Supply chain resilience: an empirical model

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Abstract
This paper proposes a model for management of supply chain resilience. To this end the structured content analysis of media news is used to analyze a sample constituted by sixty two documents containing evidences of seventy seven companies that were affected by the Japan 2011 earthquake. The sample provides evidences that companies failed to sustain their operations mainly because capacity shortages and material shortages. Also provides empirical evidence of twelve resilience practices to reduce the disturbance severity and the recovery time. Based on these findings four propositions were made and aggregated to propose a model for supply chain resilience management.

Keywords: Supply chain resilience, secondary data, theory building

Introduction
Interest in supply chain (SC) disruptions and respective negative consequences has been growing in last years and the topic is becoming a main stream (Stock et al., 2009). Whereas in the past the principal objective of SC chain design was cost minimization or service optimization, the emphasis today has to be upon resilience (Blackhurst et al., 2011; Pettit et al., 2010; Ponomarov and Holcomb, 2009; Tang, 2006). Resilient SCs may not be the lowest-cost, but they are more capable of coping with the uncertain business environment. However, there are still fundamental issues that researcher need to address in order to offer managers prescriptive model of how to create resilient SCs. First, much of the existing researches focus on the question on why the companies are vulnerable to SC disruptions (Blackhurst et al., 2011). While important, this question becomes irrelevant because it is increasingly clear that organizations will need to deal with SC disruptions wherever they are more or less vulnerable. The Japan earthquake in March 2011 is a perfect example of

how an unexpected event can affect global SCs. Second, the development of the field tends to focus on anecdotal studies and there is lack of empirical evidences on how companies improve the SC resilience. Blackhurst et al. (2005) state that there is a limited amount of information on how to deal with SC disturbances from a practical in both the short and the long term perspective.

The main objective of this research is to propose a model for management of SC resilience. The fundamental research questions are related to the companies' response to the SC disturbances namely:

- Research question 1: How do SC disturbances affect companies? Which are the main failure modes of SC disturbances?
- Research question 2: How do companies overcome the negative consequences of SC disturbances? Which are the followed resilient strategies?

This paper is organized as follows. First, a theoretical framework is suggested. Next, the methodology used with special highlight on the theory building approach and content analysis is described. In the subsequent section, the findings from the content analysis are described attending to the Japan earthquake impact on SCs, the SC failure modes and the deployed SC resilient strategies. Next, the SC resilience model is proposed and described and finally some conclusions are drawn.

Theoretical framework

Rupture conditions in SC are observed when organizations are subject to disruptions, caused by sudden and unforeseen events (Ponomarov and Holcomb, 2009). An example of catastrophic event is the September 11, 2001, where the terrorist attacks destroyed New York's World Trade Center Towers, automakers like Ford and Toyota had to stop their production lines in US facilities due to delays in the delivery of parts coming from foreign countries (Sheffi, 2001). However, other type of disruptions less catastrophic, but highly severe could occur; like the Robert Bosch GmbH example where in 2005 a quality defect in a small component supplied by another company resulted in the recall of several thousands of cars (Wagner and Bode, 2006).

The exploratory study of Sheffi et al. (2003) on how firms manage SC risk, conclude that managers basically shift the focus from the causes to the effects, under the rationale that for a SC the relevancy should be in the disruption type, not in its source. They had identified the following SC failure modes from the perspective of a single company: disruption in supply; disruption in transportation; disruption at facilities; freight breaches; disruption in communications; and disruption in demand. However, these are not the ultimate causes for unfulfilled orders in SC. Therefore, it is proposed the following proposition:

- Proposition 1: *"Capacity shortage in companies is a SC failure mode provoked by SC disturbances"*
- Proposition 2: *"Material shortage in companies is a SC failure mode provoked SC disturbances"*

The ability to avoid the failure modes, after a disturbance occurrence, is vital for the SC success – it is a SC resilience property. To make clear the use of this term, the following definition for SC resilience is proposed: "SC resilience is concerned with the system ability to return to its original state or to a new one, more desirable, after experiencing a disturbance. The goal of SC resilience analysis and management is to prevent the shifting to

undesirable states, i.e. the ones where failure modes could occur, and support a rapid recovering from them."

The disturbance effect on the SC performance is related to the ability to "absorb" the potential damages and to minimize the failure modes magnitude. The severity of the disturbance effect is related to the existence of mitigation strategies (Tomlin, 2006). These strategies are applied before the event occurrence and that allows minimizing or even suppressing the negative effects of the disturbances. After the event occurrence, SC managers should implement contingency strategies; those in which a firm takes an action only in the event a disruption occurs (Tomlin, 2006). The more efficient the contingency strategies are the smaller is the recovery time. In literature several authors prescribes strategies to increase SC resilience, namely: postponement (Tang, 2006); strategic stock (Tang, 2006; Iakovou et al., 2007); flexible supply base (Tang, 2006; Iakovou et al., 2007); make-and-buy trade-off (Tang, 2006); economic supply incentives (Tang, 2006); flexible transportation (Tang, 2006); revenue management (Tang, 2006); dynamic assortment planning (Tang, 2006); silent product rollover (Tang, 2006); selecting SC strategies that keep several options open (Christopher and Peck, 2004); re-examining the 'efficiency vs. redundancy' trade off (Christopher and Peck, 2004); developing collaborative working across SCs to help mitigating risk Christopher and Peck (2004); developing visibility to a clear view of upstream and downstream inventories; demand and supply conditions, and production and purchasing schedules Christopher and Peck (2004); Iakovou et al. (2007); improving SC velocity Christopher and Peck (2004); reduced in-bound lead-times and non-value added time reduction Christopher and Peck (2004); process and knowledge back-up Iakovou et al. (2007). Therefore, the two propositions are suggested:

- Proposition 3: "To overcome the failure modes a set of strategies to reduce the disturbance severity is deployed by companies"
- Proposition 4: "To overcome the failure modes a set of strategies to reduce the recovery time is deployed by companies"

These propositions were aggregated to suggest the following SC resilience management model (Figure1).

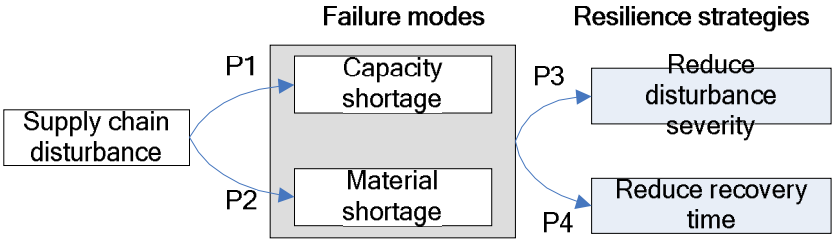

Figure 1 – Proposed model to supply chain resilience management

Methodology

The main objective of this study is to propose a model for management of SC resilience. To attain this, an inductive theory building approach is used (Golicic et al., 2005; Eisenhardt and Graebner, 2007). Our fundamental research questions are related to the companies' response to the negative effects of disturbances. Therefore a focus on companies' behaviour when a disruptive event happens is needed. While the literature has examples of single case studies, e.g. Ericsson (Norrman and Jansson, 2004), to the author's knowledge no study has examined multiple companies to build propositions based on companies' patterns of

behaviour. This study is focused on an extreme event: the Japan 2011 earthquake. This event was selected because it constitutes a paradigmatic example of the SC resilience phenomena; it had impact on different industrial sectors and in several geographic zones. In addition, this type of high impact event provokes several secondary disruptions in SC context like transportation infrastructures destructions, plant destruction or damage, energy shortage, among others; therefore it supports the rich research context related to SC disruptions.

Sampling and content analysis

In a first step it is defined the data scope for analysis, typically text based-communications. In this research it was used a broad range of sources through "Google news" and "Reuters global news agency". Electronic searches were undertaken using the combination of the terms: "SC", "Japan", "earthquake" and "tsunami". The time line was from 11 March 2011 to 6 April 2011. In total 121 documents, mainly news and articles, were obtained and analysed in detail; 62 were selected to be part of this research. The selection criterion to document be part of the study was it should describe the effect of a SC disruption provoked by the Japan earthquake in a company and the strategy used to overcome it. Appendix A contains the document titles and respective identification number (id.n.) that will be used along the following paragraphs to make citation from document. The final sample is constituted by 77 companies; which means that in some cases there are different documents describing the negative effects provoked by the earthquake in the same company.

Content analysis is a rigorous research technique for making inference by systematic and objectively identifying special characteristics or messages in a text (Rabinovich and Cheon, 2011; Krippendorff, 2003; Harwood and Garry, 2003; Spens and Kovács, 2006). The main criticism towards content analysis stems from the subjectivity in its coding process, however Spens and Kovács (2006) propose a set of actions to ensure the objectivity, validity and reliability. To increase objectivity the operational definitions for each category were developed. It was collected secondary data related to the following categories:

- *Negative effect*: it is related to direct or indirect effect of the earthquake in companies and respective SCs behaviour;
- *Failure mode*: it is the core reason why the companies failed in maintaining its operations: i) capacity shortage, when the existing production capacity (machine or human) is not sufficient to satisfy the next demand level because, for example, the facilities were damaged or there was no energy available; and ii) material shortages, when there is not enough materials to satisfy the customer demand because, for example, materials were destroyed or suppliers do not delivery on time.
- *Resilient strategies*: it is any type of action made by the company to avoid, minimize or overcome a failure mode. For example, production has been halt because there is a lack of materials or the production capacity has been damaged.

Regarding the sample analysis, it is important to note that only the information contained in the selected documents has been used. This means that this study does not cover all the possibilities of failures and resilience strategies. It covers only the episodes and strategies reported in the sample.

Findings from the content analysis of Japan earthquake

Japan earthquake impact

The automotive sector is referred as the one more affected by this event: "*With some 500 parts firms affected in the quake and tsunami-devastated northeast, cutting off supply of electronic parts, resin-based products and more, Japan's auto industry is especially vulnerable to a ruptured SC*" [id.n.1]; "*About 13% of worldwide auto output has been lost due to parts shortages and IHS Automotive has estimated it may cut output by as much as 30% within six weeks in a worst-case scenario.*" [id.n.23]; "(...) *there are 30,000 parts to build a car. We might see an impact on practically every production line in North America and most of Europe because of this supply interrupt, this black swan for the global auto industry in Japan"* [id.n.22]. The companies in sample belong to the automotive sector are: Toyota, Honda, General Motors Co, Nissan, Ford Motor Co, PSA Peugeot Citroen, Renault, Autoliv, Chrysler, Hitachi, ON Semiconductor, Daimler and Volvo, Fuji Heavy Industries, Fujinomiya, GKN PlC, GM's Opel, JATCO's Fuji, Kia Motors, Mazda Motor Corp, Mitsubishi Motor, Opel, Robert Bosch, Shimizu Kogyo, Suzuki Motor Corp, Volkswagen and Isuzu Corp.

However there are others sectors highly dependent of the Japanese-made electronic parts: "(…) *Japan accounted for more than 10 percent of the transmission and power train parts used in America in 2009* (...). *Almost a third of the capacitors - an electronic component - used in 2009 were from Japan* (...) *Japan accounted for about 15 percent of the turbines for generating energy sold in the United States* (…)"[id.n.25]. The sample provides evidences that the following companies affected by the earthquake are: Kureha, NSK Ltd, Sony Ericsson, Texas Instruments, Vivitek, ZTE Corp, HTC, Konica Minolta, M. Setek Co, Sony Corp, Apple, Canon Inc, Nokia, Nikon, Alcatel, Arrow Electronics, Echelon and Intel Corp,

The semiconductors industry was also severely damaged: *"Japan is a dominant chip industry player with around one-fifth of the world's semiconductor production*." [id.n.11]; "(...) *produces 60 percent of the world's supply of silicon wafers, and the disruption in assembly could cause a shortage of about 200,000 wafers per month for two to three months*". "*Japan responsible for 32 per cent of the chips found in cars* (...)"[id.n.1]. The companies in sample belong to this sector are: ASML, AT&S, Elpida Memory Inc, Hynix Semiconductor, MEMC Electronic Materials Inc, ON Semiconductor, Renesas Electronics Corp, SanDisk, TSMC and Wintek.

The chemical sector was also affected, e.g., GlaxoSmithKline, Merck KGaA, Mitsubishi Gas and Chemical, Taiwan's ASE and Roche. Namely the production of a particular product the hydrogen peroxide was interrupted: "*Mitsubishi Gas and Chemical, Adeka Fuji and Nippon Peroxide account for 75 per cent of global production of H^2O^2*" [id.n.30]; "*However, Sodhi warns that car manufacturers are not the only businesses affected by the SC disruption: "The technology and electronics industry will be immediately affected as some chemicals which are made for computer chips are only made in Japan."* [id.n.33].

The impact of the earthquake was also extended to the following sectors: *logistics* – FedEx, Hapag-Lloyd and Moller-Maersk; *food* – McDonalds, Starbucks, Subway; *machinery* – Deere & Co and Caterpillar Inc; *aeronautics* – Boeing and Jamco; *retailing* – Edgewise Media; *pharmaceutical* – Novo Nordisk; *fashion* – Hennes & Mauritz; and *energy* – IATA.

The sample also provides evidences that the negative effects of the Japan event were propagated to others geographic zones. Although the majority of the companies in sample

are located in Japan, the negative effects of this event were propagated to nearby regions, like China, Philippines, Korea, as well as to distant geographic zones like Europe and North America. The results show that none type of industry is free from negative effects of SC disturbances. Therefore it is necessary to develop propositions and theory that would be generalized to a wide range of companies. This sample also allows identifying the full spectrum of SC resilience practices across the different industrial sectors.

Supply chain failure modes

Despite the numerous problems directly provoked by the earthquake and tsunami, like roads destructions, plant damage, infrastructures damage, etc, there are others secondary disruptions that had derived from this event; examples are energy shortages or materials damage. Table 1 contains the main negative effects and the number of evidences found in the sample. Energy cuts are preventing plants to resume operations "*power cuts* (...) *could make a return to full production levels difficult*" [id.n.34]. The gasoline shortage in addition to the damages in the transports infrastructures also prevent the staff mobility "(...) *one of the problems at its plants in southern Japan was a lack of gasoline which was affecting distribution of products and stopping staff getting to work in areas like the island of Kyushu, where train services are minimal*" [id.n.34].

Table 1 – Earthquake negative effects found in the sample

Negative effect	**N.º**	**Negative effect**	**N.º**	**Negative effect**	**N.º**
Supplier disruption	113	Customer disruption	3	Employees safety	1
No information	20	Radiation contamination	3	Equipment damage	1
Energy shortage	20	Infrastructure damage	2	Facility contamination	1
Facility damage	12	Resources allocation to	2	Infrastructure damage	1
Transportation disruption	10	emergency relief support		Material shortage	1
Human resources shortage	4	Capacity lost	1	Product destruction	1

However, these negative effects do not represent the final consequences in companies, the Japan earthquake ultimate result in companies behaviour are given by the failure modes. The failure mode most frequent in sample is "**capacity shortage**", with a total of 127 evidences found in sample. This negative effect is referred by the companies located in the event impact area (Japan), since their facilities were destroyed or damaged. "*Not only is the struck region one of our production bases, those directly hit and vastly affected include our dealers, suppliers and numerous other partners* (...)" [id.n.28]. It also reflects the Japan workforce unavailability. Unfortunately the Japan event was a tragedy provoking a high number of effects; therefore several companies in an attempt to support emergency relief efforts had "(...) *asked all its employees in Japan to stay at home*" [id.n.41]. Another negative effect is "**parts/components shortages**", with a total of 60 evidences found in sample. This negative effect occurs when the supply of a particular part/component was interrupted: "(...) *factories have not suffered major damage, the disaster has disrupted shipments of key components and "normal production cannot be expected for many months"* (...)" [id.n.61]. A third negative effect is related to the "**demand reduction**" derived from the disruptions at the customer level: "*British parts maker (...) may have to cut the number of components it makes because some of its Japanese customers, which include Mitsubishi and Nissan may be unable to take deliveries*" [id.n.61]. However, in the research sample this failure mode is marginally represented, only 3 evidences were collected.

According to the content analysis, the following research propositions are supported:

- Proposition 1: *"Capacity shortage in companies is a SC failure mode provoked by SC disturbances"*
- Proposition 2: *"Material shortage in companies is a SC failure mode provoked SC disturbances"*

Resilient strategies

In the sample the company response to the SC disruptions were assessed considering the strategies that allow to reduce the disturbance severity and to speed up the recovery of normal function. In what is concerned with the disturbance severity, although the negative impact of the Japan event was felt immediately in the Japan geographic zone (in the areas hint by the earthquake and tsunami), some companies expected to fell the negative effects in a latter time window. Examples of this behaviour are given by Adeka Fuji – "*Based on current raw wafer inventories, there would be no chance of any serious shortfalls before July*" [id.n.41] and Renault – *"We have an inventory until the end of March. But we expect the crisis to be prolonged until April before being normalised in May"* [id.n.52].

In sample not all companies make public what it was or what is the expected recovery time. However the sample provides some evidences on this, namely Nissan – *"*(...) *hoped the company's Japanese factories could start up again in 2-3 days*" [id.n.28]; Honda – *"*(...) *it would resume production of parts for overseas use on April 4, and production at all its car factories on April 11. Operations are scheduled to resume at about 50 percent of its original plan*" [id.n.62]; Toyota – "(...) *unprecedented 20-day suspension at most factories since March 14*" [id.n.55].

Table 2 contains the number of occurrences in each strategy used to improve the company resilience.

Table 2 – Number of evidences in sample linking resilience to management strategies

Failure mode		**Strategy**	**Examples of citations from sample**	**N.º**
Capacity shortage	Severity	Use alternative production path	*"Texas Instruments warned its two suspended plants would take until July to return to full production, though it had managed to re-direct 60 percent of their output to other sites."*	5
		Use alternative delivery path	*"(...) FedEx account executives in Japan are working "day in, day out" with customers to see if they need alternative locations for deliveries and pickups (…)"*	2
	Recovery	Change production schedule	*"(Sony) said five more of its plants, mostly in central and southern Japan (…) were hit by parts shortages and would close or cut output until the end of March."*	119
		Recovery production capacity	*"(…) an assembly line at a plant in Japan making small liquid crystal displays for smartphones and other devices will be closed for a month to repair damaged machinery."*	6
		Reallocate resources	*"Honda said it would also temporarily transfer some functions such as car development and procurement out of its R&D facilities in Tochigi (…)"*	5
Materials shortage	Severity	Use materials buffers	*"Boeing has also "categorically" said it has enough inventory to cope with any short-term disruptions its Japanese suppliers may face."*	26
		Use alternative suppliers	*"(...) suppliers are more likely to supply Apple, as Apple is more likely than competitors to maintain strong orders"*	8
	Recovery	Change delivery schedule	*"We are optimizing the usage of parts that are or might be in short supply as a result of the earthquake in Japan" "(...) other manufacturers with dwindling inventories are looking at slowing production of low-selling models."*	9
		Find new suppliers	*"The troubles in Onahama are forcing some carmakers to find alternative suppliers". "(...) was looking for secondary suppliers to replace Japanese ones"*	8

		Redesign products	*"circuit board makers are starting to redesign their products so that they can more easily switch components if there is a shortage"*	6
Capacity & Materials shortage	Severity	Create SC visibility	*"Toyota told dealers an assessment of inventory and the status of suppliers following the disaster prompted action to ensure enough components for the North American market."*	6
	Recovery	SC common response	*"assessing the situation at one plant in Utsunomiya that had temporarily halted production and would investigate any supply chain problems"*	25
		Demand management	*"(...) limit or suspend orders for vehicles in several colours that employ Xirallic."*	19

These results make possible to support the following two research propositions related to the resilient strategies and included in the proposed model to SC resilience management:

- Proposition 3: *"To overcome the failure modes a set of strategies to reduce the disturbance severity is deployed by companies"*
- Proposition 4: *"To overcome the failure modes a set of strategies to reduce the recovery time is deployed by companies"*

Conclusions

A number of unexpected events or disturbances are continuously appearing leading to SC failure. The identification of SC failure modes and resilient strategies was the base of this study. Secondary data was collected from a sample of seventy seven companies affected by the Japan earthquake in 2011. The sample provides evidences that despite the earthquake provoked several negative effects, the companies failed to sustain their operations mainly because of capacity shortages and material shortages. These failures characterize the negative effects of disturbances on SC. The sample also provides empirical evidences of twelve resilience practices that can be deployed to reduce the disturbance severity and the recovery time

Using an inductive theory building approach, four propositions and one conceptual model are proposed to support the development of SC resilience. The proposed model intends to offer a holistic perspective towards SC resilience improvement, which decision makers could consider in SC design and implementation of resilient strategies. From the managerial point of view the proposed model provides to managers a deeper knowledge on how disturbances could affect the SC behaviour and which strategies are more appropriated to reduce the occurrence of failure modes. Despite the paper achievements some limitations to the study remain. The model was developed with secondary data. Therefore, its validity is limited to the studied sample, for that reason the model is biased by the available information in documents. Future researches should include the model validation by performing in-depth case studies to identify disturbances, failure modes and strategies that maybe are not referred in the sample.

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Appendix A

Because of paper dimension restrictions, the authors provide a partial list of documents, with the respective identification number (id. n.), used in this study. On request the authors can provide the full list that constitutes the studied sample.

Document title	**Document available at:**	**Id. n**
Analysis - Japan car recovery may take months	http://www.reuters.com/article/2011/03/25/uk-japan-quake-autos-idUKTRE72O1HZ20110328	1
Analysis: Japan disaster could fuel production shift overseas	http://www.reuters.com/article/2011/03/23/us-exporters-japan-idUKTRE72M1BZ20110325	2
Analysts Call Japan Disaster Worst Supply Chain Impact Ever	http://www.supplychaindigital.com/industry-focus/logistics-and-distribution/analysts-call-japan-disaster-worst-supply-chain-impact-eve	3
Apple's Japan Supply Chain Solid:	http://www.thestreet.com/story/11071010/1/apples-japan-supply-chain-solid-	4

Analyst	analyst.html?cm_ven=GOOGLEN	
ASML says sees no impact on supply after Japan quake	http://www.reuters.com/article/2011/03/29/asml-idUKWEA143020110329	5
AT&S sees minimal impact from Japan quake -CEO	http://www.reuters.com/article/2011/03/21/ats-idUSTST00087120110321	6
Automakers face paint shortage after Japan quake	http://www.reuters.com/article/2011/03/26/japan-pigment-idUSN2528593420110326	7
Boeing supplier concerned over Japan gas supply	http://www.reuters.com/article/2011/03/18/uk-japan-quake-boeing-idUSLNE72H02920110319	8
Carmakers running low on Japanese parts	http://www.malaya.com.ph/apr05/busi2.html	9
Caterpillar sales step up, Deere sees Japan delays	http://www.reuters.com/article/2011/03/18/us-caterpillar-sales-idUSTRE72H3Y020110316	10
Chip prices jump as Japan quake threatens supply	http://www.reuters.com/article/2011/03/15/oukin-uk-japan-quake-supplychain-idUKTRE72E4S520110321	11
Japan carmakers take steps in North America to fight disruption	http://www.reuters.com/article/2011/03/30/business-us-japan-automaker-output-idUKTRE72T0M320110333	22
Japan could cause auto supply chain rethink: Expert	http://www.moneycontrol.com/news/world-news/japan-could-cause-auto-supply-chain-rethink-expert_532800.html	23
Japan Disaster Wipes out Part of UK Supply Chain	http://www.creditplus.co.uk/used-car-and-finance-news/Motoring/Japan-Disaster-Wipes-out-Part-of-UK-Supply-Chain/998699582/	24
Japan impact on U.S. economy more than realized: trade group	http://www.reuters.com/article/2011/03/31/us-japan-usa-study-idUKTRE72T5WJ20110331?type=companyNews	25
Japan quake strains supply chain from chips to ships	http://www.reuters.com/article/2011/03/15/us-japan-quake-supplychain-idUSTRE72D7RZ20110316	28
Japan supply chain break down to hurt global production	http://www.bbc.co.uk/news/12858580	29
Japan supply chain faces bleach shortage	http://blogs.ft.com/fttechhub/2011/04/bleach-outlook-for-japan-supply-chain/	30
Japan Supply Chain Worries Now Hit Many US Sectors	http://www.economywatch.com/economy-business-and-finance-news/japan-supply-chain-worries-now-hit-many-us-sectors.30-03.html	31
Japan supply paralysis spreads as firms cut output	http://www.reuters.com/article/2011/03/22/us-japan-supplychain-idUSTRE72L0VZ20110325	32
Japan Supply Shortage Hits European Firms	http://news.sky.com/skynews/Home/Business/Japan-Tsunami-Affects-European-Businesses-Belgian-Ford-Factory-Shut-Over-Supply-shortage/Article/201104115965815?lpos=Business_First_Buisness_Feature_Teaser_Region__0&lid=ARTICLE_15965815_Japan_Tsunami_Affects_European_Businesses%3A_Belgian_Ford_Factory_Shut_Over_Supply_Shortage	33
Japan woes set to hit Europe auto sector-analysts	http://www.reuters.com/article/2011/03/25/japan-quake-autos-idUSLDE72O16620110325	34
Quake impact may spread beyond Japan automakers	http://www.reuters.com/article/2011/03/15/us-japan-quake-autos-idUSTRE72E6IB20110322	41
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