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Framework for modeling multi-sector business closure length in earthquake-struck regions

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ABSTRACT

Regions impacted by natural disasters such as earthquakes may suffer enormously from interruptions to their economic systems, which usually have long-lasting and profound impacts. Business closure length (BCL), which refers to the post-disaster period during which businesses completely stop their operation, is a critical indicator of the overall impacts of disaster-induced business interruptions. This study proposes a new analytical framework for modeling the BCL of businesses in different economic sectors, based on the downtimes of their operation factors. The proposed framework first identifies the essential operation factors of businesses in each sector. Then, for each individual business, the framework quantifies the downtimes of its operation factors, and establishes the quantitative relationships between these downtimes and the BCL of the business. A case study of Mianzhu, a county located in the most impacted region during the 2008 Wenchuan Earthquake, was conducted to test the performance of the proposed framework. Particularly, the BCL of businesses in the manufacturing and retailing sectors in Mianzhu was examined. The results showed that the proposed framework could estimate the BCL of all businesses with promising accuracies. The results also demonstrated that the framework could distinguish the sector-specific dependence of businesses on different operation factors, and could reflect the fact that the reopening of businesses does not require all operation factors to be fully restored to the pre-disaster level. The practical implications of the findings, and the potential of the framework to be extended for predicting the BCL before earthquakes happen, are also discussed in the paper.

1. Introduction

The world has suffered enormous economic losses valued at thousands of billions of US dollars from natural disasters in the past twenty years, even though half of the disaster events are not yet included due to lack of official economic statistics data [1]. Historical cases show that, in addition to losses of physical assets including buildings, infrastructures, equipment, materials and inventories (also known as direct losses), regions impacted by the natural disasters also suffer enormously from interruptions to their economic systems (also known as business interruption (BI)), which usually have long-lasting and profound impacts [2–4]. For instance, when the Great East Japan Earthquake in 2011 caused direct losses that exceeded two hundred billion US dollars, it also forced over 22% commercial and industrial businesses in Iwate, Miyagi and Fukushima prefectures to close temporarily or permanently [5]. Similarly, when Hurricane Katrina struck New Orleans in 2005, in addition to the direct losses that exceeded one hundred billion dollars, the city experienced significant economic interruption and recession, and it took the city five years to see its economy recover to the pre-disaster level [6]. When businesses are interrupted, it not only lowers production in all economic sectors, but also cuts residents' incomes due to unemployment, which in turn reduces their consumption expenditures [3,4]. Consequently, urban or regional economic vitality is significantly impacted. To develop effective mitigation strategies of economic risks, an in-depth understanding about the effects of disaster events on economic systems is required. In this respect, it is vital to assess the BI following a disaster, for supporting evaluation of policies and development of strategies and measures to prevent or reduce possible economic recess.

Earthquake is one of the most destructive natural hazards [7,8]. Under an extreme earthquake, buildings and infrastructures could collapse or break down, equipment, materials and goods could be ruined, and humans could be injured or killed [3,4]. Meanwhile, production and sale flows in an earthquake-struck region could be significantly reduced over a period of time [9]. Such BI can take on different

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Nomenclature

BCL	Business closure length
b_L^j	Dependence of sector j on land
T_L	Downtime of land
T_L^{dam}	Restoration time of damaged land
b_B^j	Dependence of sector j on buildings
T_B	Downtime of functional buildings
T_B^{dam}	Restoration time of damaged buildings
T_B^{tem}	Construction time of temporary buildings
b_E^j	Dependence of sector j on equipment
T_E	Downtime of functional equipment
T_E^{dam}	Restoration time of damaged equipment
T_E^{new}	Purchase time of new equipment
b_S^j	Dependence of sector j on raw materials/goods supplies
T_S	Downtime of raw materials/goods supplies
T_{su}	Supplier downtime
T_{tr}	Transportation disruption time
b_I^j	Dependence of sector j on infrastructure services
T_I	Downtime of infrastructure services
$b_I^{j,i}$	Dependence of sector j on infrastructure service i
T_I^i	Downtime of infrastructure service i
b_W^j	Dependence of sector j on workforce
T_W	Downtime of workforce

forms in different economic sectors. For instance, for the manufacturing sector, production decline could result from factory collapse, equipment breakdown, lifeline failure, transportation disruption and workforce losses [10,11]. For the construction sector, profit decline and delivery delay could be caused by collapse of construction in process and breakdown of equipment [12]. For the wholesaling and retailing sector, and many other service sectors alike, revenues could be largely impacted by building collapse, transportation disruption and reduction in customer demand [13]. As a whole, businesses of almost all economic sectors may be forced to close immediately after an earthquake, and stay closed for a certain period of time before they can reopen for businesses, usually at a reduced production or service level [9].

Business closure length (BCL), which refers to the period during which businesses completely stop their operation, is a critical indicator of the overall impacts of BI [9]. Understanding the BCL and its causes could contribute to the proposal of recovery measures for reopening businesses as soon as possible and hence reviving regional economic vitality. Previous studies have identified various factors that may influence the BCL, including property damages [14–16], infrastructure service interruptions [17–20], logistic disruptions [21–23], workforce losses [7,21,24], pre-existing business characteristics [25–27], and economic and social environments [28–30]. Based on these factors, several studies aimed to predict whether businesses could reopen at a certain point, e.g. half a year, one year or two years after a disaster, by using logistic regression [21,23,31] or probit regression [13]. However, these studies focused on predicting the operating status of businesses at specific points in time. Two recent studies proposed methods to estimate the exact length of business closure [32,33]. However, extra local data of historical disasters are required to calibrate the models when applying them in other cases.

Business recovery time (BRT) refers to the time the business needs to fully recover to the pre-disaster level. BCL is part of and could be much shorter than BRT, since businesses could reopen after an earthquake, likely at a reduced level of capacity, as soon as essential amounts of operation factors they depend on are available. There is distinct difference between the concept of BRT which focuses on the overall resilience of businesses and accounts for its entire recovery process, and the concept of BCL which focuses on the capability of the business to survive the initial impact of the disaster and sustain its operation. Although the methods for estimating BRT [8,11,34–36] could be used as reference for estimating the BCL, it is significant to recognize the differences between the BCL and BRT, otherwise using the above BRT estimation models could lead to substantial overestimation of the BCL.

To address the above gaps, this study aims to propose an analytical framework for quantitatively modeling the BCL of multiple economic sectors in earthquake-struck regions. Since business closure is mainly caused by shortage of operation factors, the direct determinants of BCL should be the downtimes of operation factors [36]. Accordingly, the proposed framework focuses on the effects of downtimes of operation factors on BCL. In the proposed framework, the downtime of an operation factor is defined as the time it takes for a minimum amount of the operation factor to become available to suffice the need of a business to reopen after an earthquake, even though the operation factor may not have fully recovered to its pre-earthquake level. The framework identifies the essential operation factors of businesses in each economic sector, and establishes the quantitative relationships between the BCL of the businesses and the downtimes of their operation factors based on production theories and principles. To test the framework, a case study was conducted, which investigated the damage and recovery of Mianzhu, a county in Sichuan, China that was badly struck by the Wenchuan Earthquake in 2008. The results showed that the proposed framework could demonstrate the impact of sector-specific dependence of the businesses on different operation factors. Moreover the framework could also consider the fact that business reopening only requires essential amounts of their operation factors to be available. The findings are expected to support the development of informed recovery strategies and measures to effectively reduce the BCL in earthquake-struck regions.

2. Literature review

2.1. Impact factors on BCL following natural disasters

Previous studies have identified a few factors that are potentially influential on the BCL of businesses impacted by natural hazards. These factors can be divided into six categories, including property damages, infrastructure service interruptions, logistic disruptions, workforce losses, pre-existing business characteristics and economic and social environments. All categories are reviewed in detail below.

2.1.1. Property damages

Prior research has pointed out that most economic sectors are vulnerable to property damages, including damages to buildings [14–16], equipment [7,37,38], raw materials and inventory stocks [7,37,38]. The impacts of the property damages may vary depending on the type of damaged properties and the characteristics of the businesses that bear the damages. For instance, interruptions to hotel businesses mainly result from building damages, manufacturing businesses may suffer most from damages to buildings and equipment, while retailing stores are relatively more susceptible to damages to inventory stocks [13]. Meanwhile, small-scale businesses are usually more vulnerable to equipment and inventory stocks damages than large ones [13]. Moreover, in addition to preventing accessibility to the properties needed for normal business activities, property damages are also likely to affect the financial conditions of businesses, which indirectly impacts their BCL [21].

2.1.2. Infrastructure service interruptions

Interruptions of critical infrastructure services, such as electric power supplies, water supplies, transportation, sewage, and telecommunication, are crucial to BCL [17,39–41]. Tierney and Nigg [18] found that, during the 1993 Des Moines, Iowa floods, the BCL of local businesses was impacted more by infrastructure service interruptions than by property damages. Several other studies found that infrastructure service interruptions could cause long BCL to businesses that did not even suffer property damages [19,20]. For instance, in New Orleans, the power, natural gas, and clean water systems did not function for two to eight weeks after the city was hit by Hurricane Katrina. As a consequence, most businesses in the city had to stayed closed during that period, regardless of their level of property damages [38]. In addition, Chang et al. [20] compared the economic impact of interruptions of multiple infrastructure services, including electric power, gas and water supplies, in Memphis, Tennessee in the event of a large hypothetical seismic event. Their results showed that interruption of electric power supplies had the most severe impacts on the BCL of local businesses, followed by interruptions of water and gas supplies.

2.1.3. Logistic disruptions

Business closure could also be caused by logistic disruptions. Previous studies found that businesses, especially in the retailing sector, could suffer operational interruptions due to the difficulties in getting supplies of products and raw materials [21–23]. Supplier failure and transportation disruption are regarded as two main causes of logistic disruptions. For instance, Cater and Chadwick [42] emphasized the importance of preventing supplier disruption in supply chain logistics when responding to natural hazards. Stevenson et al. [22] also found businesses with reliable suppliers tended to be reopened early. On the other hand, logistic disruptions caused by transportation failures were found to be a significant factor that led to business closures immediately after Hurricane Katrina [38]. Similar findings on the effect of transportation disruptions were also reported by Rodríguez et al. [43].

2.1.4. Workforce losses

Businesses may face operational disruptions due to workforce losses. Natural disasters often induce workforce shortages due to casualties, home-related losses as well as an inability of employees to travel to work [7,21,24]. For example, in the 1994 Northridge Earthquake, businesses in Los Angeles experienced widespread operational disruptions, partly because the commuting conditions of employees did not fully recover until more than 18 months after the earthquake [44]. Similarly, Stevenson et al. [22] identified workforce shortage as a major challenge to businesses in earthquake-struck regions following the 2010–2011 Canterbury earthquakes, observing that much of the local workforce market was consumed in addressing home and family issues caused by the earthquake. Corey and Deitch [38] also found in their study that locating qualified employees and related staffing issues were the major roadblocks to business reopening in the Greater New Orleans area after Hurricane Katrina.

2.1.5. Business characteristics

Business size, measured as sales revenues or number of employees, has a significant impact on post-disaster business closure. Prior research revealed that small businesses tend to be more significantly impacted by natural hazards than larger ones, since the former are less capable to afford to engage in preparedness activities due to lower profits and smaller cash reserves [25–27]. In addition, Wasilewski et al. [23] posited that economic sector of businesses was a significant determinant of their BCL following earthquakes. They found that businesses in the wholesale or retail sectors were more likely to close compared to businesses that operate in the financial or manufacturing sectors following an earthquake or hurricane. Similarly, it was also found that businesses in finance, insurance, and real estate sectors tend to reopen earlier compared with wholesale and retailing trade businesses [45,46]. Another influential business characteristic could be business age. Several studies observed that older businesses took fewer preparedness measures for disaster mitigation, possibly because they were unenterprising and lack of risk awareness [47]. For example, after studying the impacts of 1992 Hurricane Andrew in Florida, Webb et al. [40] reported that younger businesses were able to adapt more easily to changing physical environments, such as building damages, that were caused by the hurricane. In another study, Howe [48] found a significant negative relationship between the business age and the owner's perception about impacts of floods. To the contrary, several other studies suggested that older businesses could be more prepared for the impacts of disasters, and the possible reason was that they would likely have more past experiences with disasters [24,49,50].

2.1.6. Economic and social environments

BCL of a business is also sensitive to its economic and social environments. First of all, economic climate and trend of the region or community are impactful on the closure and recovery of businesses [28]. For instance, Xiao and Drucker [29] found that compared to high concentration of a few industries, a diverse economy with a mix of different industries tends to reopen its businesses faster after a disaster event. In another study, Dahlhamer and Tierney [26] found that businesses in a fast developing community prior to the Northridge earthquake showed better recovery performance than other businesses. Similarly, in the Loma Prieta earthquake and Hurricane Andrew, businesses of those positively developing communities were significantly more likely to report positive recovery outcomes [40]. In addition, decrements of local population also play a role in the business closure and recovery. For instance, Tierney [24] found that customer loss after resident dislocation was a major impact factor on post-disaster business closure. Meanwhile, when populations are displaced, local businesses may suffer workforce losses that add to the difficulty in business reopening [16]. Another significant social factor affecting BCL is related to social bonds or networks. For instance, Tierney [28] found that the reopening decision of businesses in New Orleans following Hurricane Katrina depended on the opening statuses of their competitors in the neighborhood. The spiritual support from neighbors and friends was also found to be a key factor for efficient business recovery from natural disasters [51].

2.2. Possible methods for modeling the BCL

Based on the impact factors on business closure, a few studies have attempted to model the BCL in the aftermath of natural disasters. For instance, Wasileski et al. [23] used logistic regression to estimate the probabilities of business closure or relocation immediately after an earthquake or hurricane event. Logistic regression was also used to estimate the probabilities of the operating status (operational or closed) of small businesses two years after Hurricane Katrina, by taking into account factors related to both business characteristics [31] and property damages [21]. Similarly, Lee [13] used probit regression to estimate the probabilities of the operating status of small businesses in both six months and one year after Hurricane Harvey. While the above studies identified a number of significant impact factors on business closure, they focused on the operating status of businesses at specific points in time. Estimating the exact length of business closure, which is key to estimating the impacts of BI of natural disaster-struck businesses, largely remains unaddressed. To address this limitation, Lee [32] modeled the exact BCL based on different factors by conducting a duration analysis. He identified that several factors, especially social capitals, play a key role in determining the BCL. A main drawback of these studies, however, is that although quantitative equations could be concluded to estimate the BCL by regressions, parameters in these equations would vary from case to case. As a result, the equations derived in the above study are hardly directly applicable to other cases, as the equations and their parameters are conditional on city characteristics and disaster events. Moreover, the estimation accuracies of these equations were not tested in the above studies. Aghababaei et al. [33] proposed a model for quantifying post-disaster BCL through Bayesian methods. It was found that the model inherently accounted for the incidental and epistemic uncertainties in the BCL, which had not been addressed by earlier studies. However, local data of historical disasters were required to calibrate the model when applying it to other cases.

A few other studies focused on estimating the BRT, namely the time for businesses to fully recover to the pre-disaster level. The methods for estimating BRT could be used as reference for estimating the BCL. For instance, based on records of historical earthquake events, Holden et al. [8] conducted an empirical analysis to estimate the BRT in the Bay Area after a magnitude-6.9 earthquake. Yang et al. [34] developed an accelerated failure time model to estimate the business stagnation and recovery time of individual businesses under floods based on inundation depth. The above studies, however, mostly regarded hazard severity as the primary determinant factor of BRT. They did not recognize the fact that different businesses depend on different operation factors to operate, whose post-disaster downtimes may be different. This would result in significant variance in BRT, even under the same hazard severity and damage level. To address this limitation, in a recent study, Cremen et al. [36] proposed an analytical framework to model BRT based on earthquake-induced downtimes of multiply operation factors, including buildings, utilities and suppliers. They also considered mitigation measures, such as relocation of businesses and backup infrastructure resources, in their framework. By comparing estimation results of BRT based on their framework with those only based on building downtime, it was found that the accuracy of their estimation was improved by over 70%. One limitation of their work, however, is that they did not recognize the dependence of businesses on the operation factors is economic sector-specific. Meanwhile, downtimes of other significant operation factors such as workforce and equipment were not taken into consideration. Lastly, the significance to distinguish the differences between the BCL and BRT needs to be noted. Particularly, business reopening only requires an essential amount of operation factors, while the full recovery of the business requires all operation factors to be restored to their pre-disaster levels.

3. Proposed framework

An analytical framework for modeling the BCL in earthquake-struck regions is proposed in this study. Property damages, infrastructure service interruptions, logistic disruptions and workforce losses, which are associated with the operation factors essential for business operations, were found to be the main causes of the BCL in previous studies [14,19,21]. In most cases, business closure is directly caused by the disaster-induced shortage of operation factors, suggesting that the direct determinants of the BCL are the downtimes of operation factors [36]. Meanwhile, other factors, such as business characteristics and economic and social environments, may also impact the BCL [26,31,46]. However, their impacts are indirect, mostly through their influence on the downtimes of the above operation factors. Therefore, the proposed framework, as illustrated in Fig. 1, focuses on the effects of the downtimes of different operation factors on the BCL. The proposed framework is developed for businesses in multiple economic sectors impacted by earthquake events. It needs to be pointed out, while this study focused on investigating how the downtimes of the operation factors determine the BCL of businesses, an understanding of what may affect the downtimes, such as damage extent, business size and age and economic and social environments, is beyond the scope of this study.

Based on classic production theory, business production is a process to use and transform a combination of operation factors into products, and the business output is mainly determined by the quantity of these factors [52]. The production theory is generally applicable in almost all economic sectors including agriculture, manufacturing, construction, wholesale and retailing [52]. Based on business economics theory [53], operation factors could be divided into fundamental factors and management factors. Fundamental factors could be further divided into production means, generalized materials and workforce. Production means include land, buildings, equipment, and generalized materials include raw materials, goods and infrastructure service. All above fundamental operation factors may be subject to earthquake-induced damages [2], and a business that is forced to close temporarily could reopen only if fundamental operation factors are recovered [36]. Accordingly, the BCL should be determined by downtimes of 1) land, 2) functional buildings, 3) functional equipment, 4) raw materials and goods supplies, 5) infrastructure services, and 6) workforce. Functional buildings and functional equipment respectively refer to buildings and equipment that are able to function to support business operations. Since different economic sectors are dependent on different sets of operation factors, the sector-specific dependence of businesses on the operation factors should be identified for each economic sector. For example, since equipment is not essential for retailing, downtimes of functional equipment is not a determinant of retailing BCL. Thus, for any individual business, its post-earthquake BCL can be estimated based on Equation (1):

$$BCL = max\{b_L^j T_L,\ b_B^j T_B,\ b_E^j T_E,\ b_S^j T_S,\ b_I^j T_I,\ b_W^j T_W\} \tag{1}$$

where T_L, T_B, T_E, T_S, T_I and T_W respectively denote the downtimes of land, functional buildings, functional equipment, raw materials and goods supplies, infrastructure services and workforce, j denotes the economic sector the business belongs to, and b_L^j, b_B^j, b_E^j, b_S^j, b_I^j, b_W^j respectively denote the dependences of businesses in sector j on the corresponding operation factors (0 = independence, 1 = dependence).

- **Downtime of land (T_L).** Land is essential for businesses in various sectors including agriculture, property development, and construction. Land could be damaged and inoperable when suffering cracking or being buried from ground motion, landslide and debris flow. Businesses could reopen with an essential amount of land, which is usually smaller than the pre-earthquake amount. There are two sources of land in the aftermath of an earthquake, including land that suffers no damage from the earthquake, and land that is restored from damage. If a business has no immediate access to essential amount of land after the earthquake, it would have to wait until damaged land is restored before it can reopen for operation.
- **Downtime of functional buildings (T_B) and functional equipment (T_E).** Both Buildings and equipment are usually required for business activities. After an earthquake, buildings and equipment could be damaged and lose their function. Their damages can be assessed at four levels, including none, slight, moderate and severe [54–56]. Buildings or equipment that suffer no or slight damages would remain fully or partially functional [55], whereas those that suffer moderate or severe damages would become inoperable until restored. Since different sectors have different requirements for functional buildings and equipment, they can be classified into different categories based on whether partially functional buildings or equipment are acceptable for their business activities. In addition, businesses could reopen with an essential amount of functional buildings or equipment, which is usually smaller than the pre-earthquake amount. There are three sources of functional buildings and equipment in the aftermath of an earthquake, including buildings and equipment that suffer no or slight damages from the earthquake, buildings and equipment that are restored from moderate or severe damages, and temporary constructed buildings and newly purchased equipment after the earthquake [12]. If a business has no immediate access to essential amount of functional buildings or equipment after the earthquake, it would have to wait until either damaged buildings or equipment are restored, or temporary buildings are constructed or new equipment is purchased, before it can reopen for operation. In that case, as showed in Fig. 1, the downtime of functional buildings or equipment is the minimum

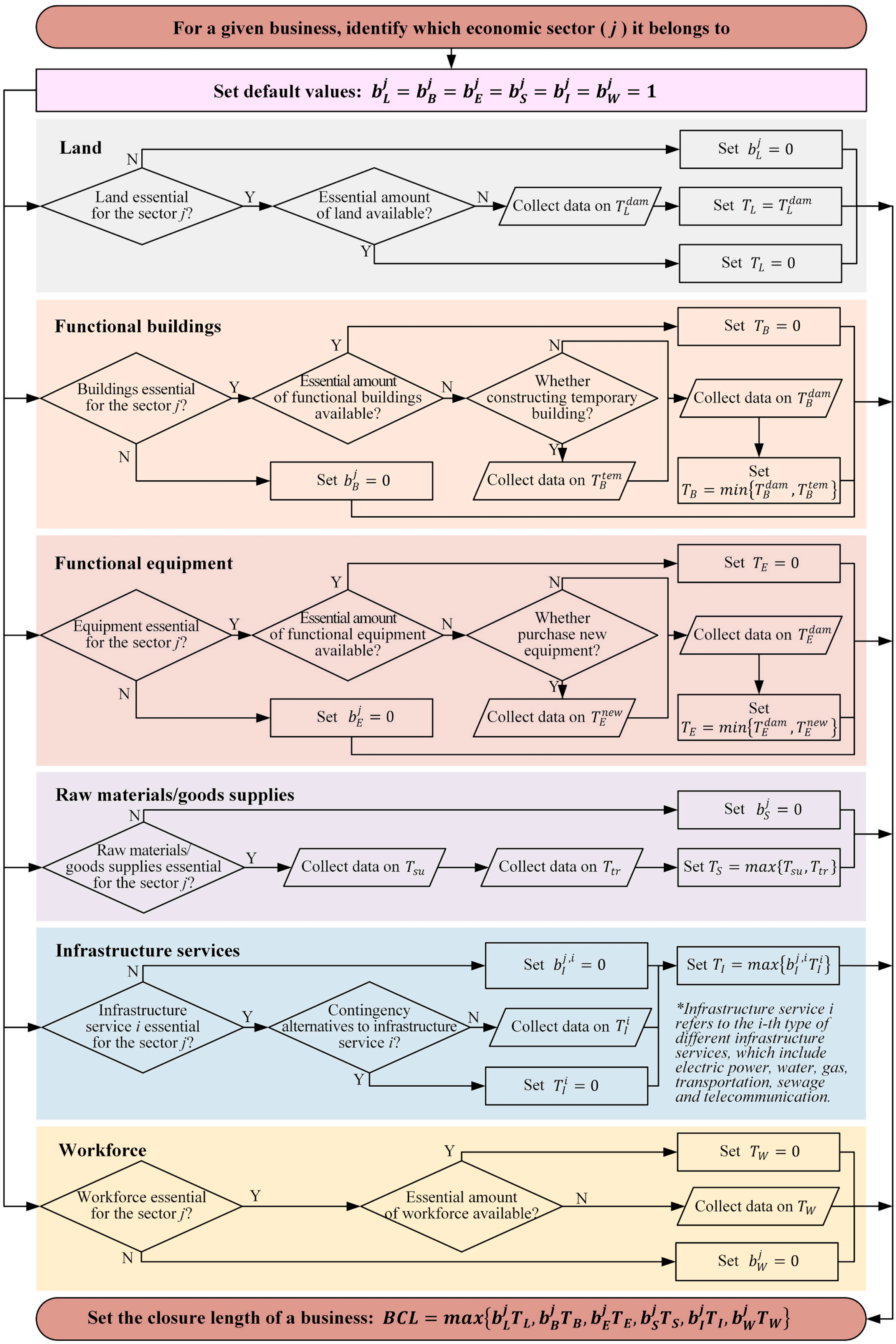

Fig. 1. The proposed framework.

between the restoration time of damaged building or equipment, and the construction time of temporary buildings or purchase time of new equipment.

- **Downtime of raw materials and goods supplies (T_S).** Raw materials and goods supplies are required for most business activities. For instance, manufacturing businesses require raw materials for production, and retailing businesses require supplies of goods for sale. Post-earthquake access to raw materials and goods supplies can be interrupted by either supplier shutdown or transportation disruption [21–23]. Substitution of suppliers was found to be an important possibility and play a role in the downtime of supplies [21]. However, substitutability of critical supplies is significantly context-dependent, which is beyond the scope of this study. Thus, for any given business, as showed in Fig. 1, its downtime of raw materials and goods supplies is the maximum of supplier downtime and transportation disruption time.
- **Downtime of infrastructure services (T_I).** Businesses in different sectors require different infrastructure services, ranging from electric power to water, gas, transportation, sewage and communication, for operation [18,20,23]. For example, gas is required only by a small number of sectors, such as machinery manufacturing, while almost all sectors require electric power supplies. Thus, the sector-specific dependence of businesses on the infrastructure services should be identified. Since businesses may have to stay closed as long as one of the essential infrastructure services is disrupted, as showed in Fig. 1, the overall downtime of infrastructure services should be the maximum downtime among all essential infrastructure services. In addition, in case some businesses have access to useable contingency alternatives to certain types of infrastructure services, e.g. using electric generators to provide temporary power supplies, the overtime of such infrastructure services should be counted as zero.
- **Downtime of workforce (T_W).** Businesses in earthquake-struck regions may suffer workforce losses. To restart operation after an earthquake, businesses typically do not require full workforce. Instead, only a minimum proportion of workforce would be required to meet the essential needs [22,38]. Hence, as showed in Fig. 1, downtime of workforce should be zero if essential amount of workforce is available for the business. Otherwise, it should wait until essential amount of workforce becomes available before it can reopen for operation.

4. Case study

4.1. Basic information

A case study was conducted in this study to implement and test the proposed framework. The case study investigated the disruption and recovery of businesses in Mianzhu, a middle-sized Chinese county, during Wenchuan Earthquake in 2008. Located at the northwest of Sichuan Basin, Mianzhu had a population of nearly half million and annual gross domestic product (GDP) of approximately 14 billion Chinese yuan (approx. 1.9 billion US dollars) as of 2007 [57]. Measured by GDP, it was one of the most developed counties in Sichuan [57]. It was also among the most impacted counties during the Wenchuan Earthquake, with direct losses exceeding 140 billion Chinese yuan (approx. 20 billion US dollars), which was more than ten times its GDP of the previous year [58]. The annual GDP of Mianzhu dropped by about 30% in 2008, and did not recover to the pre-earthquake level until three years later [59].

The case study investigated the post-earthquake BCL in the secondary and tertiary industries in Mianzhu. Particularly, this case study focused on the manufacturing and retailing sectors, which were the largest sector in the secondary and tertiary industries in Mianzhu, respectively. As of 2007, the manufacturing sector contributed to half of the county's GDP, and the retailing sector contributed to over 70% of total sales from wholesale, retailing, catering and lodging sectors [57].

Table 1
Subsector statistics of the respondents.

Sector	Subsector	Number of respondents
Manufacturing	Beverage manufacturing	9
	Chemical feedstock and chemical manufacturing	5
	General-purpose equipment manufacturing	3
	Manufacturing of agricultural and non-staple foodstuff	2
	Foodstuff manufacturing	2
	Non-metallic minerals product	2
	Electric machinery and equipment manufacturing	2
	Chemical fiber manufacturing	1
	Automotive Manufacturing	1
	Manufacturing of textile costumes, shoes, and caps	1
	Wood processing and manufacturing	1
	Printing and reproduction of record media	1
Necessity retailing	Food, beverages and tobacco	30
	Textiles, clothing and household goods	20
	Products of agriculture, forestry, animal husbandry and fishery	10
Non-necessity retailing	Hardware/building materials/furniture	15
	Household appliances/electronic products	12
	Medicine and medical equipment	2
	Stationery and sporting goods	2
	Automobile/motorcycle/bicycle	5

Table 2
Business characteristics of the respondents.

Business characteristics	Manufacturing		Retailing			
			Necessity		Non-necessity	
	Mean	SD	Mean	SD	Mean	SD
Business age (years)	21.39	7.47	19.50	5.99	18.92	6.89
Employee number[a]	72.16	82.05	1.84	0.71	2.20	0.83
Building area (square meter)	5936	6258	115.4	91.1	183.7	192.4
Monthly production/sales (thousand CNY)[b]	2396	2837	3.91	7.78	3.79	5.85

[a] Employees refer to all operating staff including owners.
[b] The exchange rate between Chinese yuan (CNY) and US dollar (USD) was approximately 6.94 CNY/USD in 2008.

More importantly, both sectors were badly hit by the Wenchuan Earthquake. Almost all manufacturing firms and half of retailing stores were forced to close for some time ranging from days to months, making these two sectors a primary target for the BCL investigation.

4.2. Data collection

A survey was developed in the case study to investigate the damage and recovery of manufacturing and retailing businesses. The survey included seven parts organized in the following order: (1) questions on business characteristics, including sector, age, monthly output, number of employees, and asset quantity; (2) questions on downtimes of essential infrastructure services, including electric power, water supply, telecommunication, natural gas and transportation, and related contingency alternatives; (3) questions on amount of damaged buildings (measured as square meter) at each damage level, and the time it took to restore the damaged buildings or construct temporary building; (4) questions on amount of damaged equipment (measured as monetary value) at each damage level, and the time it took to restore the damaged equipment or purchase new equipment; (5) questions on supplier

Table 3
Downtimes of business operation factors (in days) reported by the respondents.

Operation factors	Manufacturing sector		Retailing sector			
			Necessity		Non-necessity	
	Mean	SD	Mean	SD	Mean	SD
Functional buildings	94.83	143.24	91.61	126.43	18.86	34.19
Functional equipment	48.83	126.95	184.82	173.12	185.14	193.87
Raw materials and goods supplies	37.20	36.66	66.09	81.33	34.26	41.44
Infrastructure services	40.63	34.47	74.18	83.66	35.71	40.49
Workforce	66.40	81.64	0	0	0	0

downtime; (6) questions on workforce losses and downtimes of workforce; and (7) questions on the actual BCL of the business during the Wenchuan Earthquake. The survey was slightly modified for separate use in the manufacturing and retailing sectors, by adjusting a few terms that were sector-specific, examples of which included “production” and “factory” in the manufacturing survey versus “sales” and “store” in the retailing survey. According to local official records about the earthquake impacts [58] and additional interviews conducted with two manufacturing businesses and four retailing businesses, it was found that, among all operation factors, the land and sewage service generally did not suffer any disruptions that were sever enough to impact the operation of businesses in the above two sectors. Thus, the land and sewage service were not considered in the case study.

The survey went through several rounds of revision, during which inputs and feedback from local official statisticians were collected and incorporated. Then, a pilot test of the survey was conducted with owners of two manufacturing businesses and four retailing businesses, in order to test and improve the design and implementability of the survey. Then, the full-scale survey on manufacturing businesses was conducted between October 31, 2019 and January 8, 2020. Through the Bureau of Economy and Information Technology of Mianzhu, an electronic version of the survey was sent to all manufacturing businesses in Mianzhu that were above designated size (annual revenue over five million Chinese yuan, or approx. 684 thousand US dollars) as of 2007 and experienced the Wenchuan Earthquake. The survey on retailing businesses was conducted between October 24 and November 6, 2019, filled in by official statisticians of the Commerce Bureau of Mianzhu during their face-to-face interviews with owners of retailing businesses that experienced the Wenchuan Earthquake. To improve the reliability of the responses, only businesses whose ownership had not changed since 2008 and whose representatives that responded to the survey were owners or senior managers in 2008 were considered in the case study.

By the end of the survey, a total of 30 valid responses were collected from manufacturing businesses. These responses represented around 20% of the manufacturing businesses above designated size in Mianzhu that initially survived Wenchuan Earthquake in 2008, as well as most of those that survived Wenchuan Earthquake and were still operating at the time of this study. As for the retailing businesses, a total of 194 valid responses were collected, which covered all 21 administrative towns in Mianzhu. Each respondent in the survey represented a different business.

Unlike manufacturing businesses, around half of the retailing businesses had small BCLs that were less than a week. Additional face-to-face interviews were conducted with nine of such businesses. These interviewed businesses, which were randomly selected and accounted for around ten percent of all surveyed businesses, covered six towns distributed across the county and sold five typical types of goods including food, clothing, products of daily use, building materials and household appliances. It was found that these businesses did not suffer significant infrastructure service interruptions or building damage from

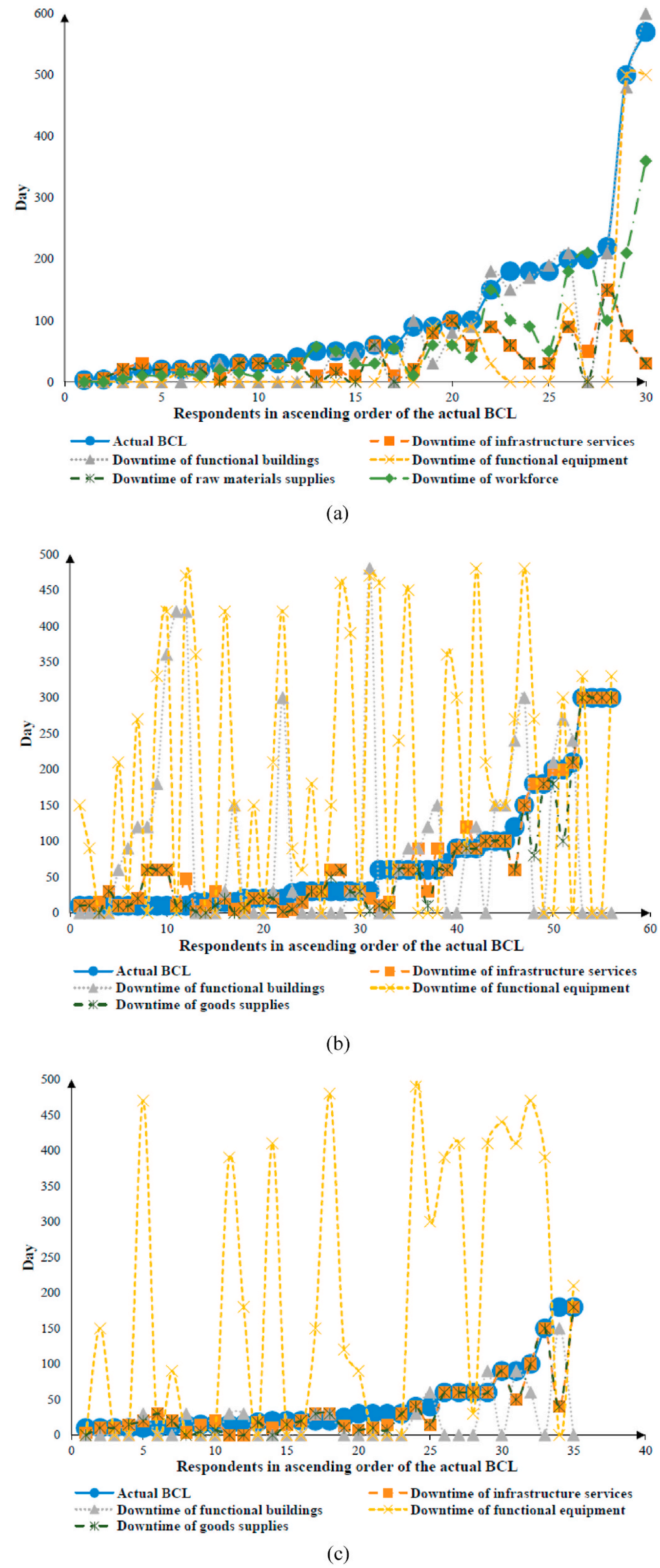

Fig. 2. The actual BCL and operation factor downtimes of businesses in (a) manufacturing, (b) necessity retailing, and (c) non-necessity retailing.

the earthquake. Therefore, they were not forced to close at all, or only had to close for a few days due to executive orders by local authorities or drastic reduction of demands in non-necessity goods, both of which did not last beyond a week. Since external factors such as executive orders

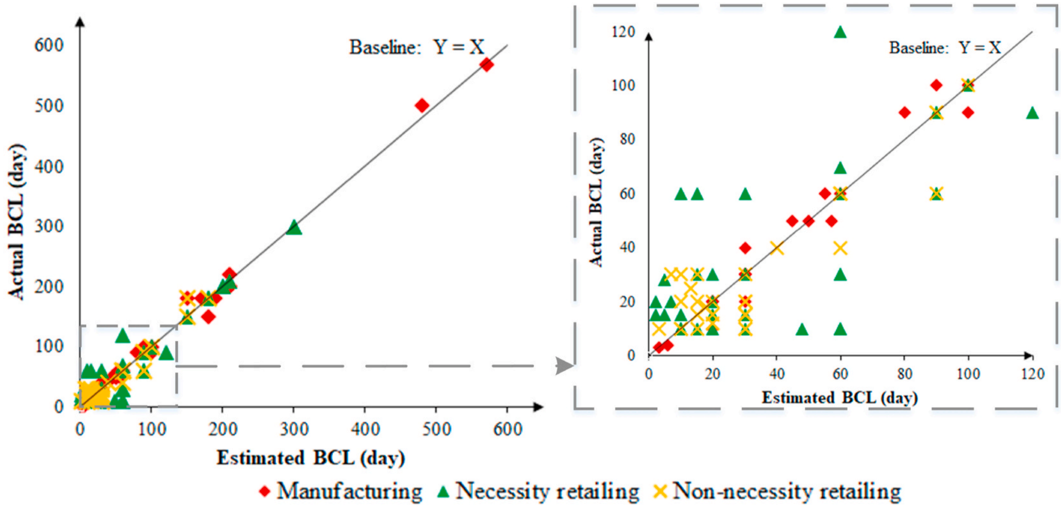

Fig. 3. Comparison of the estimated and actual BCL of all businesses.

Table 4
BCL estimation error assessments.

Variation of downtimes		−10%	−5%	0	5%	10%
Manufacturing	RMSE	19.2 (17.5%)	13.5 (12.3%)	10.7 (9.8%)	15.9 (14.6%)	21.7 (19.8%)
	MdAE	8.5 (7.8%)	3.6 (3.3%)	6 (5.5%)	3.5 (3.2%)	6.5 (5.9%)
Necessity retailing	RMSE	22.5 (31.0%)	21.1 (29.1%)	28.9 (39.8%)	22.6 (31.1%)	25.2 (34.7%)
	MdAE	14.4 (19.8%)	10.1 (13.9%)	0 (0%)	9.9 (13.6%)	13.2 (18.1%)
Non-necessity retailing	RMSE	13.6 (31.2%)	12.7 (29.2%)	13.5 (31.1%)	13.1 (30.2%)	14.4 (33.1%)
	MdAE	8 (18.4%)	7.2 (16.4%)	5 (11.5%)	7.5 (17.3%)	8.3 (19.3%)

Note: numbers in the parentheses are percentages compared to the average actual BCL.

and temporary consumer demand changes were beyond the scope of the proposed framework, the case study only considered the retailing businesses whose actual BCL was above a week so as to focus on testing the proposed framework. Hence, a total of 91 valid responses from the retailing sector were considered in the framework test.

4.3. Model test and error metrics

Based on the survey data, all variables in the proposed framework were calculated according to Fig. 1. These variables included estimated BCL, downtime of infrastructure services, downtime of functional buildings, downtime of functional equipment, downtime of raw materials and goods supplies, and downtime of workforce.

The actual BCL for each business was collected in the survey. This study employed two commonly used error metrics to measure the alignment of the BCL calculated by the proposed framework with the BCL the businesses actually experienced in 2008. The two metrics are the root mean squared error (RMSE) [60] and the median absolute error (MdAE) [61], which are defined in Equations (2) and (3), respectively.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(E_i - O_i)^2}{n}} \tag{2}$$

$$\mathrm{MdAE} = \mathrm{median}(|E_i - O_i|) \tag{3}$$

where E_i and O_i respectively denote the estimated and actual BCL of the i-th respondent, and n denotes the total number of respondents.

Additional sensitivity analysis was conducted in this study to test the effect of possible noise involved in downtimes collected in the survey. By increasing and decreasing the downtimes of all operation factors by 5% and 10% respectively, the estimation errors, measured with RMSE and MdAE, were calculated.

5. Results

5.1. Business characteristics

As shown in Table 1, the respondents from the manufacturing sector covered 12 out of 31 subsectors, based on the Chinese Standard Industrial Classification (GB/T 4754–2017) [62], which covered most manufacturing subsectors in Mianzhu. Two subsectors with the most respondents were beverage and chemical feedstock manufacturing, as Mianzhu is famous in the country for its liquor and phosphorite production. Meanwhile, the respondents from the retailing sector covered 8 out of 9 subsectors based on the Chinese Standard Industrial Classification (GB/T 4754–2017) [62]. Among the 91 respondents, 55 sold necessities, mainly food, beverage and tobacco, 35 sold non-necessities, and one sold both.

Basic business characteristics of all survey respondents are summarized in Table 2. In comparison, respondents from the manufacturing and retailing sectors had a similar distribution of business age, while manufacturing businesses generally had more employees, larger building areas and higher outputs than retailing businesses. Most retailing businesses were owned and operated by one or two persons.

5.2. Downtimes of business operation factors

Based on the survey responses, downtimes of infrastructure services, functional buildings, raw materials and goods supplies, and workforce were calculated according to Equations 2-7. The results are summarized in Table 3.

Specifically, the survey results showed that transportation and electric power contributed the most to the downtime of infrastructure services for both manufacturing and retailing sectors. While telecommunication was also essential for both sectors, it recovered within a few days after the earthquake, which was much faster than other infrastructure services. Gas supplies, required only by heavy manufacturing, did not impact the overall downtime of infrastructure services, since heavy manufacturing businesses generally had contingency resources. In addition, 23.3% of manufacturing businesses had contingency electric power supplies, and 13.3% of them had contingency water supplies.

With respect to functional buildings and equipment, the survey results showed that manufacturing businesses regarded only buildings and equipment that suffered no damage as functional. Retailing businesses regarded buildings and equipment with no or slight damages as functional, and regarded equipment as non-essential. Although severely struck by the earthquake, 36.6% of manufacturing businesses and 34.6% of retailing businesses had access to enough functional buildings required for their operations immediately after the earthquake, and 63.3% of the manufacturing businesses had access to enough functional equipment. Moreover, 30.0% of the manufacturing businesses constructed temporary steel structures and used them as factory buildings, while 37.6% of the retailing businesses set up tents or constructed portable shelters and used them as temporary stores.

As for workforce losses, according to the survey results, manufacturing businesses required at least 50% workforce to restart production, and 30.7% of them could not meet this requirement in the immediate aftermath of the earthquake. Meanwhile, few retailing businesses reported workforce shortage. In addition, supplier downtime was found to be much shorter than transportation disruption time. As a result, the downtime of raw materials and goods supplies was mostly determined by the transportation disruption time.

5.3. Business closure length estimation

Based on the survey responses, a scatter diagram of the actual BCL of all respondents and the downtimes of their operation factors is illustrated in Fig. 2 (Fig. 2a for manufacturing, Fig. 2b for necessity retailing and Fig. 2c for non-necessity retailing). Since most retailing businesses were operated by the owners and their families and did not experience any workforce shortage, the downtimes of workforce were not included in Fig. 2b and c. The respondents were numbered in ascending order of their actual BCL in these figures. As Fig. 2a shows, for most manufacturing businesses none of their operation factors' downtimes exceeded their actual BCL. There were only few exceptions, where the actual BCL of the businesses was marginally shorter than their operation factors' maximum downtime. Moreover, for most manufacturing businesses their actual BCL was close to the maximum among the downtimes of all their operation factors. These findings confirmed the assumption in the proposed framework that the reopening of manufacturing businesses requires access to essential amounts of different operation factors. As for the retailing businesses, as shown in Fig. 2b and c, there were a number of necessity retailing businesses whose downtimes of functional buildings and equipment were much longer than their actual BCL. This suggested that the functional buildings and equipment were not essential to the reopening of necessity retailing businesses. Similarly, it was found that the functional equipment was not essential to the reopening of non-necessity retailing businesses. In sum, the estimated BCL of manufacturing, necessity retailing and non-necessity retailing businesses could be calculated based on Equations (4)–(6), respectively, which were case-specific transformations of Equation (1) in this case study.

$$BCL = max\{T_B,\ T_E,\ T_S,\ T_I,\ T_W\} \tag{4}$$

$$BCL = max\{T_S,\ T_I\} \tag{5}$$

$$BCL = max\{T_B,\ T_S,\ T_I\} \tag{6}$$

A comparison of the estimated BCL of all businesses and their actual BCL is illustrated in Fig. 3. It indicates that although the estimated BCL of a small number of retailing businesses were notably different from their actual BCL, the alignment between estimated and actual BCLs of most businesses were close to baseline Y = X. The errors of BCL estimation, measured with RMSE and MdAE, are summarized in Table 4. The estimation error for manufacturing businesses, measured with both error metrics, were 10.7 and 6 days, which were respectively 9.8% and 5.5% of the average actual BCL. For necessity retailing, the RMSE and MdAE were 28.9 and 0 days, or 39.8% and 0% of the average actual BCL, respectively. For non-necessity retailing, the RMSE and MdAE were 13.5 and 5 days, or 31.1% and 11.5% of the average actual BCL, respectively.

Table 4 also shows the estimation errors when downtimes of operation factors increase or decrease by 5% or 10%. For manufacturing businesses, the RMSE increased by up to 11 days (10%) when the downtimes varied. Meanwhile, the MdAE varied within 2.5 days (2.3%). For necessity retailing businesses, the RMSE decreased by up to 7.8 days (10.7%), while the MdAE increased by up to 14.4 days (19.8%). For non-necessity retailing, the RMSE varied within 1 day (2.3%), while the MdAE increased by up to 3.3 days (7.8%).

6. Discussions and conclusions

This study proposes an analytical framework to model the BCL of businesses in multiple sectors in earthquake-struck regions, based on the downtimes of operation factors of the businesses. The proposed framework quantifies the downtimes of essential operation factors, and establishes sector-specific quantitative relationships between these downtimes and the BCL of the businesses. A case study was conducted in Mianzhu, a county that was struck by the 2008 Wenchuan Earthquake, to test the proposed framework. This section discusses the performance of the proposed framework, its practical implications, its potential to be extended for predicting the BCL of businesses before earthquakes happen, and the limitations of this study and recommended directions for future research.

6.1. Performance of the proposed framework

The case study results showed that the proposed framework could estimate the BCL of businesses based on downtimes of their essential operations with promising accuracies. The estimation error for manufacturing businesses, measured with both error metrics, was within 10% of the average actual BCL, which indicated the estimated BCL values were reasonably accurate [60,61]. As for the necessity and non-necessity retailing businesses, their RMSE values were over 30% of the average actual BCL, which was mainly because the estimated BCLs of a small number of retailing businesses were notably different from their actual BCLs, and the RMSE was sensitive to abnormal values. Yet, the associated MdAE values were much smaller (0% and 11.5% of the average actual BCL, respectively), hence the accuracy for the retailing businesses could still be considered acceptable despite the RMSE values, as other studies have indicated [60,61]. In sum, the overall accuracy of the BCL estimation in the case study using the proposed framework was satisfactory and outperformed the very few studies that have ever addressed this problem and reported quantitative results [36]. In addition, the case study results also showed that the actual BCL of businesess and the longest downtime among their operation factors were highly aligned. These findings implied that the reopening of businesses requires the partial or full recovery in quantity of all essential operation factors, and that businesses would be ready to reopen as soon as essential amount of these operation factors become available [36]. Therefore, given the exact downtime of the operation factors, the BCL of the businesses could be estimated with reasonably good accuracy. Lastly, the sensitivity analysis results showed that the proposed framework was not notably sensitive to noises in values of the input variables, suggesting that the BCL estimation accuracy would not be significantly impacted even if the downtimes of operation factors were not accurately quantified.

The results of the case study also demonstrated the significant role of economic sector, a major factor considered in the proposed framework, in determining the BCL of the businesses. The impact of economic sector is fourfold. First of all, the retailing businesses generally have fewer requirements of operation factors than the manufacturing businesses. For instance, most manufacturing production requires all operation factors, whereas certain operation factors such as equipment may not be essential for retailing sales. Second, goods that are essential for people's daily life such as food and household products are delivered to end consumers through retailing businesses. Hence, reopening of retailing businesses is usually prioritized to meet the basic needs of local residents [14,31]. Third, the manufacturing businesses are normally demanding with buildings and equipment, requiring them to be fully functional to ensure production safety, whereas partially functional buildings would be acceptable for retailing businesses. This impacts the time the businesses would have to wait to access their essential operation factors. Fourth, in the case study, half of the retailing businesses reopened within a week since they were not forced to close, or only had to close for a few days due to reasons unrelated to their operation factors, such as executive orders by local authorities and drastic delcines in consumer demands Echoing the findings in Mohammad et al.'s work [63], this suggested a distinct determinant of the BCL that applied to the retailing sector only. By introducing the economic sector as an important factor and developing sector-specific estimation of the BCL, the proposed framework not only improves the accuracy of the estimation of BCL, but also supports the development of informed guidance of recovery measures.

Moreover, the results of case study showed that the proposed framework recognizes the important fact that business reopening does not require full recovery of operation factors. Instead, businesses forced to close by an earthquake may become ready for reopneing when only an essential amount of their operation factors are recovered [63]. For instance, manufacturing businesses could operate as soon as an essential amount of builidngs and equipment for one production line is recovered. A reduced level of workforce, as demonstrated in the case study, would also be sufficient to support the reopening of the businesses after the earthquake. Althought ignored by most prior studies on disater-induced business interruption, this fact has significant impliations for the accurate estimation of BCL.

6.2. Practical implications of the proposed framework

The proposed framework and the findings from the case study imply several practical strategies and measures that could help shorten the BCL in earthquake-struck regions. First, the recovery of certain operation factors should be prioritized. For instance, recovery of transportation should be given high priority, since transportation is significant for raw materials and goods supplies in both manufacturing and retailing. For manufacturing and non-necessity retailing, access to functional buildings, through either restoration of damaged buildings or construction of temporary buildings, should also be prioritized to avoid a typical bottleneck in reopening these businesses. The proposed framework also suggests that repair of slightly damaged buildings and equipment should be prioritized, as these assets could be immediately used to support the reopening of closed businesses.

Second, several contingency alternatives and backup resources are recommended. Speficially, ensuring accessibility to contingency alternatives of infrastructure services is critical to aviod prolonged business closure [36,64]. In addition, steel structures can provide temporary functional workshops and warehouses for manufacturing production, while tents and portable shelters can be used as temporary sites for retailing sales [12].

Third, the case study results suggested that enhancing the seismic performance of even a small portion of buildings and equipment could largely shorten BCL in the manufacturing businesses. Improving the structural strength of a portion of buildings and equipment could make them more likely to remain functional after an earthquake, which would effectively prevent the businesses closure or reduce the BCL [21]. Meanwhile, efforts to recover those slightly damaged buildings and equipment firstly would largely shorten the downtimes of functional buildings and equipment and therefore reduce the BCL.

6.3. Potential for predicting BCL

The proposed framework models the BCL of earthquake-struck businesses based on the downtimes of their operation factors. Since the downtimes of different operation factors are unknown before or immediately after an earthquake, there is still a gap to predict the BCL, which would be required for certain application scenarios, such as prediction of possible seismic losses and evaluation of different BI reduction strategies.

Extending the proposed framework to predict the BCL requires incorporation of methods to predict the downtimes of different operation factors. While this is beyond the scope of the present study and is the focus of the authors' future work, it is noteworthy that a few methods have already been developed in the literature for operation factor downtime prediction. For instance, the downtime of infrastructure services, including electric power, water, gas and telecommunication, could be estimated based on a modified repair-time model [65] or exceedance probability model [66]. For transportation disruptions, Basöz and Mander [67] developed a downtime fragility curve, which was later integrated in the highway transportation lifeline module of HAZUS [68]. Moreover, prediction of transportation flow and post-disaster recovery time could be done using dynamic equilibrium models [69,70]. For example, Feng et al. [70] developed a scenario-based model to simulate the performance of a transportation network immediately after an earthquake. The model accounts for impairment in traffic capacity and irrational behavior of drivers due to unavailability of traffic information. For predicting the downtimes of buildings and equipment, a number of probabilistic models are available, where the HAZUS methodology is a notable example [71,72]. Although there are few methods for directly predicting the downtimes of workforce and raw materials and goods, several factors affecting these downtimes have been found by previous studies and would be worthy of further investigation in future research. For example, the downtime of workforce could be possibly affected by their home damages [22] or disruptions to their commuting conditions [21]; raw materials and goods supplies could be interrupted by either supplier shutdown or transportation disruption [21–23].

6.4. Transferability, limitations and future work

The proposed framework establishes the quantitative relationships between the BCL of the businesses and the downtimes of their operation factors based on production theories and principles. These relationships are fundamentally determined by economic sector and would be applicable to different disaster scenarios regardless of various contextual factors, such as city characteristics, disaster severity, emergency response decisions, regional economic vitality, and so on. Yet, these contextual factors could significantly impact the magnitude of the downtimes [36], and such impacts and the resulting downtimes of the operation factors may need to be analyzed on a case-by-case basis. In addition, as aforementioned, there could be cases where the BCL is mainly determined by external factors such as executive orders and temporary consumer demand changes. Under such circumstances, the proposed framework may not be directly applicable. Rather, businesses whose BCL is determined by the downtimes of their operation factors should be identified first, for which the logistic regression method [23,38] could possibly be used, before the proposed framework can be applied.

Lastly, it is noteworthy that, in addition to the gap between modeling and prediction of the BCL, the proposed framework bears three other limitations that could be addressed in future research. First, the proposed framework is developed for estimating the BCL of individual businesses. In reality, access to fine-grained data of all individual businesses in a region is not always guaranteed. Whether the proposed framework can be used to estimate the average BCL in a region based on coarse-grained and aggregated data needs to be tested in future research. Second, the proposed framework does not consider businesses that are permanently demised by the earthquake. Further efforts could be made to identify these vulnerable businesses and consider them in the assessment of BI in a region. Third, the case study had a limited scope. More operation factor downtimes, such as supplier downtime, and more economic sectors, such as catering, could be further studied in future research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2020.101916.

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