Analysis of Recovery of Production Capacity of Natural Hazards: Case Study of 2016 Kumamoto Earthquakes

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Abstract This paper aims to propose an estimation methodology of recovery of production capacity in the industrial sectors by a natural disaster and apply it to the case of the 2016 Kumamoto Earthquakes. The production capacity is fundamental information to capture the economic loss due to natural hazards. This paper focuses on the analysis and comparison of the recovery process according to time from different initial damage states. In the estimation of recovery of production capacity, survival analysis and multinomial logistic model are selected to estimate the extent of damage and recovery of production capacity. The results of multinomial logistic model are then compared with the results of survival analysis in an attempt at model validation.

Key Words : *production capacity, 2016 Kumamoto Earthquakes, multinomial logistic model, survival analysis, initial damage states*

1. Introdution

The 2016 Kumamoto earthquake sequence started with an M_{JMA} 6.5 earthquake at a shallow depth in Kumamoto Prefecture, which is in the central part of Kyushu Island, southwest Japan, at 21:26 Japan Standard Time (JST) on April 14, 2016 (12:26 UTC on April 14, 2016). A larger earthquake of M_{JMA} 7.3 occurred at 01:25 JST on April 16, 2016 (16:25 UTC on April 15, 2016), just 28 h after the M_{JMA} 6.5 earthquake (Asano and Iwata[1)], 2016). Estimate of the economic impact on the prefecture worth ¥3.8 trillion. Homes suffered the worst damage at about ¥2 trillion, with approximately 170,000 houses affected including around 8,000 that were completely destroyed. Damage to the business sector, including factories and hotels, was estimated at ¥820 billion and damage to roads, bridges and other public infrastructure at ¥268.5 billion (Kumamoto prefectural government[2)], 2016).

The production capacity losses caused by the earthquakes are considered as one of the most significant factors to the severe economic impact (Fig.1). In order to effectively reduce the losses induced by large-scale disasters in the future, it is vital to study in detail the economic losses, including the structure of complex damage propagation and to reflect upon them (Kajitani and Tatano[3)], 2014). Analysis of recovery of production capacity can provide an important source of information for understanding the scale of an economic disruption in an industrial sector, especially the dimension of its output.

In consideration of this background, this paper aims to propose an estimation methodology of recovery of production capacity in the industrial sectors by a natural disaster and apply it to the case of the 2016 Kumamoto Earthquakes. This research focuses on the analysis and comparison of the recovery process according to time from different initial damage states. Meanwhile, this research seeks to advance the estimation of recovery process of production capacity in different industrial sectors considering initial damage states. Firstly, recovery process of three different industrial sectors from five initial operation levels are estimated by multinomial logistic model. Secondly, the survey data is applied to survival analysis, which is a fundamental methodology for recovery probability of production capacity. Thirdly, the results of multinomial logistic model are then compared with the results of survival analysis in an attempt at model validation.

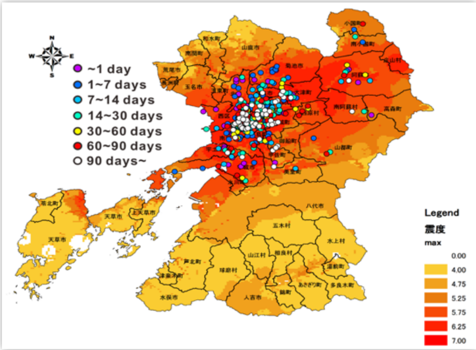

Fig.1 Recovery time to maximum operation level.

2. Methodology

In statistics, multinomial logistic regression is a classification method that generalizes logistic regression to multiclass problems with more than two possible outcomes. It is a model that is used to predict the probabilities of the different possible outcomes of dependent variables, given a set of independent variables (Greene and William H[4]. 2012).

(1) Outline of the model

Firstly, operation capacity is divided into five different states. Secondly, the probability of operation capacity at recovery time T from five operation states are estimated by multinomial logistic regression. Thirdly, the recovery process from all operation states are estimated by the weighted average of five operation levels (Fig. 2).

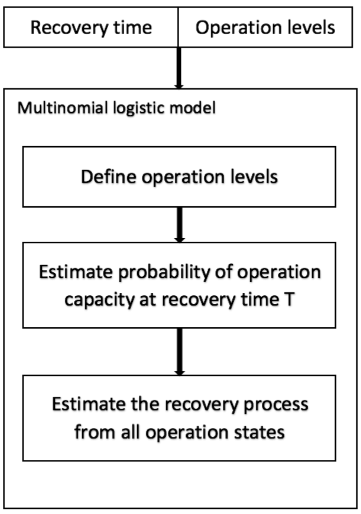

Fig.2 Framework of proposed methodology.

(2) Multinomial logistic model

a) The model

First, operation capacity is divided into five different levels as Table 1.

Table.1 Categories of operation levels.

J=1	*J=2*	*J=3*	*J=4*	*J=5*
Operation level About 0	Operation level 1~25%	Operation level 25~50%	Operation level 50~75%	Operation level >75%

For the multinomial logistic regression model, we equate the linear component to the log of the odds of a *jth* observation compared to the *Jth* observation. That is, the *Jth* category is considered to be the baseline category, where logits of the first $J-1$ categories are constructed with the baseline category in the denominator.

$$\log\left(\frac{\pi_{ij}}{\pi_{iJ}}\right)=\log\left(\frac{\pi_{ij}}{1-\sum_{j=1}^{J-1}\pi_{ij}}\right)=\sum_{k=0}^{K}x_{ik}\beta_{kj} \quad i=1,2,\ldots,N \quad j=1,2,\ldots,J-1 \tag{1}$$

π_{ij} can be solved as:

$$\pi_{ij}=\frac{e^{\sum_{k=0}^{K}x_{ik}\beta_{kj}}}{1+\sum_{j=1}^{J-1}e^{\sum_{k=0}^{K}x_{ik}\beta_{kj}}} \tag{2}$$

$$\pi_{iJ}=\frac{1}{1+\sum_{j=1}^{J-1}e^{\sum_{k=0}^{K}x_{ik}\beta_{kj}}} \tag{3}$$

x_{ik} stands for recovery times, which are continuous time series. π_{ij} stands for the probability of observing the *jth* value of the dependent variable for any given observation in the *ith* time.

b) Parameter estimation

The kernel of the log likelihood function for multinomial logistic regression models is:

$$L(\beta|y)\cong\prod_{i=1}^{N}\prod_{j=1}^{J}\pi_{ij}^{\,y_{ij}} \tag{4}$$

By replacing the Jth terms and substituting π_{ij} and π_{iJ} by equations (2) and (3), it can be transformed as:

$$\prod_{i=1}^{N}\prod_{j=1}^{J-1} e^{y_{ij}\sum_{k=0}^{K} x_{ik}\beta_{kj}} \cdot \left(1+\sum_{j=1}^{J-1} e^{\sum_{k=0}^{K} x_{ik}\beta_{kj}}\right)^{-n_i} \quad (5)$$

Taking the natural log of equation (5) gives us the log likelihood function for the multinomial logistic regression model as:

$$l(\beta)=\sum_{i=1}^{N}\sum_{j=1}^{J-1}\left(y_{ij}\sum_{k=0}^{K} x_{ik}\beta_{kj}\right) - n_i \log\left(1+\sum_{j=1}^{J-1} e^{\sum_{k=0}^{K} x_{ik}\beta_{kj}}\right) \quad (6)$$

Taking the derivative of the log likelihood and setting to 0, we get

$$\frac{\partial l(\beta)}{\partial \beta_{kj}}=\sum_{i=1}^{N} y_{ij}x_{ik}-n_i\pi_{ij}x_{ik}\equiv 0 \quad (7)$$

Thus, parameter can be estimated by equation (7).

3. Model application based on survey data

(1) Application of multinomial logistic model for industrial sectors

Based on the survey data, multinomial logistic model is applied to estimate the recovery process of production capacity from five different initial operation levels. In this research, manufacturing, construction, wholesale and retailing industries are analyzed.

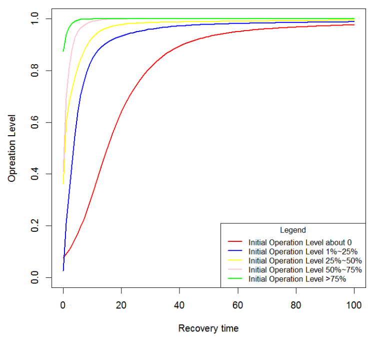

Fig.3 The recovery process of production capacity of manufacturing industry.

Taking manufacturing industry as an example, the recovery process is illustrated in **Fig.3**. The red line represents the recovery process from initial operation level at about 0. The blue line represents the recovery process from initial operation level at 1% ~ 25%. The yellow line represents the recovery process from initial operation level at 25% ~ 50%. The pink line represents the recovery process from initial operation level at 50% ~ 75%. The green line represents the recovery process from operation level at > 75%.

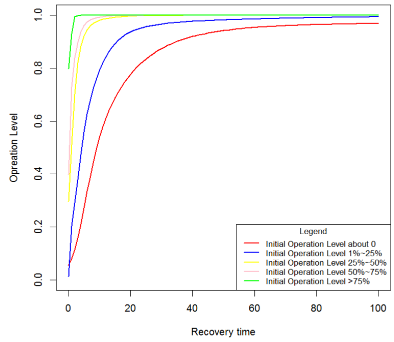

Fig.4 The recovery process of production capacity of construction industry.

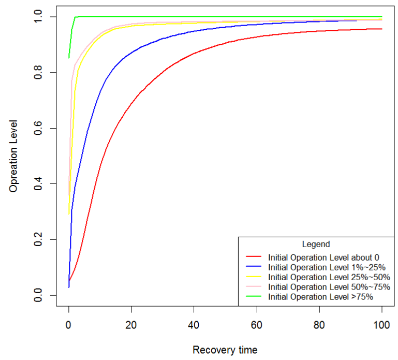

Fig.5 The recovery process of production capacity of wholesale and retailing industry.

(2) Application of survival analysis model for industrial sectors

In this research, Kaplan-Meier estimator of survival analysis model is adopted to conduct statistics of recovery probability regarding recovery time. The results of survival analysis are set to be a standard to evaluate the estimation results from multinomial logistic model.

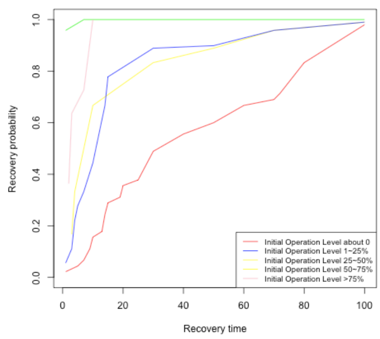

Fig.6 The recovery probability of manufacturing industry.

Taking manufacturing industry as an example, the recovery probability is illustrated in **Fig.6**. The red line represents the recovery probability from initial operation level at about 0. The blue line represents the recovery probability from initial operation level at 1% ~ 25%. The yellow line represents the recovery probability from initial operation level at 25% ~ 50%. The pink line represents the recovery probability from initial operation level at 50% ~ 75%. The green line represents the recovery probability from operation level at > 75%.

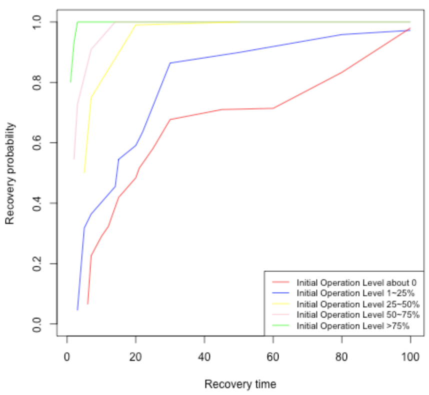

Fig.7 The recovery probability of construction industry.

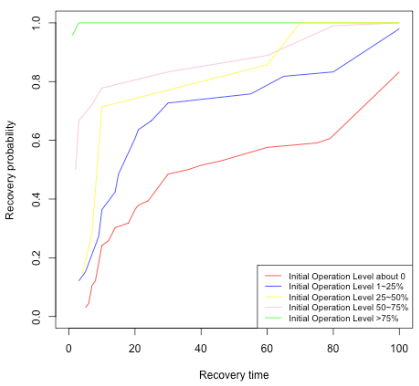

Fig.8 The recovery probability of wholesale and retailing industry.

(3) Model validation

The estimation results of the recovery process from multinomial logistic model are compared with the statistics results of recovery probability from survival analysis model as model validation. The comparison results are illustrated as **Table.2**. The recovery probabilities on recovery days 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 40, 60, 80, 100 are selected to compare in the graph.

Table.2 The comparison results of recovery probability of two models.

Recovery days	1	2	3	4	5	6	7	8	9	10
Manufacturing										
Multinomial logistic										
IOL about 0	0.204	0.222	0.241	0.261	0.281	0.301	0.322	0.343	0.364	0.384
IOL 1~25%	0.029	0.421	0.479	0.540	0.598	0.648	0.690	0.724	0.751	0.772
IOL 25~50%	0.251	0.656	0.671	0.686	0.702	0.717	0.732	0.746	0.761	0.774
IOL 50~75%	0.500	0.846	0.869	0.892	0.914	0.934	0.950	0.963	0.974	0.981
IOL >75%	0.972	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Survival analysis										
IOL about 0	0.022	-	-	-	0.044	-	0.067	0.089	0.111	0.156
IOL 1~25%	0.056	-	0.111	0.222	0.278	-	0.333	-	-	0.444
IOL 25~50%	-	-	0.167	0.333	-	-	-	-	-	0.667
IOL 50~75%	-	0.364	0.636	-	-	-	0.727	-	-	1.000
IOL >75%	0.958	-	-	-	-	-	1.000	-	-	-
Construction										
Multinomial logistic										
IOL about 0	0.177	0.217	0.259	0.303	0.348	0.390	0.430	0.466	0.498	0.527
IOL 1~25%	0.010	0.411	0.456	0.503	0.550	0.593	0.630	0.663	0.690	0.714
IOL 25~50%	0.250	0.511	0.573	0.722	0.830	0.881	0.915	0.942	0.963	0.977
IOL 50~75%	0.561	0.680	0.777	0.839	0.874	0.895	0.909	0.920	0.929	0.937
IOL >75%	0.937	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Survival analysis										
IOL about 0	-	-	-	-	-	0.065	0.226	-	-	0.290
IOL 1~25%	-	-	0.045	-	0.318	-	0.364	-	-	-
IOL 25~50%	-	-	-	-	0.500	-	0.750	-	-	-
IOL 50~75%	-	0.546	0.727	-	-	-	0.909	-	-	-
IOL >75%	0.800	0.933	1.000	-	-	-	-	1.000	-	-
Wholesale and Retailing										
Multinomial logistic										
IOL about 0	0.181	0.209	0.238	0.269	0.301	0.332	0.362	0.391	0.419	0.444
IOL 1~25%	0.045	0.466	0.497	0.515	0.534	0.551	0.569	0.586	0.603	0.619
IOL 25~50%	0.250	0.517	0.603	0.746	0.812	0.844	0.873	0.901	0.926	0.948
IOL 50~75%	0.463	0.857	0.860	0.863	0.865	0.868	0.871	0.874	0.877	0.879
IOL >75%	0.979	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Survival analysis										
IOL about 0	-	-	-	-	0.030	0.045	0.106	0.121	-	0.242
IOL 1~25%	-	-	0.121	-	0.152	0.182	0.212	0.242	0.273	0.364
IOL 25~50%	-	-	-	0.143	-	-	0.286	0.429	-	0.714
IOL 50~75%	-	0.500	0.667	-	-	-	0.722	-	-	0.778
IOL >75%	0.956	-	1.000	-	-	-	1.000	-	-	1.000

Recovery days	15	20	30	40	60	80	100
Manufacturing							
Multinomial logistic							
IOL about 0	0.482	0.566	0.689	0.774	0.884	0.944	0.974
IOL 1~25%	0.838	0.872	0.906	0.926	0.956	0.976	0.987
IOL 25~50%	0.830	0.869	0.913	0.939	0.971	0.987	0.994
IOL 50~75%	0.996	0.999	0.999	0.999	1.000	1.000	1.000
IOL >75%	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Survival analysis							
IOL about 0	0.289	0.356	0.489	0.556	0.667	0.833	0.980
IOL 1~25%	0.778	-	0.889	-	0.899	0.958	0.990
IOL 25~50%	-	-	0.833	0.889	0.958	0.990	-
IOL 50~75%	-	-	-	-	-	-	-
IOL >75%	-	-	-	-	-	1.000	1.000
Construction							
Multinomial logistic							
IOL about 0	0.625	0.684	0.760	0.811	0.878	0.922	0.951
IOL 1~25%	0.793	0.846	0.915	0.952	0.985	0.995	0.998
IOL 25~50%	0.998	0.999	0.999	1.000	1.000	1.000	1.000
IOL 50~75%	0.967	0.984	0.996	0.999	0.999	0.999	1.000
IOL >75%	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Survival analysis							
IOL about 0	0.419	0.484	0.677	0.710	0.714	0.833	0.980
IOL 1~25%	0.545	0.591	0.864	-	0.899	0.958	0.972
IOL 25~50%	-	0.990	-	1.000	-	-	-
IOL 50~75%	-	1.000	-	-	-	-	1.000
IOL >75%	-	-	-	1.000	-	-	1.000
Wholesale and Retailing							
Multinomial logistic							
IOL about 0	0.543	0.608	0.695	0.760	0.853	0.913	0.950
IOL 1~25%	0.687	0.737	0.802	0.844	0.898	0.930	0.952
IOL 25~50%	0.993	0.999	0.999	0.999	1.000	1.000	1.000
IOL 50~75%	0.893	0.907	0.931	0.951	0.977	0.990	0.995
IOL >75%	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Survival analysis							
IOL about 0	0.318	0.364	0.485	0.515	0.576	0.606	0.833
IOL 1~25%	0.485	0.606	0.727	0.758	0.818	0.833	0.980
IOL 25~50%	-	-	-	-	0.857	1.000	1.000
IOL 50~75%	-	-	0.833	-	0.889	0.990	1.000
IOL >75%	-	-	-	-	-	1.000	1.000

5. Conclusions

In this study, a probabilistic methodology for estimating recovery of production capacity of industrial sectors is proposed. The multinomial logistic regression model is adopted to estimate the recovery process regarding recovery time from different initial operation levels. By defining five operation levels, estimating the probability of the five operation levels at recovery time t, the recovery process of different industrial sectors is estimated. Meanwhile, Kaplan-Meier estimator of survival analysis is adopted to conduct statistics of recovery probability regarding recovery time. It is a generally applied analysis methodology for recovery of production capacity. Thus, the results of survival analysis are set to be a standard to evaluate the estimation results from multinomial logistic model.

By comparing with Kaplan-Meier estimator of survival analysis, there are two aspects that multinomial logistic model is superior. Firstly, by defining the five operation levels, the survey data can be expanded according to recovery time. As a result, the recovery days in the estimation results of multinomial logistic regression model are continuous, which makes the estimated recovery process continuous and more specific. On the other hand, Kaplan-Meier of survival analysis can only conduct statistics on existing recovery days in the survey data, which is not time-continuous. Secondly, only the companies that are recovered can be considered in the Kaplan-Meier of survival analysis. On the other hand, both recovered and unrecovered companies can be considered in the estimation of multinomial logistic model, which makes the model analyze larger amount of data and more comprehensive.

This research is significant in improving the estimation methodology of recovery process of production capacity from micro perspective for individuals considering more comprehensive states. But some improvements in this research can be done in the future work. Firstly, in the application of multinomial logistic model, the use of weighted average of the operation levels lead to the inaccuracy of estimation from initial operation level at about 0. Therefore, improvement of the methodology need to be researched in the future study. Secondly, the estimated probabilities of multinomial logistic model are larger than the standard results of survival analysis at earlier stages. Therefore, the factors that may lead to the difference need to be added in the evaluation model in the future study.

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