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Abstract

Diversification is the preferred hedge to supply chain risks, but many companies use sole sources anyway for long-term strategic benefits. The enormous damage caused by the March 2011 magnitude 9.0 earthquake in Japan to industrial supply chains warns again that sole sourcing is risky, as many companies or industries around the world were halted due to the loss of their sole suppliers in Eastern Japan. In the literature on contingency actions, temporary diversification has been seen as a feasible response, especially for rare-but-long disruptions. However, little is known about the limits of this approach and the situations where it is applicable. This paper describes and compares two disaster recoveries: the well-known Aisin Seiki fire and the less well-known Riken earthquake, first systematically documented in this paper. Numerous suppliers and competitors volunteered to make parts for Aisin Seiki whereas no such response occurred in the Riken case, despite important similarities in day-to-day operations strategy: sole or nearly sole sourcing, deep supplier relations, low inventory, and severe disruption. Our comparative analysis suggests that characteristics of the affected product and/or its production methods (i.e. generic or asset-specific) limit the recovery alternatives. Temporary diversification was and remains impossible at Riken due to the high degree of specificity required in the design and production methods of the disrupted item. Unawareness of such limits to temporary diversification may result in over-optimism regarding its availability and insufficient disaster preparedness. We also briefly describe two other European cases.

1. Introduction

Supply chain disruption can result from natural and other disasters, such as earthquakes and fires (Kleindorfer and Van Wassenhove, 2004). Most recently and severely in March 2011, the 9.0 magnitude quake and subsequent tsunami in Eastern Japan damaged or destroyed many factories and disrupted the world's electronics and automotive supply chains for a few months. A single firm, Renesas Electronics lost $156 million as a result of damage to its Naka facility, which was designed to withstand an 8.0-magnitude earthquake, and it took three months to put the Naka facility back in operation (Courtland, 2011). Currently (2012) the hard disk drive industry is dealing with hundred-year floods in Thailand. Such disaster-induced risk is often more severe than the operational risks of supplier unreliability affecting quality and delivery.

In spite of the increasing disruption risks due to rare but devastating disasters and a diversification strategy being typically advisable to mitigate the risk (Wang, 2006; Wang and Tomlin, 2010), many companies still insist on concentrated supply of certain components and parts, or as we call it below, fortification--i.e. the use of few suppliers and reliance on vigorous recovery actions. They do so for the value of long-term learning abetted by repeated and deepened relationships, and a deliberate tradeoff of these long-term benefits against some obvious short-term risks (Sheffi, 2005; Nakamoto, 2007). Companies that resolve the tension between diversification and fortification by favoring the latter receive considerable criticism from the lay press when a disaster strikes (Allbusiness, 2007; Reitman, 1997a; Chozik, 2007a).

When a crisis occurs, the loss can be limited through effective recovery actions (Sheffi, 2005; Tomlin, 2006; Tomlin and Wang, 2010). Some of these recoveries using temporary diversification (i.e. temporarily using alternate suppliers) become famous, as in the case of the fire in 1997 at Toyota's brake valve supplier Aisin Seiki (Treece, 1997; Reitman, 1997b; Nishiguchi and Beaudet, 1998), where Aisin Seiki temporarily procured brake valve machining from a variety of volunteer suppliers before it fully recovered its machining capacity. This case has gained somewhat mythic status in supply chain risk management literature. It makes one believe that the availability of temporary diversification makes Just-In-Time (low inventories, rapid response at low cost, etc.) and sole source supply chains *resilient* in an event of disruption, so as to limit losses. Yet, many recoveries from severe disasters do not involve numerous suppliers rising up to produce the item lost in the disaster, and temporary diversification may not be a viable option in some situations. Our understanding of the enablers and constraints of temporary diversification in response to supply chain disruption is still limited.

This research aims to contribute to the supply chain risk management literature by providing multiple cases that allow comparison of different disaster response scenarios and elaborating on the economic-technical factors, notably asset specificity, that enable or constrain them. We primarily compare the Aisin Seiki fire case to another less well-known recovery case after an earthquake that disrupted production of piston rings at Riken Corporation in Niigata Japan in 2007. The comparison is based on data collected from the authors' fieldwork at both Aisin Seiki and Riken, augmented with public data. The two cases share many crisis antecedents but have very different responses. Both similarly involve fortification in day-to-day operations: sole or nearly sole-source arrangements, low inventories, deep supplier relations, and severe disruption. However, after the disruption at Riken due to the earthquake, no upwelling of alternate supplier support to make piston rings emerged. Our field investigation found that temporary diversification was and remains impossible at Riken because of the degree to which piston rings are specifically designed and made for their respective engines, an instance of asset specificity (Williamson, 1981). The authors hold that a Riken-like response is more likely than the Aisin Seiki response because so many parts in complex products require specific assets, while recognizing further research on this point is needed.

The rest of this paper is organized as follows. We first review the relevant literature in Section 2. Section 3 covers the well-known Aisin Seiki fire case, including new information obtained from our own interviews conducted in 2010 and 2011. Section 4 details the new case on the Riken disruption, primarily based on the authors' fieldwork and interviews at Riken in 2010. Section 5 briefly describes two European recovery cases that follow the Aisin Seiki pattern because the assets needed were not very specific. In Section 6, we trace the similarities and differences of these two responses to fundamental economic and technological factors. Section 7 concludes with summarizing our main findings, contributions and direction for future research.

2. Literature Review

2.1 Supply Chain Disruption Risk Management

Supply chain risks fall into two broad categories: (1) *operational risk* from supplier unreliability and its accompanying need for burdensome coordination to overcome supply-demand mismatches (i.e. due to quality and delivery issues), and (2) risk from disruption of normal activities due to strikes, terrorist attacks, fires, natural and other disasters (Kleindorfer and Saad, 2005; Van Wassenhove, 2006). This paper is mainly concerned with *disruption risk*.

Disruption risk management is often divided into risk mitigation, i.e. preparedness before the disruption, and responsiveness, i.e. contingency actions once the disruption has occurred (Tomlin, 2006; Van Wassenhove, 2006). A few operational strategies that managers can use to manage supply chain disruption risks have been studied. In the literature, typical risk mitigation strategies include carrying buffer inventories (Song and Zipkin, 1996; Tomlin, 2006), diversifying suppliers (Tomlin and Wang, 2005; Dada et al, 2007; Tomlin, 2009) and strengthening customer-supplier relations (Krause, 1997; Handfield et al. 2000; Liker and Choi, 2004; Krause et al, 2007). Typical response strategies include using alternate or standby suppliers (Tomlin, 2006; Chopra et al., 2007; Tomlin, 2009) and demand shift or demand management (Tomlin, 2009).

Each of these risk management strategies has strengths and limitations, for which Tomlin and Wang (2010) provide a comprehensive review. In some circumstances, combining several of the above strategies can provide significant value. For example, Wang et al. (2010) suggests a combined strategy of strengthening the relationship with suppliers while pursuing dual sourcing, while Tomlin (2006) suggests the mix of carrying inventory and using backup suppliers, under certain conditions. In addition, a complete supply chain risk management program should also include risk monitoring, identification and assessment (Kleindorfer and Saad, 2005). We must note that all these involve costs (Van Wassenhove, 2006), whether for finding out how much the risk is, mitigating it, or setting up responses.

In fact, we cannot separate risk mitigation and response as they are intertwined. For instance, better preparation before the disruption leads to a better response once the disruption occurs

(Van Wassenhove, 2006). Furthermore, the risk mitigators (e.g. inventory, sourcing diversification, close manufacturer-supplier relationship) are also the keys of the day-to-day supply chain operations, which affect overall benefits such as efficiency and learning. However, the typical literature on supply chain risk management has paid little attention to long-term benefits, which motivate firms' overall operations strategy. In the following, we review the benefits and risks (and the associated costs) of supply chain strategies, which determine the context of our two primary cases that follow in Sections 3 and 4.

2.2 Supply Chain Strategy Considering Risk Management

First, maintaining a high inventory in anticipation of a disruption may reduce blackout periods (Tomlin and Wang, 2010). However, during regular days, the high inventory may reduce working capital and obscure operational problems. It is especially unfavorable if disruptions are infrequent (Tomlin, 2006). Second, the risk mitigation literature often prefers diversification (don't put all your eggs in one basket) over concentration or fortification (put all your eggs in one basket and watch it carefully). Diversification reduces the risk of losing all resources in a disaster, and limits the loss from not having the resources for the blackout time (Tomlin and Wang, 2010). Diversification also offers opportunities to learn from alternate sources, plus enhancement of competition due to greater ease of switching. However, diversification incurs costs from added operational and organizational complexity, limits the depth of mutual trust and relationship with individual suppliers, and loses some value available from concentration, such as scale economies (Sheffi, 2005).

The decision to fortify rather than diversify induces higher risk of losing the whole resource if a disaster strikes. Additional risks include dependence for knowledge and technology (Fine and Whitney, 1999) and holdup (Williamson, 1981). The potential benefits of fortification include making it more possible to pursue the alignment of product design choices with manufacturing methods and operational strategy, plus opportunities for mutual learning about these alignments (Whitney, 1993) and conventional advantages such as scale economies.

Fortification becomes particularly crucial when the procured part is highly interdependent with other parts of the final product, because that demands coordination in design and manufacturing across assembler and supplier, and requires both parties to invest in skills, assets and resources that are valuable only in the context of their specific relationship

(Asanuma, 1998; Sako, 1992; Fujimoto, 2007; Luo et al., 2011), in order to deliver a competitive level of quality, price and service (MacDuffie, 2008; Handfield et al. 2000; Wang, Gilland and Tomlin, 2010). In contrast, diversification is relatively easier to apply to parts that are modular (Baldwin and Clark, 2000) and that can be made using general capabilities readily available from alternate sources.

Therefore, from a mitigation perspective, "lean" or JIT supply chains bear a high risk of disruption in the event of disaster due to the deliberate choices of low inventory and fortification made for long-term operational benefits. The lean production principles (Womack et al, 1990) emphasize cost minimization (keeping inventory low), problem solving, long-term relationships, and collaborative learning and capability building, all of which fortification fosters. In the Japanese automotive industry (the context of our two main cases), Toyota and other manufacturers generally hold the belief that the benefits of minimal inventory and fortification (sole supplier for specialized automotive components/parts) far outweigh the risks of supply chain disruptions and associated losses (Sheffi, 2005; Nakamoto, 2007). For additional reading on these points, see MacDuffie (1995), Hopp and Spearman (2004), and Fujimoto (2001; 2007). Thus, despite repeated criticism from the lay press every time a disaster strikes and disrupts the lean supply chain, these companies consistently stick to such strategies (Reitman, 1997a; Chozik, 2007a,b; Allbusiness, 2007; Nakamoto, 2007).

Actually, fortification and low inventory are not necessarily wholly negative for risk management as they can offer benefits for response effectiveness. Fortification, through working closely with sole partner for a long time, can provide opportunities to explore synergies and strengthen relationships, which are beneficial for effective cooperation, coordination and collaboration across the customer and supplier firms in recovery efforts (Kleindorfer and Saad, 2005). In addition, tight inventories quickly reveal problems in the supply chain after they occur, allowing them to be addressed promptly (Nakamoto, 2007).

2.3 Temporary Diversification and Limits

Blackout time and economic loss due to disruption can be trimmed if responses are effective. The literature on contingency actions has paid increasing attention to temporary diversification, i.e. temporarily using alternate suppliers (Sheffi, 2005; Tomlin and Wang, 2010). Tomlin (2006) implies "contingent rerouting" (which we call temporary diversification) is increasingly favored over mitigation strategies as disruptions become less frequent but longer. In Tomlin and Wang (2010), the same strategy is called backup supply. Nonetheless, these studies only considered one single alternative source that temporarily steps in during the disruption and assumes that this alternate was identified, contracted in advance of any specific disruption, and has the necessary capacity on standby reserve. Studies on the recovery of Aisin Seiki show that the sourcing of P-valves was temporarily diversified to a huge number of *impromptu* suppliers before Aisin Seiki fully recovered (Reitman, 1997b; Nishiguchi and Beaudet, 1998; Sheffi, 2005, pp. 211-215).

Scholars have considered various enablers of such a wide range of temporary diversification, including self-organization and social networking (Watts, 2003, pp. 254-260), knowledge emergence (Kakihara and Sørensen, 2002), collaborative spirit, trust and capability sharing (Nishiguchi and Beaudet, 1998; Sheffi, 2005) etc. Nishiguchi and Beaudet (1998) further argue that the Japanese "institutionalized mechanisms," such as supplier associations and Keiretsu, foster trust building and capability sharing among firms, which make possible such a broad range of suppliers for temporary diversification.

However, our analysis below of a more recent disruption recovery (at Riken Corporation) in the same culture context (Japan), industry context (automotive parts), and operational context (JIT, low inventory and sole sourcing), show that Riken and Toyota's contingency actions did not involve alternate suppliers. Clearly temporary diversification is not the only response pattern, and knowledge-sharing and trust might not be the only influences to disaster responsive capabilities. Tomlin and Wang (2010) implies that contingent rerouting is only available when there is an additional provider capable of performing the disrupted activity, and it must also have additional capacity, i.e. volume flexibility (Tomlin, 2005) when called upon.

There might be additional factors that constrain the range of temporary diversification, for example, product design and production process. It seems reasonable to suggest that the more specialized the item or the more specialized the activity, the fewer capable temporary providers there are likely to be. The design and nature of products for which the supply chain is created, such as product complexity, uniqueness (Lamming, 2000) and customization versus standardization (Asanum, 1988), are believed to have an impact on the production processes used and riskiness of the supply (Kleindorfer and Saad, 2005; Tomlin and Wang, 2010). But the technical attributes of product and production process have not been explicitly studied in supply chain risk literature. In our comparison of two main empirical cases, we will consider them as possible factors that may have determined the differences in the range of responses in the two cases.

In the following, we first describe our two main cases in Japan respectively in detail, then two additional cases in Europe briefly, and then conduct a theoretical and comparative analysis to trace their differences to fundamental enablers and/or constraints to disruption responses.

3. Aisin Seiki

The Aisin Seiki fire and how the supply chain of P-valves (proportioning valves for automotive brakes) recovered from the disaster was first well documented and analyzed by Nishiguchi and Beaudet (1998; 2000), and re-examined from various perspectives by other researchers (Kakihara and Sørensen, 2002; Watts, 2003; Sheffi, 2005). The authors conducted their own interviews with Aisin Seiki in 2010 and 2011.

Aisin Seiki Co. Ltd presently one of the dominant auto suppliers in the world, is a leading supplier of brake systems. A P-valve is a machined casting into which are inserted a number of valves, springs, and seals, as shown in Figure 1. It is about the size of a pack of cigarettes and, while not that complicated a part, it is critical to safety and must be custom designed for each vehicle type in which it is installed--even four-door and five-door variants of the same car model will likely need different P-valves. The machining process, disrupted by the fire, consists of drilling holes of different sizes and at different angles in different but similar castings, all in one plane, varying with the requirements of each car model.

Figure 1. A Typical P-Valve. Left: Size comparison to a pen. Right: Cutaway view.

(Source: Philipp Mayrl, photographed during the authors' visit to Aisin Seiki in 2010). Note the style differences between these two examples (and the one partially visible in the right photo) in terms of number and orientation of pipe connections.

Over many years, Aisin Seiki developed strong operational capabilities required to provide Toyota with the required number and type of P-valve from among a growing variety on a JIT basis. As Aisin Seiki developed this capability, Toyota increased the number of different varieties. Soon, Aisin Seiki was so good at accommodating Toyota's variety demands, low inventories, and rapid response at low cost that it had won nearly all of Toyota's requirements for this part. To meet these needs, Aisin Seiki developed specialized equipment that could machine the castings in many varieties with almost transparent and fast changeover capability to match Toyota's mix of required types, low inventory, and short delivery cycles. It was this equipment that was destroyed in the fire on Feb 1, 1997. Unaffected were the supply of castings themselves, production of components assembled into the machined castings, and the assembly area itself.

As shown in Table 1, in 1996, about 89.8% of Toyota's P-valve purchases in Japan came from Aisin Seiki. To pursue efficiency and scale economy, Aisin Seiki located all its P-valve manufacturing lines in Japan in a single building on a seven-building complex in Kariya, Japan, with a daily volume of 32,500 P-valves when the fire broke out in 1997. Table 1 summarizes the shipments between the major suppliers and customers in the automotive P-valve market in Japan in 1996.

At 4 AM on Saturday, February 1, 1997, a fire broke out that ignited several wooden platforms in building No.1 at the Kariya complex. It has been impossible to pinpoint the exact cause of the fire, but the current plant management holds that the most likely cause was an overheated generator that had been located on the shop floor. The building essentially burned down. The special-purpose equipment for machining P-valve castings was destroyed. By 9 AM that day, Aisin's production capacity for P-valves had vanished almost entirely. Toyota and Aisin Seiki only held two or three days of stocks because of their dedication to JIT production principles. On Tuesday, February 4, Toyota had to shut down 20 of its 30 Japanese vehicle assembly lines because it had no more P-valves, and production ceased at all of its lines on Wednesday February 5. Consequently, several hundred suppliers to Toyota also had to stop production.

Table 1. Monthly Supplies and Purchases of Proportioning Valves (P-valves) in Japan, in 1996

P-value Supplier	Total Production (1,000 units / Month)	Market Share	Manufacturer	Purchases (1,000 units / Month)	Percentage
Aisin Seiki	365.7	41.9%	Toyota Motor	237	64.8%
			Mitsubishi Motor	76	20.8%
			Isuzu Motor	22.5	6.2%
			Suzuki Motor	21	5.7%
			Daihatsu Motor	9.2	2.5%
			Nissan Motor	0.01	0.0%
Nissin Kogyo	162.8	18.7%	Honda Motor	104.9	64.4%
			Toyota Motor	27	16.6%
			Daihatsu Motor	25.9	15.9%
			Suzuki Motor	5	3.1%
Nabco	126.4	14.5%	Nissan Motor	55	43.5%
			Fujitsu Heavy Industry	39.9	31.6%
			Suzuki Motor	31.5	24.9%
Tokico	88.65	10.2%	Nissan Motor	62.45	70.4%
			Mazda Motor	26.2	29.6%
Shinei Kogyo	47	5.4%	Mazda Motor	39	83.0%
			Nissan Motor	6	12.8%
			Suzuki Motor	2	4.3%
Bosch Japan	42.99	4.9%	Mitsubishi Motor	19.6	45.6%
			Suzuki Motor	15.5	36.1%
			Nissan Motor	6.54	15.2%
			Honda Motor	0.6	1.4%
			Nissan Diesel	0.5	1.2%
			Isuzu Motor	0.25	0.6%
Sumitomo Electric	33.15	3.8%	Daihatsu Motor	25.9	78.1%
			Mazda Motor	3.8	11.5%
			Isuzu Motor	2.25	6.8%
			Mitsubishi Motor	1.2	3.6%
Akebono Brake	5.3	0.6%	Hino Motor	2.4	45.3%
			Nissan Diesel	1.6	30.2%
			Fujitsu Heavy Industry	1.1	20.8%
			Mitsubishi Motor	0.2	3.8%

Source: IRC, 1999

At that time, Toyota was producing about fifteen thousand cars per day in Japan. But it would take Aisin months to rebuild because of the requirement of procuring replacement machinery and creating a new production site. However, potentially enormous losses were largely averted by the immediate efforts of other suppliers, from both inside and outside the Toyota group, to recover the P-valve supplies. While the day-to-day relationship was sole source and fortification, the response can be characterized as temporary diversification.

Aisin Seiki and Toyota immediately took measures to set up alternate production facilities of varying efficiency inside Aisin Seiki Group facilities that ultimately machined most of the P-valves, before full production on the original equipment was restored (See Figure 2, based on author's interviews). At the same time and within just one day of the fire, other suppliers including those with little experience with P-valves responded to requests for help, obtained engineering drawings and technical information from Aisin Seiki, and set up alternative production sites and taskforces to machine the castings, which would be delivered to Aisin Seiki. After being inspected and approved by Aisin Seiki, the castings were assembled to the other components and sent to Toyota and other clients of Aisin Seiki. The first acceptable in-house P-valves were available in very low quantities from February 5, and from collaborating suppliers beginning on February 7. Note that most of the P-valve castings were machined by Aisin Seiki after the first month using less efficient methods until the original machines were refurbished and returned to production. The temporary alternate suppliers never provided more than about 30% of Aisin Seiki's needs (Author interviews at Aisin Seiki).

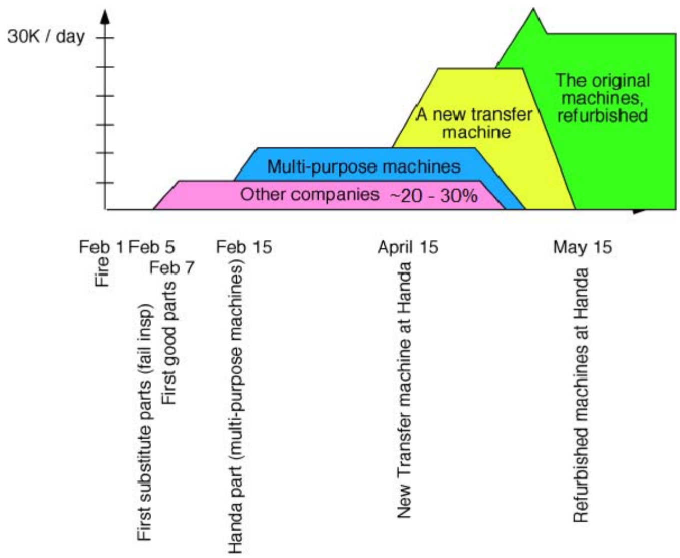

Figure 2. Rough image of volumes supplied and recovery timeline for the Aisin Seiki disaster (Source: interviews by the authors at Aisin Seiki).

More than 200 companies participated in the collaboration for impromptu supplies of machined castings, and approximately 62 of these firms directly produced P-valves. Such active collaborative efforts, including managing schedules and delivery priorities, were orchestrated by Aisin Seiki.

By Thursday, February 6, two of Toyota's assembly plants were reopened. On Monday, February 10, nine days after the fire started, all Toyota group plants were back to pre-disaster production volumes. In all, Toyota lost only four and a half days of production, despite Aisin Seiki's having lost at least five weeks of production. Total loses by Aisin Seiki and Toyota are estimated to have been several hundred million dollars. Without the cooperation of the suppliers, losses would surely have been much higher.

Aisin Seiki's long-term response to this disaster was to rebuild the factory complex of seven buildings where the fire occurred, replacing them with one modern building extensively equipped to prevent fires from occurring or spreading. A fire remembrance day is held each year on February 1 and fire drills are frequent. In 2010, Aisin Seiki transferred this factory to ADVICS Co. Ltd, an affiliated company, to focus on other products. Today, many of the functions of the P-valve have been incorporated into other brake system components and only about half as many P-valves are made each year as were made in 1997.

4. Riken

In order to (re)construct the comparative case of the Riken earthquake and disruption of piston ring production, we have collected information and data from various sources, including our visit and interviews at the plant in 2010, news articles, public reports, company press releases and data books on Riken Corporation and the 2007 Niigata Earthquake, to document how Riken's production of piston rings recovered after the disaster.

Riken Corporation is the largest supplier of piston rings in Japan. A piston ring is a tiny working part in an internal combustion engine, and requires special processes and tools to produce because its precision is essential to an engine's efficiency and durability (see Figure 3). There are only three major automotive piston ring producers in Japan.

Figure 3. Typical piston rings. Each piston usually has three rings, each of a different design and purpose. (Source: Riken Corporation)

Since 1926 when Dr. Keikichi Ebihara of the Okochi Research Laboratory of the Institute of Physical and Chemical Research developed a new manufacturing method for piston rings, which was patented and commercialized (Riken Website), Riken has specialized in piston ring design and manufacturing technologies so that other suppliers have had difficulty emulating Riken. This situation also made it difficult for carmakers to diversify their piston ring purchasing sources in Japan (Nakamoto, 2007). As shown in

Table 2, in 2005, Riken held a 49.9% share of the automotive engine piston ring market (by quantity) in Japan, and supplied to all 12 major Japanese automobile manufacturers.

While every reciprocating engine has piston rings and they look superficially alike to a lay person, in fact piston ring design and production are highly specialized and tailored to each target engine. It takes several years of design and testing to develop suitable piston rings for a given engine. Engine designers visit Riken frequently and interact deeply with the developers of “their” rings and the specific process equipment that will be used to make the rings for “their” engine (Authors’ interviews at Riken, 2010)

Table 2. Monthly Supplies and Purchases of Piston Rings in Japan, in 2005

Piston Ring Supplier	Total Production (1,000 units / Month)	Share	Manufacturer	Purchases (1,000 units / Month)	Percentage
Riken Corporation	485.2	49.9%	Honda Motor	93.3	19.2%
			Toyota Motor	81.2	16.7%
			Suzuki Motor	76.1	15.7%
			Mazda Motor	71.4	14.7%
			Nissan Motor	69.2	14.3%
			Fujitsu Heavy Industry	29.2	6.0%
			Mitsubishi Motor	23.9	4.9%
			Daihatsu Motor	18.8	3.9%
			Nissan Diesel	10.9	2.2%
			Mitsubishi Fuso	9.4	1.9%
			Isuzu Motor	1.0	0.2%
			Hino Motor	0.9	0.2%
Teikoku Piston Ring	294.3	30.2%	Toyota Motor	141.3	48.0%
			Daihatsu Motor	59.3	20.1%
			Mitsubishi Motor	41.6	14.1%
			Suzuki Motor	21.3	7.2%
			Honda Motor	16.5	5.6%
			Isuzu Motor	6.5	2.2%
			Nissan Motor	3.0	1.0%
			Hino Motor	2.4	0.8%
			Mitsubishi Fuso	2.3	0.8%
			Nissan Diesel	small quantity	0.0%
Nippon Piston Ring	193.6	19.9%	Toyota Motor	78.2	40.4%
			Nissan Motor	31.0	16.0%
			Daihatsu Motor	26.1	13.5%
			Mazda Motor	17.8	9.2%
			Isuzu Motor	12.7	6.6%
			Fujitsu Heavy Industry	10.2	5.3%
			Hino Motor	9.8	5.1%
			Suzuki Motor	4.1	2.1%
			Mitsubishi Motor	2.7	1.4%
			Nissan Diesel	0.5	0.3%
			Mitsubishi Fuso	0.5	0.3%

Source: IRC, 2008

On July 16, 2007 at 10:13 AM, a magnitude 6.6 shallow earthquake occurred near the west coast of Honshu, and was followed hours later by a magnitude 6.8 deep earthquake in Niigata, Japan. Riken's piston ring production facilities in Japan, located in the city of Kashiwazaki close to the epicenter of the earthquakes, were hard hit by the earthquake. Production of piston rings was completely shut down for two weeks because of the significant damage to that plant facilities and equipment, in particular the heavier ones. Figure 4 shows the overturned machines and spilled inventory at Riken after the earthquake. This led to an estimated loss to the Japanese automotive industry of about 100 billion Japanese Yen, or about US$820 million. (Arup, 2007). Riken has stated that its direct loss due to the earthquake was 1.5 billion Japanese Yen.

Figure 4. Damage at Riken (Source: Riken Corporation)

The larger industry losses reflect what was incurred by the downstream automakers and the many affected suppliers who were impacted by the consequent ripple effects through the automotive supply chains. In this case, the automakers held low inventories of piston rings, and were heavily dependent on Riken for piston ring supplies. Riken was the sole-source supplier of the piston rings for many car models of the automakers at the time of the earthquake (Nakamoto, 2007). With Riken shut down, automakers could not manufacture many engines and vehicles.

Toyota was forced to stop operations at all 12 of its domestic plants, and lost production of more than 120,000 cars (Global Risk Miyamoto, 2007). According to Honda (2007), 7 plants, including 3 for automotive production, 3 for engine production and 1 for motorcycle production, were halted due to the piston ring production disruption at Riken.

Immediately after the shutdown, the automakers provided various forms of assistance, including engineering and repair, to Riken. According to a Riken Corporation Press Release on July 19, three days after the earthquake, its customer companies including automakers as well as equipment manufacturers had sent approximately 650 people including many equipment engineers to help its recovery. The recovery was orchestrated by Toyota, which utilized experience it had gained from the Kobe earthquake in order to decide what kind of help was needed in what sequence. Such management and collaboration helped Riken restart its production of piston rings much more quickly than it would have been able to on its own. Riken had its own disaster recovery plan but that proved immediately to be inadequate. Production resumed on July 23 (Riken Corporation Press Release, 2007), within a week of the earthquake, and fully recovered within two weeks (Global Risk Miyamoto, 2007). Figure 5 documents the milestones in the recovery process.

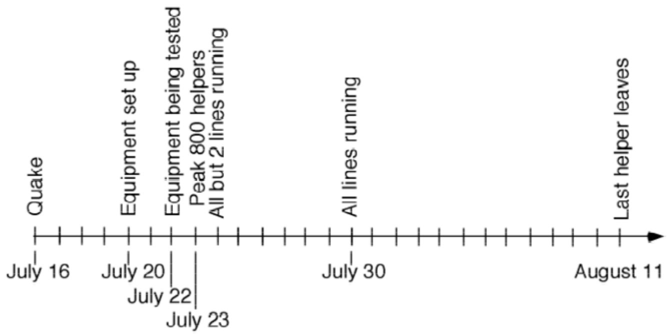

Figure 5. Timeline of Riken Recovery (Source: Riken interviews by the authors)

After the disaster, Riken planned to spread out its production of piston rings to multiple locations in Japan and even abroad due to the effects of this earthquake (Global Risk Miyamoto, 2007). However, this diversification was not instituted. Instead, Riken reinforced its buildings, anchored down its production equipment and still today produces all of its piston rings for Japanese customers in Japan in the same buildings at and around the same site. However, as a buffer against any future severe disruptions, it has placed about a week of inventory nearer to its customers' factories. Riken still provides a large fraction of the Japanese car industry's piston rings. It has also completely rewritten its disaster recovery manual.

5. Comparison to Other Supply Chain Disasters

In this section, we further provide brief descriptions of two other cases of supply chain disaster and recovery in Europe. The two cases are based on interviews with company representatives conducted by the authors' collaborators based in Europe and public data.

5.1 Fire at a German Painting Company

In 2010, a fire destroyed two main paint lines of a German company that paints car door handles for a supplier of handles for most German auto manufacturers. This company painted all of the supplier's products at that time. Because color matching is crucial for products like automobiles, where color is part of the product's attractiveness, it is not unusual to use a single supplier for colored items of a given type, such as door handles. Volkswagen bought all of its door handles in Germany from this supplier while Audi, Daimler and Opel procured most of theirs. The supplier makes 20 million handles per year or about 70,000 per day using dozens of colors.

Within a few hours after the fire, the supplier's employees were on the phone seeking alternate painters. Competitor door handle manufacturers were asked to do the rest. Information about colors and paint formulations had to be obtained from the painter. Special racks for holding some types of handles also had been destroyed so their designs had to be obtained as well. The painter started up a secondary line that painted a small fraction of the needed handles but not nearly enough. It took about three weeks to get all the colors and paint processes set up at these alternate painters. These painters did not communicate with each other but instead were managed by the door handle supplier. The supplier held daily meetings to manage schedules, check paint and color quality, and dispatched employees to the substitute painters to check on the processes, construction of new special racks, and color accuracy. Eventually all of the logistics of painting handles and delivering them to the car companies was taken over by the different painters.

In some cases these painters were not equipped to use the original paint formulations, so paint manufacturers reproduced the colors in compatible formulations. An additional barrier was the secrecy surrounding some of the colors. Most car companies released this information eventually but one car manufacturer would not and subsequently decided to buy its door handles from one of the competitors who helped during the crisis. The other car companies worked with the original supplier and, because of their flexibility regarding paint formulations, were able to get every car its handles in a relatively short period of time, although there was a delay of about two weeks for a while. As of 2011, recovery is still ongoing and the door handle supplier has now given some of the paint work to one of the other painters who helped. While the door handle supplier feels that it was fair to all the substitute painters, the negotiations over compensation after the fact were not easy, and if such a problem happens again it will try to settle compensation terms first.

5.2 Fire at Rotoflex in Switzerland

In 2005 a fire destroyed 80% of the facilities of Rotoflex, a small Swiss company that makes special dyes for coloring flexible food packaging film. The dyes are made using flammable volatile solvents. Fires in this industry occur often enough that other firms in the industry typically go to each other’s aid. Rotoflex is still the only Swiss supplier of this kind of dyes, which explains why it has sole source relationships with its customers. The fire was especially threatening because 2005 was a time of consolidation in the industry, and crises like fires are often the pretext for a takeover attempt. In fact one of Rotoflex’s first responses to the fire was to solicit a competitor to buy them, without success. However, this competitor agreed to help, and another volunteered without being called. Eventually surplus capacity was found at three other companies. These agreed to start up production without any legal or financial agreements in place but later drove hard bargains. Rotoflex survived in part due to the loyalty of its customers.

Some special mixing equipment was destroyed so the manufacturer of the equipment worked to build replacements on an accelerated schedule. The rest of the equipment was repaired. The building was restored and after six months all of the manufacturing capacity was restored plus an additional 50%, which the company installed in the hope of increasing its business. The restored facility has greatly increased safety and fire abatement capability and subsequent small fires have been put out quickly. The fire and recovery process was financially draining, and the company is still paying back loans it took out at the time. It was helped by one of its chemical suppliers who advanced credit for six months.

5.3 A Brief Summary of the Cases

So far we have described two main cases in Japan in detail and two brief cases in Europe. Table 3 summarizes the key information of the cases and illuminates some similarities and differences.

Table 3. Summary and comparison of four sole-sourcing supply chain disruptions due to disasters

	Case 1	**Case 2**	**Case 3**	**Case 4**
Customer	Toyota, Japan	Toyota, Japan	Automotive parts supplier, Germany	Manufacturers of lacquers for flexible packaging films, Europe
Supplier	Aisin Seiki, Japan	Riken, Japan	Painting firm, Germany	Rotoflex, Switzerland
Date	1997	2007	2010	2005
Disruption	Fire burned specialized machining equipment	Earthquake knocked over machines	Fire destroyed paint application equipment and fixtures	Fire destroyed dye mixing and formulating equipment and the factory building
Item(s) disrupted	Brake proportioning valves	Piston rings	Car door handles for several car manufacturers	Manufacture of specialized colors for flexible packaging films
Importance of item(s)	Needed for nearly all Toyota's cars assembled in Japan; sole source relationship for each specific car model	Needed for 27% OF Toyota's cars assembled in Japan; sole source relationship for each specific car model	Painter painted 90% of these handles for the supplier, its customer; total 20 million parts per year; one sole source auto customer	No other color company makes this formulation in Switzerland; all customers dependent on this company
Processes disrupted	Machining of valve castings	Specialized machining, heat treating and finishing	Painting: dozens of colors; millions of parts per year	Manufacturing of colors based on flammable ingredients
Product specificity	Designed for each car, dozens of types, complex fulfillment on JIT basis	3 year design and process development needed to match ring to engine	OEM-designed parts and OEM-specified colors	Customer-specified colors and chemical composition
Process specificity	General machining – many shops capable of the necessary machining	Tailored to piston ring processes – only another piston ring manufacturer could do it	Many paint companies could do it, but some could not use the exact paint formula needed but provided substitutes	Several nearby competitors are able to do it
What was done	Dozens of competitors and other shops machined them using their own processes; no single shop could machine all the different types or meet the huge demand	Riken machines were put back in place – no spare industry capacity and no time existed for lengthy process development	Competitor painters helped, as did paint manufacturers; paint company started up a small line that was not damaged; initial difficulty encountered duplicating colors	One competitor volunteered; another responded to a call for help; manufacturer of destroyed equipment sped up order for replacement equipment
How long did the disruption last	3 months	1 month with schedule disruptions for several months	Ongoing, but most production has been restored; sole source not resumed	6 months
How quickly did substitute or recovered operations start	4 days	6 days	Two weeks	Two weeks at substitute suppliers, 4 weeks at Rotoflex
Other comments	Toyota continues sole source procurement of these parts	Toyota organized the recovery but Riken managed the schedules and resolved priority conflicts among its customers	Recovery was managed by the parts supplier; some new painting contracts given to competitors; one OEM defected to another door handle supplier	Companies in this business know the danger of fire and often help each other; no customers defected; some holdup by competitors for price to use their equipment

Sources: Cases 1 and 2: public data and reports plus the authors' interviews at the respective companies. Cases 3 and 4: public data plus telephone interviews with company representatives.

All of these cases involve severe disruption of one or more intentional sole source arrangements. All include evidence that the recovery was somewhat impromptu and began almost immediately, that some special techniques were involved in making the affected item, and that ingenuity was required to carry out the recovery. The only major difference is that case 2 (Riken) requires a process that is impractical to duplicate within the time horizon needed, whereas in all the other cases, alternate suppliers and competitors volunteered or were willing and able to help with temporary diversification when asked.

In particular, our two temporary diversification cases in Europe are not that different from the Aisin Seiki case in fundamental ways. In fact, they indicate that some of the characteristics of the Aisin Seiki case that have been deemed unique to Japan or especially praise-worthy (tightness of Japanese customer-supplier relationships, self-organizing capability, organizational learning, practice with JIT and low-inventory systems, etc.) are more widely distributed than may have been thought. The Aisin Seiki case is extreme in the number of suppliers needed, a direct consequence of the huge number of pieces needed per day and the lack of efficient substitute processes, and in turn the need for an elaborate organizational effort. This in no way diminishes the achievement itself or the lessons it teaches about resourcefulness in the face of crisis.

Instead, case 2 provides the exception, which offers an opportunity to reveal a "variable" of response pattern. Specifically, the lost asset of Riken is sufficiently specific that no substitution is possible. In this aspect, the two European recoveries follow the Aisin Seiki pattern to greater or lesser extent because the assets needed were not very specific. In the case of the paint, it is not really generic but substitute kinds of paint could be found at substitute suppliers. In the following, we focus our analysis on this point.

6 Discussion

6.1 Disruption Responses and Limits

Of interest is why the responses to our main case disruptions were different. In this Section, we trace the different responses to differences in economic and technological fundamentals, related to products, production methods and the benefits/costs of strategic sourcing concentration.

In both main cases, the disrupted suppliers were the sole source of the assembler, Toyota, for a specific automotive part used in its vehicles. The essential difference is that in principle almost any competent machine shop can, on short notice, machine the casting for a P-valve that will satisfy the needs of the car for which it is intended. The mere fact that dozens of companies, some from outside the automotive industry, could gear up so quickly is *prima facie* evidence that P-valve machining is really not very difficult to learn and do correctly, even though most of the responding companies had difficulties for the first day or two. Such difficulties are in fact not that unusual in typical production ramp-ups. However, it is not possible for anyone, even another piston ring manufacturer, to make, on short notice, a piston ring that will function properly with a given engine. Piston rings and engines are co-designed over a period of approximately two to three years with constant and close coordination between their respective designers to develop the correct design and manufacturing technique, and to verify that the final output on the full-volume line precisely meets the design requirements (Authors' interviews at Riken, 2010).

A P-valve's manufacturing method and process are rather independent of a car, whereas the design of a P-valve is coupled to the design of a specific car. Coupling of car and P-valve gives rise to small differences in shape and interfaces that do not affect the manufacturing technique in principle. In relief from the fire in 1997, the substitute suppliers indeed did not use Aisin Seiki's maching methods or achieve its low costs, flexibility, and high volumes. But machining for P-valves is generic enough that alternate methods, with different capability for volume-variety combinations, can be learned very quickly (hours or days). In response to the disruption, many alternate suppliers were needed due to the huge volume and variety needed, and the relative inefficiency of the alternate methods the different suppliers had to use. No single alternate supplier necessarily had to, or perhaps even could, provide all the different types or the whole quantity needed of each type.

The unspecific nature of P-valve' production methods/processes and the ease of substituting suppliers on short notice would seem to be atypical of manufactured parts. In automobiles, we can think of commodity fasteners as among the least specific parts used. Tires are often substitutable because their sizes and internal construction are somewhat standardized. But nearly everything else, from alternators and radiators to seats and dashboards, are designed specifically for a given car. Even if capable manufacturers exist for each of these kinds of items, the differences between parts that make them suitable for a given car require months or years to develop in each case. Temporary diversification for high-volume/high-variety parts on short notice after a disaster is likely to be only rarely possible.

Temporary diversification is impossible with a part like a piston ring. Piston rings are among the most specific parts in a car due to the tight coupling of their design and manufacturing method to their intended engine. This coupling makes it impractical not only to find substitute suppliers after a disruption but also to create multiple suppliers *a priori* by dividing the supply of piston rings for one engine among two or more suppliers because of the expense and time required to duplicate the lengthy design process and validation of correct manufacturing methods. This creates quite high asset specificity (Williamson, 1981; 1985) between the supplier and assembler. Asset specificity is an important concept in the economic and transaction cost literature. High asset specificity makes it difficult to obtain or learn capabilities quickly when needed. The historical evolution of the piston ring industry in Japan further reduces the possibilities for temporary multiple sourcing, there being only three companies in Japan that can mass produce piston rings for automobiles.

In addition, luck played a large role in both cases. Had the fire occurred in the next-door building where Aisin Seiki made most of its brake master cylinders, the observed rapid response would have been even harder to achieve due to the more difficult maching steps required for master cylinders (Author interviews at Aisin Seiki). Similarly, had the earthquake measured 9.0 (as in the earthquake in March 2011) instead of 6.6, the damage to Riken's specialized machines might have been permanent rather than temporary, causing many months of disruption.

None of the companies involved has changed its basic policies. Toyota's supply chain strategy maintains sole-sourcing and long-term relationships with suppliers, and Toyota reaps both design synergies and operational benefits. ADVICS (Aisin Seiki's successor company for P-valve production) still supplies nearly all of Toyota's P-valves, and Riken has not built another piston ring plant in Japan. While earthquakes cannot be prevented, they rarely strike with devastating effects (an increase of 1 in magnitude means a decrease in likelihood by a factor of 10) and usually only at long intervals in any one region of less than a few 10's of km in diameter. Defending against a truly devastating earthquake or widespread conflagration would require so much inventory or slack alternate reserve capacity that it would never be economically attractive. Instead, as the response to the March 2011 earthquake shows, intense recovery efforts are the only practical method.

6.2 General supply chain strategy and perseverance in fortification

The juxtaposition of the Aisin Seiki and Riken cases provides an opportunity to compare disaster responses when supply chain strategies are nearly the same. For normal operations, Toyota, Aisin Seiki, and Riken used fortification as the general sourcing strategy, and still do so after the respective disruption events. In our interviews with them, all three companies cited the benefits of this apparently risky choice.

In the case of automotive piston rings for which specificity is the key to product and operational excellence, diversification may impose operational and organizational complexity and loss of value (quality, cost and delivery) achievable from concentration, and thus a disadvantage vis-à-vis the competitors which adopt concentration for the item. The piston ring industry as a whole is highly concentrated in Japan (see Table 2). In fact, U.S. car manufacturers also adopt the single source strategy for the piston rings of a given engine even though there are more available U.S. suppliers.

In the case of P-valves, the relatively low asset specificity required for machining them and the successful temporary diversification in Aisin Seiki recovery may drive one to consider supply diversification for the item even during normal days, which can potentially mitigate the risk of supply disruption, reduce the cost of restoration and the loss in revenue. Simply put, for P-valves, supply diversification is a feasible choice but not taken by Toyota for day-to-day operations. Why?

Generally, fortified supply can reinforce the alignment of product design and manufacturing method, foster mutual learning about these alignments, and create scale economies. Specifically, in the case of Toyota's sourcing of P-valves, because Toyota cars use a huge variety of P-valves, the supplier that outperforms competitors must have effectively combined operational efficiency with flexibility. To address Toyota's variety needs, Aisin Seiki developed and applied flexible equipment with low or zero change over costs, with the ability to meet Toyota's JIT requirements. Despite being capable of making a P-valve, no other machine shop than Aisin Seiki could do this complex fulfillment when Toyota increased its variety of P-valves over time. This gave Aisin Seiki an unbeatable cost advantage over available competitors so it had by 1997 won almost all of Toyota's business for P-valves in Japan.

Aisin Seiki indeed developed specific assets, as did Riken. The difference is that the temporary alternate suppliers of P-valves did not need to duplicate Aisin-Seiki's specific assets but could each provide some of the required types and quantities of some P-valves using their own machining assets and methods (same in the two European cases). Because these alternate assets were relatively inefficient, many substitute suppliers were needed. The Mikawa region of Japan, where Toyota and Aisin Seiki are located, is rich in machine shops due to the nearby presence of Toyota, Mitsubishi Motors, and the region's heritage as a center of aircraft production in past decades.

In summary, diversification is relatively easier to apply to assets that require less specific capabilities and are readily available from alternate sources. Aisin Seiki's P-valves fall into this category. Diversification is more difficult to apply to specialized assets or those with few alternate sources. Riken's piston rings fall into this category. However, Toyota used and still uses fortification rather than diversification for day-to-day supplies of both cases, with the belief that long-term benefits of learning, quality, and efficiency from it far outweigh the risks.

7 Conclusions

In this paper, we have sought to understand similarities and differences of two disruption response cases in Japan, plus two in Europe, and relate them to known bodies of economic theory. The main conclusion is that asset specificity required in the manufacturing methods and processes of a disrupted item or process constrain the range of responses to supply chain disasters. Yet we find that Toyota (as well as other lean manufacturers) persists in a fortification strategy for sourcing, because of the belief that long-term strategic benefits of fortification will outweigh the risks of disruption. We suspect that relatively few items in most competitive industries are generic enough in production methods that temporary impromptu diversification will be possible. Thus the Riken-type response may be more likely to be the one that emerges after disasters rather than the Aisin Seiki type.

This research contributes to the supply chain risk management literature by identifying the economic-technical factors that influence the possible responses to disruption. For practitioners, unawareness of the fundamental limits to temporary diversification or being overly optimistic about its availability may result in insufficient or inappropriate disaster preparedness. Therefore, it is important for supply chain managers to understand the extended range of responses available to recover a disrupted supply chain, and, particularly, the enablers (and constraints) to different responses. In this paper, asset specificity is identified as such a factor.

To advance understanding further, additional cases (more countries, more industries, and more products) will be desirable. Comparing more examples will allow us to illuminate more response alternatives to supply chain disasters and any hidden factors, which may influence the responses but were not revealed by the cases in the present paper.

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