approach

The second approach to estimate the impact of COVID-19 on Taiwan stock market is to evaluate market's reaction to major COVID-19 events. The four events are as shown in Table 2. For each event, we define three days prior to and three days after the event day, a total of six days, as the event period. Peterson (1989) suggested the best length to observe the financial influence of an event was between 100 to 300 trading days. Thus, an estimation period of 150 days prior to the event period was included in the empirical studies. Figure 2 illustrates the event and estimation periods in the timeline.

Table 2 Event Days in the Empirical Studies

Date	Events
2020.01.30	1.WHO declared COVID-19 a "Public Health Emergency of International Concern (PHEIC)" 2. The first confirmed case in Taiwan
2020.03.11	WHO announced COVID-19 a pandemic
2020.03.19	Travel restrictions imposed to non-citizens entering Taiwan
2020.04.20	Navy trainees were confirmed with COVID-19

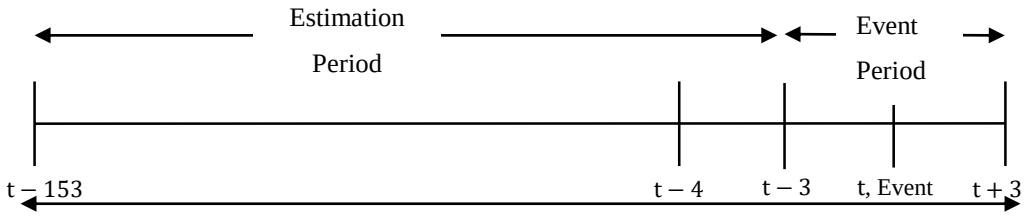

Figure 2 Definition of Event and Estimation Period in the Timeline

According to Bollerslev et al. (1992), when data is presented with the volatility clustering effect and when data is gathered at discrete intervals, it is recommended to utilize the generalized autoregressive conditional heteroskedastic model (GARCH) to evaluate a financial impact which is characterized by cumulative average abnormal returns (CAARs). Taiwan stock market had displayed the volatility clustering effect during the outbreak. Therefore, in this research, we utilized GARCH (1,1) model. Let R_{mt} be the market return at time t, and ε be the error term of ordinary least squares regression following the normal distribution. β is the regression coefficient. Then, the return of stock j at time period t, R_{jt}, can be represented by Eq. (5). h_{jt} in Eqs. (6&7) represents the conditional heteroskedasticity of stock j at time t.

$$R_{jt} = \alpha_j + \beta_j R_{mt} + \varepsilon_{jt}, \tag{5}$$

$$\text{where } \varepsilon_{jt}|\psi_{t-1} \sim N(0, h_{jt}), \tag{6}$$

$$h_{jt} = \omega_j + \delta_j h_{jt-1} + \gamma_j \varepsilon_{jt-1}^2, \tag{7}$$

$$\omega_j > 0,\ \delta_j \geq 0, \text{ and } \gamma_j > 0.$$

Next, the abnormal return of stock j at time t, AR_{jt}, is calculated by the difference between actual and expected returns as in Eq. (8).

$$AR_{jt} = R_{jt} - E(R_{jt}), \tag{8}$$

where R_{jt}: actual return of stock j at time t,

$E(R_{jt})$: the expected return of stock j at time t.

Then, the cumulative average abnormal returns of N stocks in a certain time period T are obtained by Eq. (9).

$$\mathrm{CAAR_T} = \frac{1}{\mathrm{N}}\sum_{\mathrm{t=1}}^{\mathrm{T}}\sum_{\mathrm{j=1}}^{\mathrm{N}}\mathrm{AR_{jt}}. \quad (9)$$

Finally, it is assumed that returns of the stock market deviated from the normal distribution, therefore, we employed the sign test shown in Eq. (10). If the abnormal return of stock j at time t, $\mathrm{AR_{j,t}}$, is positive, $\mathrm{S_{j,t}} = 1$. Otherwise, $\mathrm{S_{j,t}} = 0$, and $\hat{\mathrm{p}}$ denotes the frequency of positive residuals of a stock during a time period.

$$\mathrm{S} = \frac{\mathrm{p_0} - \hat{\mathrm{p}}}{\sqrt{\frac{\hat{\mathrm{p}}(1-\hat{\mathrm{p}})}{\mathrm{N}}}} \sim \mathrm{N}(0,1), \quad (10)$$

$$\text{where } \hat{\mathrm{p}} = \frac{1}{\mathrm{N}}\sum_{\mathrm{j=1}}^{\mathrm{N}}\frac{1}{\mathrm{T_j}}\sum_{\mathrm{t=1}}^{\mathrm{T_j}}\mathrm{S_{j,t}},$$

$$\mathrm{S_{j,t}} = \begin{cases} 1, & \text{if } \mathrm{AR_{j,t}} > 0 \\ 0, & \text{otherwise} \end{cases}.$$

3.4 Regression Model

The third approach in this paper is to examine the relationship between the global disease situation and stock performances. Variables in this regression mode include (1) daily rate of returns of Tesla in the US stock market and 10 Tesla related stocks in Taiwan, (2) the cumulative number of confirmed cases in Taiwan, China, and USA, (3) daily market value of each stock, and (4) dummy variables representing day effects. Detailed definitions and formulas are listed in Table 3. A set of regression equations were also constructed to examine the effect of COVID-19 on the daily rate of returns of Tesla and ten Tesla related stocks in Taiwan given in Eqs. (11-20).

Table 3 Notation and Definitions of Variables

Notation	Definition	Formula	Average
Panel (A) Daily rate of returns (%)			
RT	Daily rate of return of Tesla (Nasdaq)		-5.1%
R_1	Daily rate of return of BizLink		-17.6%
R_2	Daily rate of return of Mechema		-13.9%
R_3	Daily rate of return of CoreMax		1.6%
R_4	Daily rate of return of Mechema		-11.8%
R_5	Daily rate of return of Delta Electronics	d(Ln(Price)) *100	-3.8%
R_6	Daily rate of return of K.S. Terminals		-15.8%
R_7	Daily rate of return of Hota		-20.5%
R_8	Daily rate of return of Sumeeko		-11.9%
R_9	Daily rate of return of Eson		-8.5%
R_{10}	Daily rate of return of InnoLux		-32.5%

Panel B: Cumulative number of confirmed cases with COVID-19			
TWCC	Cumulative cases in Taiwan	Cumulative number of cases of the previous day (persons)	440.000
USCC	Cumulative cases in the USA	Cumulative number of cases of the previous day (in 10 thousand of people)	136.406
CHCC	Cumulative cases in China	Cumulative number of cases of the previous day (in thousands of people)	82.919
Panel C: Market values (in 100 million NT dollars)			
MC_1	Market value of BizLink	Natural logarithm of market value: Ln(market value)	241.237
MC_2	Market value of Mechema		38.672
MC_3	Market value of CoreMax		51.913
MC_4	Market value of Mechema		107.486
MC_5	Market value of Delta Electronics		3457.51
MC_6	Market value of K.S. Terminals		58.471
MC_7	Market value of Hota		250.197
MC_8	Market value of Sumeeko		19.315
MC_9	Market value of Eson		50.659
MC_{10}	Market value of InnoLux		-684.209
Panel D: Dummy variables			
EV	Event day effect	EV=1 represents the event day. Otherwise, 0.	0.043
FRI	Friday effect	FRI=1, if t=Friday. Otherwise, 0.	0.174
MON	Monday effect	MON=1, if t=Monday. Otherwise, 0.	0.217

*The unit root test showed that variables were stationary.

$$R_1 = \beta_0 + \beta_1 TWCC + \beta_2 USCC + \beta_3 CHCC + \beta_4 MC_1 + \beta_5 EV + \beta_6 FRI + \beta_7 MON + \beta_8 RT + \varepsilon_1. \quad (11)$$

$$R_2 = \gamma_0 + \gamma_1 TWCC + \gamma_2 USCC + \gamma_3 CHCC + \gamma_4 MC_2 + \gamma_5 EV + \gamma_6 FRI + \gamma_7 MON + \gamma_8 RT + \varepsilon_2. \quad (12)$$

$$R_3 = \delta_0 + \delta_1 TWCC + \delta_2 USCC + \delta_3 CHCC + \delta_4 MC_3 + \delta_5 EV + \delta_6 FRI + \delta_7 MON + \delta_8 RT + \varepsilon_3. \quad (13)$$

$$R_4 = \theta_0 + \theta_1 TWCC + \theta_2 USCC + \theta_3 CHCC + \theta_4 MC_4 + \theta_5 EV + \theta_6 FRI + \theta_7 MON + \theta_8 RT + \varepsilon_4. \quad (14)$$

$$R_5 = \vartheta_0 + \vartheta_1 TWCC + \vartheta_2 USCC + \vartheta_3 CHCC + \vartheta_4 MC_5 + \vartheta_5 EV + \vartheta_6 FRI + \vartheta_7 MON + \vartheta_8 RT + \varepsilon_5. \quad (15)$$

$$R_6 = \pi_0 + \pi_1 TWCC + \pi_2 USCC + \pi_3 CHCC + \pi_4 MC_6 + \pi_5 EV + \pi_6 FRI + \pi_7 MON + \pi_8 RT + \varepsilon_6. \quad (16)$$

$$R_7 = \rho_0 + \rho_1 TWCC + \rho_2 USCC + \rho_3 CHCC + \rho_4 MC_7 + \rho_5 EV + \rho_6 FRI + \rho_7 MON + \rho_8 RT + \varepsilon_7. \quad (17)$$

$$R_8 = \sigma_0 + \sigma_1 TWCC + \sigma_2 USCC + \sigma_3 CHCC + \sigma_4 MC_8 + \sigma_5 EV + \sigma_6 FRI + \sigma_7 MON + \sigma_8 RT + \varepsilon_8. \quad (18)$$

$$R_9 = \tau_0 + \tau_1 TWCC + \tau_2 USCC + \tau_3 CHCC + \tau_4 MC_9 + \tau_5 EV + \tau_6 FRI + \tau_7 MON + \tau_8 RT + \varepsilon_9. \quad (19)$$

$$R_{10} = \varphi_0 + \varphi_1 TWCC + \varphi_2 USCC + \varphi_3 CHCC + \varphi_4 MC_{10} + \varphi_5 EV + \varphi_6 FRI + \varphi_7 MON + \varphi_8 RT + \varepsilon_{10}. \quad (20)$$

According to Zellner (1962), when the residuals of a set of regression equations are reported to be correlated, the author suggested the use of Interactive Seemingly Unrelated Regressions (ISUR) to enhance the efficiency in estimating the regression coefficients. Therefore, in the empirical studies, we conducted the Breusch-Pegan Lagrange multiplier test (BP-LM) to test the applicability of ISUR estimation to our model. BP-LM tests whether the covariance of residuals between regression equations are related. The null and alternative hypotheses are given in Eq. (21 & 22) respectively.

$$H_0: COV(\varepsilon_i, \varepsilon_j) = \sigma_{ij} = 0. \quad (21)$$

$$H_1: COV(\varepsilon_i, \varepsilon_j) = \sigma_{ij} \neq 0. \quad (22)$$

We calculated residual coefficients of variation as in Eq. (23), Lagrange multiplier (LM) in Eq. (24) and conducted the Chi-Squared (χ^2) test of independence. The sample size N= 759, the number of regression equations M=10, and the degree of freedom is 45. If LM is significantly different from $\chi^2(45)$, suggesting heteroscedasticity in the residuals, then it is appropriate to apply ISUR estimation to our data.

$$r_{ij}^2 = \frac{\hat{\sigma}_{ij}^2}{\hat{\sigma}_i^2 \hat{\sigma}_j^2}. \quad (23)$$

$$LM = N \sum_{i=2}^{M} \sum_{j=1}^{i-1} r_{ij}^2 \sim \chi^2 \left(\frac{M(M-1)}{2} \right). \quad (24)$$

4. Empirical Studies

Sections 4.1-4.3 show our results of the modern portfolio model, the event study approach, and the regression model on 10 Tesla related stocks in Taiwan respectively and section 4.4 summarizes test results of the four null hypotheses presented in section 3.1.

4.1 Results of the Modern Portfolio Model

Based on the modern portfolio model, we constructed the optimum portfolio with overall expected return and standard deviation as shown in Eqs. (1&2) and illustrated the efficiency frontiers before and after the day on which WHO declared COVID-19 a public health

emergency of international concern (also the first confirmed case in Taiwan) in Figures 3 & 4. Figure 3 illustrates the efficiency frontier of the optimum portfolio of the Tesla related stocks based on their risks and expected returns collected 70 days before the outbreak. It is observed that before the outbreak the expected return of a stock corresponded to its level of risk considerably. For example, Sumeeko had the lowest level of risk and the lowest expected return in the portfolio while Innolux had the highest level of risk, and its expected return also outperformed the rest of the stocks in the portfolio. Of all Tesla related stocks, AcBel was closest to the efficiency frontier before the outbreak. MVP in the figure represents the minimum variance point, Rf is the risk-free rate, and Point A is the equally weighted portfolio of those 10 stocks. The risk of A was 0.007 and the expected return was 0.13% before the outbreak. We used point A as benchmark and categorized stocks into four quadrants. Quadrant I is composed of stocks that had relatively higher returns and higher risks. Quadrant II represents stocks with higher returns, but lower risks. Quadrant III and IV follow similar logical definitions of quadrant I & II.

In comparison, Figure 4 plots the efficiency frontier of the optimal portfolio 70 days after the event day. It is observed that risks and expected returns moved away from the efficiency frontier compared to Figure 3. The performance of Tesla related stocks in general had deteriorated significantly. After the pandemic, this risk of A increased from 0.007 to 0.029 and the expected return dropped from 0.13% to -0.247%. However, there were stocks demonstrated outstanding performance. For example, Coremax outperformed the rest of the stocks in the portfolio in terms of the expected return, but it also faced the greatest risk. Another point of interest is the relationship between the expected return of a stock and its corresponding risk. Delta, for instance, its expected return ranked top 2 in the portfolio, and yet it had the lowest level of risk among all. Delta also replaced AcBel and became closest to the efficiency frontier. AcBel, K.S., Hota, Mechema, and Innolux fell into Quadrant IV with higher risks but lower returns showing that these stocks suffered more severely from COVID-19 pandemic than other stocks.

In Table 4, we conducted a paired sample t-test to estimate whether the mean difference before and after the outbreak in the industry was zero. We considered the ten Tesla related stocks as a sample, measured their expected means and standard deviations, and drew inferences for the industry population. We denote the mean difference in the sample as $\bar{X}_2 - \bar{X}_1$ and the standard deviation difference in the sample as $\bar{S}_2 - \bar{S}_1$. Results of the paired-sample t-test in Table 4 showed that the average risk raised significantly, and the expected return became negative after the outbreak for all stocks. To conclusion Figures 3&4 and Table 4, companies within the same industry that presumably faced the same industry environment had distinct degrees of impact during the pandemic. Well-positioned and managed companies were still able to leverage the crisis to excel and achieve competitive advantage in the industry.

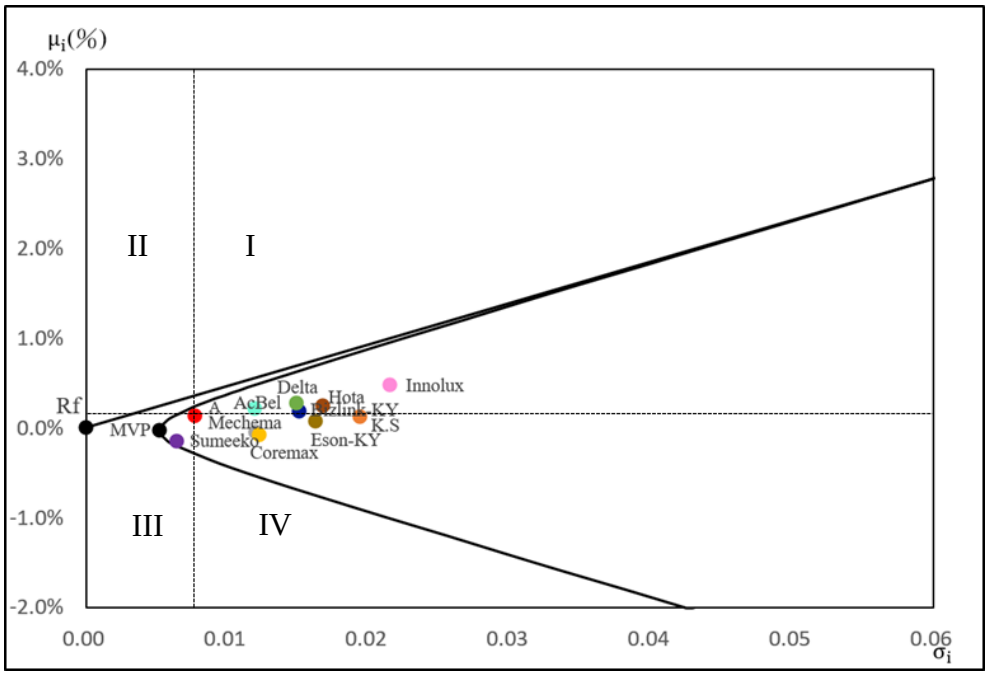

Figure 3 The Efficiency Frontier of the Optimum Portfolio 70 Days Prior to the Event Day

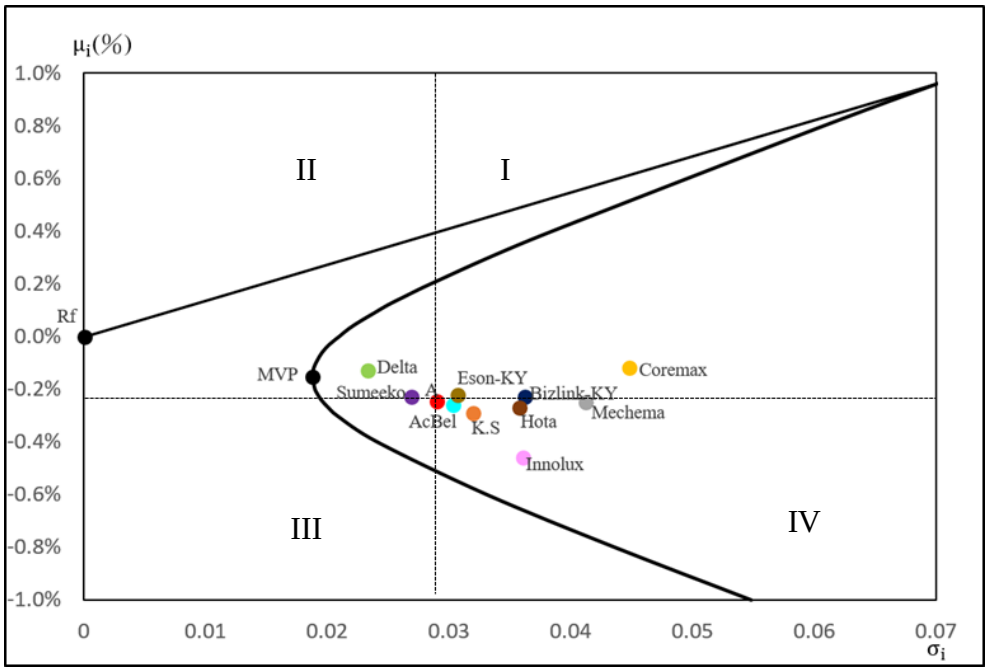

Figure 4 The Efficiency Frontier of the Optimum Portfolio 70 Days After the Event Day

Table 4 Comparison of Risks and Expected Returns Before and After the Outbreak of COVID-19

	Risk (σ)		Expected return (μ) %	
Company	Before event	After event	Before event	After event
BizLink-KY	1.506 (6)	3.616 (8)	0.185 (5)	−0.235 (5)
Mechema	1.201 (3)	4.115 (9)	−0.052 (8)	−0.251 (6)
Coremax	1.228 (4)	4.480 (10)	−0.076 (9)	−0.118 (1)
AcBel	1.193 (2)	3.034 (3)	0.210 (4)	−0.257 (7)
Delta	1.490 (5)	2.329 (1)	0.273 (2)	−0.126 (2)
K.S.	1.941 (9)	3.200 (5)	0.122 (6)	−0.295 (9)
Hota	1.672 (8)	3.579 (6)	0.241 (3)	−0.267 (8)
Sumeeko	0.643 (1)	2.691 (2)	−0.149 (10)	−0.231 (4)
Eson-KY	1.627 (7)	3.068 (4)	0.073 (7)	−0.224 (3)
Innolux	2.150 (10)	3.608 (7)	0.477 (1)	−0.462 (10)
Average	1.465	3.372	0.130	−0.247
$\bar{S}_2 - \bar{S}_1$	8.199***			
$\bar{X}_2 - \bar{X}_1$	−4.687***			

1. *** represents the level of significance at 1%.
2. Numbers in parentheses show the rank of each stock.
3. $\bar{S}_1(\bar{S}_2)$ denotes the standard deviation of the sample before (after) COVID-19 pandemic.
4. $\bar{X}_1(\bar{X}_2)$ denotes the mean of the sample before (after) COVID-19 pandemic.

4.2 Results of the Event Study Approach

The event study approach was utilized to calculate the cumulative average abnormal return (CAAR) to determine the impact of events listed in Table 2. Results from GARCH (1,1) process for the four events during event periods are showed in Table 5. Major observations include the followings. (1) Negative CAAR was immediately observed when the first confirmed case of COVID-19 in Taiwan (i.e. event I) was announced as well as one day and two days after the event day. (2) Negative CAARs remained for three days for event II when COVID-19 was declared as pandemic. In fact, negative CAARs were already noted two days before the event day. Investors anticipated and reacted early to the worsened disease situation and the negative effect on the stock returns intensified after the event day. (3) Taiwan's travel restrictions on non-citizens imposed on March 19 did not have significant impact on the stock market. (4) When navy trainees were confirmed with the disease, Taiwan stock market showed positive CAARs one day prior to and three days after the announcement.

We conclude that in the early stage of the outbreak, the unprecedented health event had caused a catastrophic impact on Taiwan stock market. However, beginning from event III, the reaction of Taiwan's investors altered. They responded insignificantly to COVID-19 events.

Before event IV, there had been zero indigenous cases observed in Taiwan for a cumulative of eight days. It might be the reason that the market started to show optimism towards the improved progress of the disease and beliefs in the contingency plans and measures taken by the authorities. Therefore, Taiwan stock market did not react nervously to COVID-19 news.

Table 5 Results of Cumulative Average Abnormal Return (CAAR) During Event Periods

Event period	-3	-2	-1	0	1	2	3
I WHO declared COVID-19 a PHEIC/ The first confirmed case in Taiwan (1/30)							
CAAR(%)	0.089	0.382	-0.237	-4.982***	-3.510**	-5.985**	-3.802
	(-0.547)	(0.162)	(0.162)	(-2.671)	(-1.963)	(-1.963)	-1.255
II WHO announced COVID-19 a pandemic (3/11)							
CAAR	0.446*	-2.236**	-3.167**	-3.684**	-7.427***	-10.275***	-11.216***
	(2.018)	(-2.413)	(-2.413)	(-2.413)	(-3.046)	(-3.046)	(-3.046)
III Travel restrictions imposed to non-citizens entering Taiwan (3/19)							
CAAR	0.015	0.591	2.698**	0.148	1.864	-2.584	-3.951
	(0.709)	(0.709)	(1.974)	(0.709)	(0.076)	(-0.556)	(-1.189)
IV Navy trainees were confirmed with COVID-19 (4/20)							
CAAR	1.765	3.746	3.820*	3.019	1.693	2.743	3.954*
	(1.052)	(1.052)	(1.718)	(1.052)	(0.385)	(1.052)	(1.718)

*, **, and *** represents the level of significance at 10%, 5%, and 1% respectively. () denotes t-values.

4.3 Results of the Regression Model

In this model, we obtained daily trading data from January 30, 2020 to May 12, 2020 and regressed daily stock returns of Tesla and ten Tesla related stocks in Taiwan on the cumulative number of confirmed cases, market value of each company, and days of the week effect as shown in Eqs. (11-20). Table 6 shows the results of the regression model. The Breusch-Pegan Lagrange multiplier test (BP-LM=769.653) suggested that heteroscedasticity was presented in the residuals, and the application of ISUR model to our data improved the estimation efficiency. Test of Goodness-of-Fit index $\overline{R}^2$ was between 0.195 and 0.425. Durbin-Watson test was conducted to detect the presence of autocorrelation in the residuals. Only Coremax was observed with the first order autoregressive process. Mechema was not conclusive and the residuals of the other eight companies did not show autocorrelation.

From Table 6, it is observed that the daily rate of return of Tesla (Nasdaq) was positively related to that of the ten Tesla related companies in Taiwan. Note that the cumulative number of confirmed cases at the time of this research was 440 in Taiwan, around 1.7 million in the USA, and 84,000 in China. Our results showed that TWCC had a positive impact on the daily rate of returns of Tesla related stocks. The relatively better control over the spread of disease in

Taiwan increased the confidence of investors. However, the cumulative number of cases in the USA had a negative impact. Tesla related stocks represent parts suppliers to the United States. The critical disease situation in the USA indeed concerned investors in Taiwan. Therefore, despite the general confidence in Taiwan's market, Tesla related stocks underperformed the Taiwan Stock Exchange Weighted Index (TAIEX) as shown earlier in Figure 1. The influence of CHCC, however, was not significant. Reasons might be that investors were cautious and uncertain about the disease situation in China or that Taiwan's Tesla supply chain is not closely bounded to Chinese automobile industry. The market value of all companies was positively related to the daily rate of return indicating that the trading volume increased during the outbreak. Dummy variable EV, a distinction of event day, was negatively related showing that information released on the event day immediately influenced investor's behaviors. Friday effect was not significant except for Mechema which was negatively influenced by the day effect. Mondays, however, imposed a negative impact on the stock market except for Innolux. It is inferred that the weekend effect existed. Investors behaved in response to bad news on Mondays. Therefore, stock price drops were usually observed on Mondays.

Table 6 Results of the Regression Model

	Bizlink	Mechema	Coremax	AcBel	Delta	K. S. Terminals	Hota	Sumeeko	Eson	Innolux
C	-189.489 ***	-95.973 ***	-123.308 ***	-138.333 ***	-178.387 ***	-158.502 ***	-228.370 ***	-155.252 ***	-129.503 ***	-118.941 ***
	(-5.502)	(-5.052)	(-6.349)	(-5.025)	(-3.819)	(-6.212)	(-5.772)	(-6.402)	(-4.501)	(-3.619)
TWCC	0.027 ***	0.034 ***	0.046 ***	0.022 ***	0.014 ***	0.032 ***	0.044 ***	0.033 ***	0.018 ***	0.028 ***
	(4.774)	(5.828)	(7.184)	(4.854)	(4.114)	(6.470)	(5.746)	(6.467)	(3.848)	(4.868)
USCC	-0.090 ***	-0.101 ***	-0.152 ***	-0.064 ***	-0.048 ***	-0.100 ***	-0.105 ***	-0.091 ***	-0.047 ***	-0.069 ***
	(-4.344)	(-4.751)	(-6.146)	(-4.011)	(-3.615)	(-5.575)	(-4.385)	(-5.266)	(-2.860)	(-3.591)
CHCC	0.041*	-0.002	-0.0005	-0.010	0.004	0.017	-0.005	0.007	0.009	-0.021
	(1.659)	(-0.084)	(-0.022)	(-0.561)	(0.279)	(0.967)	(-0.240)	(0.513)	(0.507)	(-0.923)
MC	18.321 ***	11.354 ***	14.086 ***	14.774 ***	13.910 ***	17.872 ***	22.160 ***	20.073 ***	14.923 ***	10.533 ***
	(5.520)	(5.160)	(6.449)	(5.066)	(3.837)	(6.242)	(5.837)	(6.420)	(4.518)	(3.701)
EV	-4.779 ***	-6.672 ***	-7.170 ***	-4.769 ***	-3.501 ***	-5.413 ***	-4.527 ***	-4.339 ***	-5.242 ***	-5.554 ***
	(-2.717)	(-3.826)	(-3.988)	(-3.488)	(-3.401)	(-4.215)	(-2.733)	(-4.027)	(-3.815)	(-3.432)
FRI	-0.323	-0.381	-0.439	0.209	-0.061	-0.599	-0.044	-0.241	0.178	0.666
	(-0.347)	(-0.417)	(-0.462)	(0.295)	(-0.115)	(-0.879)	(-0.050)	(-0.427)	(0.251)	(0.783)
MON	-2.102**	-2.987***	-2.626***	-1.255*	-1.897***	-1.902***	-2.574***	-1.447***	-1.496**	-0.632
	(-2.461)	(-3.573)	(-3.013)	(-1.929)	(-3.861)	(-3.034)	(-3.211)	(-2.789)	(-2.292)	(-0.812)
RT	0.078	0.085*	0.094*	0.036	0.053*	0.054	-0.012	0.019	0.052	0.049
	(1.570)	1.754	1.854	0.954	1.845	1.473	-0.268	0.628	1.379	1.089
BP-LM	769.653***									
$\bar{R}^2$	0.195	0.380	0.421	0.216	0.313	0.372	0.312	0.423	0.239	0.288

1. *, **, and *** represents the level of significance at 10%, 5%, and 1% respectively.
2. () denotes t-values.
3. $\bar{R}^2$is the adjusted coefficient of determination.
4. BP-LM follows $\chi 2(45)$.

4.4 Results for Null Hypotheses

For the convenience of readers, Table 7 summarizes conclusions derived from our empirical studies for all the hypotheses listed in Section 3.1. To conclude, we rejected most null hypotheses and proved significant impacts on COVID-19 events except for travel restrictions, the cumulative number of cases in China, and the Friday effect.

Table 7 Results of Null Hypotheses

H1: No statistical significance in the movements of risks and expected returns of Tesla related stocks before and after COVID-19 outbreak			
		Results	Positive (+)/ Negative (-) impact
H1a: test regard to risks		Reject	(+)
H1b: test regard to expected returns		Reject	(-)
H2: No statistical significance in the cumulative average abnormal returns of Tesla related stocks before and after COVID-19 events			
H2a: WHO declared COVID-19 a PHEIC/ The first confirmed case in Taiwan		Reject	(-)
H2b: WHO announced COVID-19 a pandemic		Reject	(-)
H2c: Travel restrictions imposed to non-citizens entering Taiwan		Fail to reject	Unknown[1]
H2d: Navy trainees were confirmed with COVID-19		Reject	(+)
H3: No statistical significance between the performance of Taiwan's stock market and the global disease situation			
		Tesla related stocks	Impact
H3a: Cumulative cases in Taiwan, TWCC		Reject	(+)
H3b: Cumulative cases in the USA, USCC		Reject	(-)
H3c: Cumulative cases in China, CHCC		Fail to reject	Unknown
H3d: Market values		Reject	(+)
H3e: Covid-19 event days		Reject	(-)
H3F: Stock price of Tesla in USA		Reject[2]	(+)
H4: No statistical significance in the days of the week effect			
H4a: Event day effect	Reject	Reject	(-)
H4b: Friday effect	Fail to reject	Fail to reject[3]	Unknown
H4c: Monday effect	Reject	Reject[4]	(-)

1 "Unknown" denotes that we failed to reject the null hypothesis and cannot accept the alternative hypothesis. Therefore, the impact is unknown.
2 We rejected the null hypothesis for Mechema, Coremax and Delta.
3 We failed to reject the null hypothesis of Friday effect except for Mechema. Results showed that the impact for Mechema was negative.
4 We rejected the null hypothesis of Monday effect for all stocks except for Innolux. The impact for Innolux was unknown.

5. Conclusion

5.1 Summary of Results and Managerial Insights

This paper investigated the impact of the COVID-19 pandemic on Tesla related stocks in Taiwan. To compare different perspectives and receive a thorough interpretation of the impact of the global crisis, we utilized three mathematical models: the modern portfolio theory, the event study approach, and the interactive seemingly unrelated regression model. Data of Taiwan Capitalization Weighted Stock Index and ten Tesla related stocks in the empirical studies was obtained from Taiwan Economic Journal database (TEJ) and included 759 daily trading statistics in 2020.

Results of the modern portfolio theory suggested that efficiency of the optimum portfolio constructed 70 days after COVID-19 was announced as Public Health Emergency of International Concern by WHO (also the day that the first COVID-19 case in Taiwan was announced) deteriorated compared to the efficiency of the portfolio constructed 70 days before the announcement. Average risks of the stock market increased, and the expected returns decreased substantially. However, there existed varied degrees of impact to individual stocks suggesting differences in companies' capability in response to crisis management. Delta Electronics which has implemented automation strategy long ago outperformed the rest of the Tesla related stocks in the situation of disruptive supply chains. The productivity of Delta Electronics stock became closest to the efficiency frontier. Innolux, on the other hand, suffered the most from the pandemic. In fact, Innolux had the highest expected return before the outbreak. Seventy days after the event, however, the expected return of Innolux dropped to the last place in the portfolio.

In the event study approach, we computed the cumulative average abnormal returns for four major COVID-19 events in Taiwan over an observation period of 156 days for each event. It is found that the first two events had posed a negative impact on the stock returns, but the stock market began to react indifferently to COVID-19 events since mid-March when occasional positive returns were observed within three days before or after an event.

Our regression model examined the impact of the cumulative number of cases, market values, and the days of the week effect on the daily returns of Tesla related stocks. Surprisingly to note that trading volume increased for each one of the Tesla related stocks during the period from January 30 to May 12, 2020. However, when a major COVID-19 event was announced, the stock market reacted immediately on the same day in a negative way. We also noticed the stock prices usually fell on Mondays. Investors tend to respond to bad news on Mondays. Finally, the impact of the cumulative number of confirmed cases varied from country to country. The cumulative number of confirmed cases in Taiwan was positively related to the daily stock returns while that of USA was negatively related and that of China was not conclusive.

In conclusion, the unprecedented pandemic of COVID-19 raises many concerns related to health, economy, and even information transparency. Global shutdowns to contain the spread of COVID-19 have deep and fundamental influences across all industries. No market can be exempted from the disruptive supply chains. However, compared to the global disease situation, Taiwan, possibly gained experiences and drew lessons during the severe acute respiratory syndrome (SARS) outbreak of 2003, reacted and executed contingency plans early so as to better contain the spread of COVID-19 in 2020. Thus, despite a panic reaction which caused the stock market to tremble occurred in the early stage of the outbreak, Taiwan stock market restored stability and investors reacted optimistically in their investing behaviors in the latter events in our studies when no more indigenous cases in Taiwan were discovered.

5.2 Future Research

There are several constraints in the research and possible extensions from them. First, to ensure an early observation of the COVID-19 pandemic, this research contained limited data from January 30, 2020 to May 12, 2020. As the article is drafted, the pandemic continues to accelerate after seven months since the crisis has been declared a global health emergency under the highest international law. In fact, for the past six weeks, the total number of confirmed cases doubled. Therefore, it is crucial to continue monitoring the impact of the crisis on the financial systems as types and extents of impact might alter as the disease continues to spread. Second, we only evaluated the influence of the pandemic on the automobile industry with a focus on Tesla related stocks. We propose to apply the same methodology to hard hit industries such as tourism, airlines and aviation industries and compare impacts across industries. Third, Taiwan was among the few severely infected countries during the outbreak of SARS in 2003. There were 346 SARS positive cases during the period of March to June 2003 in Taiwan, and there were 467 COVID-19 confirmed cases as of July 30, 2020. Thus, Taiwan is a precious research object to study the development of the two outbreaks and to provide guidelines in preparing for and responding to global health crisis. Fourth, impact of the COVID-19 pandemic does not limit to the stock market. The amplitude of fluctuations in oil prices, gold prices and exchange rates during the crisis are worthy paying attention to, however, these factors were not included in this research. Lastly, this global crisis also raises issues on sustainability. We realize that such emergencies cannot be foreseen by most financial models. Thus, in addition to traditional financial metrics, it is proposed for future research to emphasize a company's environmental, social and governance (ESG) performance and give an integral perspective in evaluating a company's true contributions/influences on the society.

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