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Three cases in Japan occurred by natural hazards and lessons for Natech disaster management

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ABSTRACT

Due to recent climate change, highly-connected society, and the centralization of hazardous materials, Natech is a matter of the growing concern. As Natech disasters occur with low frequency, those in charge of facilities should learn lessons from past cases to prepare for situations in the future in which they may have to respond to a potentially catastrophic event for the first time.

This paper describes three Natech cases triggered by the heavy rainfall in Japan in 2018. One resulted in violent explosions, one showed consequences half a year later, and the other managed to avoid a catastrophic situation by preparation based on prior analysis of possible damage.

The lessons which can be learnt are as follows: Undertake measures based on the hazardous conditions of materials and possible reactions; Avoid normalcy bias for improved decision-making; Identify slow developing and lagging Natech consequences; Prepare and intensify safeguards to avoid possible damage based on risk analysis; Consider employees’ safety in returning to their homes; Collect micro information and aggregate it; Provide current information about the situation to stakeholders; Plan resources required for recovery activities.

1. Introduction

1.1. Definitions of "Natech"

When nature shows its force in natural disasters, the consequences are often very significant damage to human lives, property, and social systems. History records that natural disasters due to geophysical, meteorological, hydrological, and climatological disturbances have resulted in large numbers of casualties, and land used to support human livelihood has been devastated. Often recovery has taken many years. While technological developments enable our society to forecast the arrival of some natural events, natural hazards can still create disasters that disrupt human activities by the size and scale of their physical impact.

Although the initial, primary damage caused by severe natural events may be their physical impacts, the increasing development and sophistication of human activities has generated a new type of risk accompanying such events, which is called Natech. When the term Natech first appeared, it was originally defined as “natural disasters that create technological emergencies” [1]. More recently other definitions have appeared in academic literature: for example, “natural hazards triggering technological disasters [2], “Industrial accidents triggered by natural hazards [3], “natural hazard-triggered technological disasters [4]“natural hazard-triggered chemical releases [5], “accidents triggered by natural hazards that create catastrophic technological calamity [6]. These newer definitions have a core similarity in that they address complex secondary damage caused by natural disasters in the context of technological development.

1.2. Factors magnifying Natech

Recently, Natech has been discussed in connection with climate change, highly-connected society, and the centralization of hazardous materials. Climate change is addressed by the United Nations as a defining issue of our time whose impacts are likely to be unprecedented in their size and scale ranging from shifting weather patterns to rising sea level [7]. Changing weather patterns have been experienced in Japan with more frequent occurrences of strong typhoons and increased precipitation. The number of recordings of precipitation over 50 mm per hour has increased over the last 40 years. Japan Meteorological Agency has observation stations which record the rainfall every hour of every day. Each year this centre totals the number of times there is a reading of
1.3. Three domains of Natech research

The growing international concern over Natech has let many researchers to study this field. These studies can be categorised into three domains: Natech risk management, quantitative risk assessment, and case studies.

Successful Natech risk management is a high priority since Natech disasters have different features from conventional disasters because of the coupling of the technological aspects with a natural disaster. The effects can occur in many areas simultaneously and limited resources may hinder the emergency responses. The combination of initial damage due to a natural disaster and secondary damage due to industrial emergencies can overwhelm the emergency response. The time to the recommencement of normal public life and industrial activity can be lengthy and the recovery phase can be slow and protracted, particularly when infrastructure is damaged or hazardous substances pollute the affected area. Careful planning and preparation to ensure as much continuity as possible for the community is essential from local level to regional level, or even national level in case of tremendous accidents [11]. Without such preparation a catastrophic Natech disaster could result in an “end of the time” scenario.

In terms of Natech risk assessment, a framework for quantitative risk assessment has been established by extending a framework for quantitative risk assessment in chemical facilities. This incorporates elements specific to aspects of a natural disaster such as frequency and severity of natural event occurrence, the possible damaged states of facilities, and their probabilities [12]. Some case studies have contributed to Natech risk assessment by collecting data for an equipment damage model [13]. Case studies examine and analyse Natech events to learn lessons. Such lessons are important since Natech disasters are infrequent and so those who have to cope with a Natech disaster when it happens are often doing so for the first time. Some very serious Natech events have been studied in great detail, such as Hurricanes Katrina and Rita in the USA [14], the Great East Japan earthquake and following tsunami [15,16], the L’Aquila earthquake in Italy [17], the Kocaeli earthquake in Turkey [18], and the Wenchuan earthquake in China [19]. Case studies also contribute to developing successful Natech risk management.

1.4. The scope and background of this research

To contribute to this area, this paper reports on three cases of Natech events involving manufacturing factories, caused by heavy rain and floods in Japan, 2018. One case involves severe damage to a factory as well as the local community, another concerns two fatalities in a factory as a consequence of a natural disaster, and the third case discusses a factory which fortunately managed to avoid a catastrophic accident.

In Japan, intense precipitation can cause floods and landslides [20] which have sometimes resulted in fatalities. Japan suffers from heavy rainfall caused by the Baiu front which appears in early summer most years and gives a typical rain band around Japan [21]. Typhoons are also a source of extreme precipitation. Tsuguti and Kato investigated 386 heavy rainfall events that occurred between 1995 and 2009 in Japan and found that more than 75% of these heavy rainfall events occurred between July and September [22]. In those months, facilities in Japan are supposed to prepare themselves for this type of event in order to avoid any disaster. Nevertheless, disasters have still happened as are described in this paper which indicates that Natech risk management still needs development and should be taken more seriously in industries. This paper aims to review the three cases and suggest lessons for establishing better Natech risk management, from the standpoint of local factory operators rather than from a national or regional level (Table 1).

2. Case studies

2.1. Case 1: explosion in Soja

On July 6, 2018 an aluminium recycling factory in Soja, exploded. The explosion destroyed the factory and the flying objects and shockwave also destroyed an adjacent factory and neighbouring houses. Fortunately there were no fatalities but many people were injured and many residents had to be evacuated. Since the explosion was the result of serious flooding following very heavy rainfall this can be considered a Natech disaster and is worth examining in detail. This rainfall was later named the “Heavy rain of July 2018 (Heisei 30)”. Across the whole of Japan this event resulted in 237 fatalities, 8 missing people, and 432 injured [25], so it was a serious national natural disaster.

The factory that exploded belonged to an aluminium recycling company, Asahi-Arumi Sangyo (Arumi means Aluminium in Japanese) located in Soja, Okayama prefecture. The company collected used aluminium and recycled it by smelting and refining it. Normally, the factory operates 24 h a day so molten aluminium was being processed as usual on 6th July. However, late the previous evening (at 23:45 5th July), Okayama Local Meteorological Office had issued a severe warning about heavy rainfall around Okayama prefecture, which was being caused by the Baiu front coupled with Typhoon Prapiroon [26]. Residents were alerted to the likelihood of landslides, swollen rivers, and flooding. The Met office escalated the severity of their warnings to Emergency Warnings at 19:40 on 6th July. Emergency warnings are meant to alert people to the significant likelihood of catastrophes associated with natural phenomena of extraordinary magnitude [27]. Emergency warnings linked to heavy rain are issued when the forecast is for rainfall with a level of intensity only experienced once every few decades [28].

The aluminium smelting factory in question was located between two rivers, the Takahashi and the Shimpon. The Takahashi is a major river with its banks close to the factory and the Shimpon is a tributary of the Takahashi, but only about 50 m away from factory. This location poses a risk of flooding to the factory; indeed the premises had
Table 1: Comparison of the three cases.

| Case 1 | Case 2 | Case 3 |
|--------|--------|--------|
| Place (City, Prefecture) | Soja, Okayama | Izumi, Osaka | Kure, Hiroshima |
| Date of natural event | July 6, 2018 | September 4, 2018 | July 6, 2018 |
| Type of natural event | Heavy rain | Heavy rain and wind, high tide | Heavy rain |
| Type of technical disaster | Explosion | Toxic gas release | - |
| Losses in the prefecture in insurance (JPY) | 75,582,093,000 | 600,747,050,000 | 47,510,875,000 |
| Missing and dead in the prefecture | 69 | 8 | 120 |
| Injuries in the prefecture [23] | 161 | 485 | 146 |
| The number of damaged buildings [24] | 16,373 | 42,902 | 15,828 |
| Full resumption of electricity supply [24] | 13 July<br>20 September<br>13 July | 14 July<br>11 September<br>2 August | |
| Full resumption of water supply [24] | |

* The date means that the Chugoku Electric Power fully resumed power supply in its business coverage.
* The date means that Kansai Electric Power fully resumed power supply in its business coverage.
* Data of Kurashiki which is a adjacent municipality to Soja since data of Soja was not available. Other adjacent municipalities are 10 July (Ibara city), 11 July (Yakage town), 15 July (Takahashi city). The water outage was due to break of water pipe, or flood damage of water treatment plant or water source.
* The outage was due to stoppage of pump by electricity outage.
* The outage was due to break of water pipe, blockage of water tunnel or flood damage of water treatment plant.

experienced a flood in 2011, but there was no serious damage then and so no steps were taken to mitigate a future flood. On the morning of July 6, 2018 the company continued producing aluminium, but, when one of their employees discovered how swollen the rivers were and reported it, they decided to stop the process and remove the molten aluminium from the smelting chamber. However, this decision was taken too late. The smelting chamber typically contains 40 tons of molten aluminium and it takes time to remove it. At a little before 10 p.m., when the floodwaters reached the factory, everyone evacuated the premises but that was before all the molten aluminium could be completely removed. In fact, less than half had been removed and more than 20 tons of high-temperature molten aluminium remained in the smelting chamber when the cold floodwaters reached it.

The floodwater entered the chamber and came into contact with the molten aluminium leading to a violent vaporisation of the water and the explosion. The impact of the explosion destroyed that factory, another nearby factory and neighbouring houses. The scattered molten aluminium even caused fires. A witness who was a volunteer emergency responder in the nearby flooding and was controlling traffic about 4 km away from the factory, noticed a bright explosion and fires followed by shockwaves.

All employees of the company had evacuated the factory before 10 p.m. and were safe when it exploded.

2.2. Case 2: toxic gas release in Osaka

On February 13, 2019 two men entered a tank in a factory in Osaka and were overcome by toxic fumes [29]. The men were brought out by emergency rescuers with breathing apparatus but were declared dead on arrival at hospital. Since the factory is located in a residential area including nurseries and schools, a warning was issued to advise people to shelter from the toxic gas which had escaped from the tank. The cause of this technological accident can be traced back to a serious natural disaster around six months earlier.

On September 4, 2018 the Osaka area was struck by Typhoon Jebi, which was accompanied by gales and high tides. The wind velocity was reported to reach 60 m/s (over 135 mph) [30]. Many companies in the area decided to close their businesses and the railway companies suspended their train services since the weather forecast had given serious warnings and alerted people to take appropriate measures. This typhoon was a serious natural disaster as it left more than 80,000 houses damaged, killed 14 people, and injured 1011 people. The losses due to this typhoon cost 747,700,000,000 JPY in insurance [31]. One area of substantial damage was the collision of a tanker into a connecting bridge between Kansai International Airport and the shore [30]. This ship had been anchored 2 km south of the airport on the day before the typhoon arrived. However, the strong winds associated with the typhoon blew the tanker away from its moorings and then caused it to crash into the bridge. As a result about 8000 people were stranded at the airport because the connecting bridge was damaged.

In one area of Osaka the strong winds of the typhoon caused an electricity power cut for 70 h affecting many homes, businesses and factories. One business affected was a manufacturer of material for car mats, company A, which is located in that area. As part of one of their processes company A produces an adhesive in a large tank, 2.7 m in diameter and 5.4 m high. The cut in the electricity power supply stopped the stirring of the substance inside this tank so that the material in the tank was ruined.

The ruined and now useless material was left in the tank for about half a year and then the company decided to clean it out. Two men were scheduled to clean the tank on February 13, 2019. One man entered via a manhole and was overcome by the fumes and the second attempted to rescue him but was also overcome. The toxic fumes inside the tank were hydrogen sulphide gas, H₂S, which had been created by the deterioration of the adhesive substance and then accumulated inside the tank up to a lethal level. Once the tank had been opened this toxic gas spread to the area surrounding the tank.

2.3. Case 3: landslides at Etajima, Hiroshima

On July 6, 2018 another factory was affected by heavy rainfall in the “Heavy Rain Event of July 2018”. This factory is located 150 km away from the Asahi-arumi factory described in case 1 and manufactures and sells explosives so stores and processes dangerous materials. However, in this case the heavy rainfall natural disaster did not lead to a technological disaster because mitigation steps had been taken. Thus, this is a case study of how a Natech was avoided by appropriate mitigation.

The factory, which belongs to the Chugokukayaku Co., Ltd. company and which manufactures and sells explosives and related substances, is located on the coast of Etajima, the fourth largest island in the Seto Inland Sea, which is between the Chugoku Mountains in the north and the Shikoku Mountains in the south. Normally, the islands in this inland sea have relatively less rainfall all year round because humid air from the sea ascends on the windward side of the mountains surrounding the sea causing precipitation and then the dry air descends to the islands in the inland sea. However, once every 20 or 30 years this area experiences heavy rainfall and strong winds due to typhoons, for example, Typhoon Songda in 2004. Based on that experience, the factory management had prepared emergency guidelines and an emergency response plan in case of an approaching typhoon. The plan includes moving items to higher level ground, hanging protective covers over windows to avoid them being broken by flying objects, placing sandbags at the entrance to buildings to avoid water ingress and so on, when weather forecasts or warnings issued by the meteorological observatory indicate an imminent risk. In their company guidelines, on a day when a big typhoon is expected to hit their island, they stop factory operations and give the
staff a day off, because they would have difficulty getting to work. This is because many staff travel to the island for their work and so need to commute by ferries, which will be cancelled, or come over bridges which will be closed.

In addition to the risks of a typhoon, this area is also at risk of Nankai megathrust earthquakes which are predicted to be likely in the near future and could result in a tsunami. The company has prepared a specific emergency response plan for such an earthquake. This plan specifies emergency shut-down procedures and the evacuation to areas above the expected height of a tsunami, which might possibly arrive 40 min after the earthquake.

In extreme weather conditions the factory is also exposed to the risk of landslides from collapsing protective embankments. All explosives factories are required to have embankments around each of their workshops to limit the damage of a blast in case of an unforeseen explosion. Some of the embankments at the Etajima site were constructed from natural hills, so management had assessed possible losses and damage caused by any collapses of these embankments in extreme weather conditions. Some sections which might cause severe damage if they collapsed, had been reinforced with mortar.

As the factory is on a small island, some workers commute by train and then by a company owned ferry, whereas others come in their cars and have to cross two bridges linking the mainland to the island. When the first heavy rainfall warnings were issues on July 6, 2018 and in response to information about the possible early suspension of train services to the station nearest to the island, the company organised daytime workers to share cars going home so that workers who normally commute by train could return to their homes safely in the evening even if the trains were not available. However, because the observatory had not issued warnings of urgent danger, the management decided it was safe to continue operation of the factory. This decision was also supported by the fact that workers on the overnight shift who commute in their own cars to the factory had begun to arrive. Crews on the day shifts finished work and left the factory between 17:30 to 19:00 as usual. At that moment in time, it was not raining significantly.

After the rain turned quite severe, at 19:49, an emergency alarm system was activated in an explosives drying shed because an embankment had collapsed destroying that shed but the explosives themselves were not damaged. Fortunately, other buildings including the administration office were unharmed by this collapsing embankment thanks to the reinforcement. However, another 8 facilities were damaged by other embankment collapses (Fig. 1) while landslides outside the factory damaged part of the factory’s boundary fences. Some of these collapsed embankments had been identified in their previous risk assessment and had been scheduled to be reinforced in due course, whereas others had not been regarded as dangerous areas. At about the same time, in the wider area around the factory, there were many other landslides and the erosion of the foundations of roads. A worker who had left the factory had to return because the roads to his home were blocked.

At this point, water ingress was found in some other storage sheds, however, no explosion or hazardous events occurred as the stored explosives were not reactive to water and had not been exposed to dangerous mechanical stimuli such as compression. At that time, only the explosive manufacturing plant was in operation, but it was built on elevated ground and was unaffected by the landslides and flood. The company started to shut down this process from 21:00 because some nightshift workers could not get to the factory, and the process was completely shut down by 3:30 the next morning.

As planned the factory management informed the government administering authority and their customers of the situation. The situation was uploaded and occasionally updated on the ministry of economy, trade, and industry’s website confirming there was no danger of an explosion.

The weather forecast emergency warning for this region was issued at 19:40 on the 6th and lifted at 10:50 the next day. In the town, shovels were sold out on the day after the heavy rainfall, and a home centre limited the number of shovels each customer could purchase.

Chugokukayaku Co., Ltd. started recovery work at its factory on 9th July aware of possible secondary landslides. They had to remove the sediment manually in the hot weather after the heavy rain had passed, and so they carefully managed workers’ loads to avoid any heat exhaustion. As they cleared up no damage was found in the production process, but the lack of water prevented the factory from resuming operations for 10 days. The water supply over the whole island was cut off because the main pipeline had been damaged by landslides and the production of explosives cannot be undertaken without having an emergency water sprinkling system available.

### 3. Discussion

The cases just described show some consequences of natural hazards for manufacturing facilities. In this section the findings from each case are explored and lessons drawn from what happened (Table 2).

#### Table 2

Findings from each case.

| Case | Findings |
|------|----------|
| Case 1 | Undertake measures based on the hazardous conditions of materials and possible reactions |
| Case 2 | Avoid normalcy bias for improved decision-making |
| Case 3 | Identify slow developing and lagging Natch effects consequences |
| Case 3 | Prepare and intensify safeguards to avoid possible damage based on risk analysis |
| Case 3 | Consider employees’ safety in returning to their homes |
| Case 3 | Collect micro information and aggregate it |
| Case 3 | Provide current information about the situation to stakeholders |
| Case 3 | Plan resources required for recovery activities |

**Fig. 1.** A storage shed hit by landslides.
3.1. Findings in case 1: the risk of water as a source of explosion

3.1.1. Undertake measures based on the hazardous conditions of materials and possible reactions

Many Natech disasters start with the destruction of a storage facility or a production facility as a result of the physical effects of some natural hazard. This then leads to the leakage of chemicals. Physical effects, such as vibration [32], are the features of a natural hazard that can influence the function of a technological system.

The Natech disaster at Soja was triggered by floodwater from a nearby river. Floods are well known to trigger Natech accidents [33,34]. In our previous study, heavy rain and subsequent floods were found capable of exhibiting six types of physical effects which can damage the intended operation of a target technology. Ground failure effects are when the ground condition is destabilised and can cause the collapse of a structure built on it. Submersion in water can cause permanent damage to goods which then no longer function properly. Transfer effects are when objects are moved by buoyant forces. These effects, particularly submersion and transfer effects occur frequently with heavy rainfall and flooding. For example, more than 3000 LP gas vessels floated away from their storage areas in a heavy rain event in Japan [35].

The cause of the powerful explosions at Soja was the cold floodwater coming into contact with the hot molten aluminium in a chamber which had allowed water ingress. The surrounding destruction was caused by the catastrophic effects of the explosion which propelled heavy objects through the air leading to injuries to people and damage to properties [30]. The force that propelled the objects was generated by vapour explosion.

A vapour explosion is the rapid expansion of vapour which generates a mechanical force and occurs when a liquid comes into contact with hot material. When a hot non-volatile liquid comes into contact with a cold volatile liquid, the expansion of the volatile liquid is violent due to the instantaneous creation of a new interfacial area [36]. Vapour explosions have been observed with various combinations of hot and cold liquids such as molten salt and water, molten silicates and water, etc. In the Soja case, the cold flood water came into contact with the hot surface of the molten aluminium and an enormous amount of vapour was generated instantaneously, resulting in the creation of a destructive shockwave.

This phenomenon has been studied in connection with the safety of foundries and nuclear reactors. The safety literature on nuclear reactors (Light Water Reactors) focusses on the risk of contact between molten fuel and the coolant water in a meltdown accident. A violent explosion has been recorded at a steel foundry where molten steel dropped into a trough of water at a foundry in Quebec in 1960s [37]. The report which analysed the accident concluded that the main destruction was caused by the generation of a shockwave rather than a simple phase transition, or the conversion of water to steam. It also concluded that it was unlikely that the chemical reaction of the steel with the water increased the explosive pressure.

Although this phenomenon is simple to understand and seems easy to prevent, accidents due to the contact of molten metal and cool water still occur. For example, in an accident at a Japanese factory manufacturing automobile parts, it was reported that when molten aluminium was poured into an ingot case which contained some rainwater the aluminium exploded and injured three nearby workers [38]. In 2015, in another factory in Japan, molten aluminium leaked from the smelting chamber and came into contact with water and exploded [39].

Compared to these previous accidents, the volumes of the liquids involved in the Soja accident were massive (more than twenty tonnes of molten aluminium and an enormous amount of floodwater). The windows of houses up to at least 400 m from the actual explosion were seriously damaged even though there is an embankment road between the houses and the factory. Windows were shattered completely at a convenience store 650 m away from the centre of the explosion. This damage suggests the total energy of the explosion was at least equivalent to 1.3 ton of explosive on the assumption of a 49% probability of breakage for windows facing potential explosion sites with 0.975 m² of the area of a window [40].

The Soja case highlights the risk of handling materials in hazardous conditions. The phase-change of floodwater caused by the temperature difference resulted in a vigorous explosion while most Natech events due to flood water resulted in transfer of objects due to buoyancy, or ground failure, or dampness which causes corrosion of electrical products, or submersion resulting in damaged materials. Some materials are stable in their standard condition, but usually can also be stored, handled, or transferred in a factory in a hazardous condition, such as at high temperature. However, the hazardous condition can cause severe problems in the event containment being lost. Therefore, when a natural disaster is forecast and the lead time for its onset is known an important countermeasure is to shutdown the process and stabilise the condition of the material.

There have been other violent reactions between metal and water. At the port of Kobe in Japan, 66 tons of magnesium stored in containers at the port burst into fire due to seawater ingress during the high tide caused by the typhoon on September 5, 2018. The fire continued for 51 days before it was completely extinguished [41]. Based on such accidents, water as a reactant should be taken into consideration when an operator handles material highly reactive with water.

However, aluminium does not react with water unless the temperature of the aluminium is above 2140 °F (1171 °C) and the melting point of aluminium is about 660 °C [37]. In fact in the Soja case, the chemical reaction between the aluminium and water played only a minor role in the vapour explosion as is reported in a previous study [36,37]. The fires that did arise in this case are thought to have occurred because the vapour explosion scattered some of the hot aluminium onto combustible materials which ignited.

3.1.2. Avoid normalcy bias for improved decision-making

From the viewpoint of Natech risk management, the lead time to shut down a process should be incorporated in the emergency plan for that process. When a factory handles large quantities of a hazardous (hot) substance, it can take time for the hot material to cool down (or cold materials to heat up) to a safe temperature. In the Soja case, all molten aluminium can usually be completely removed from the smelting chamber in about 4.5 h, but on this occasion the decision to remove the hot material was only made about 3 h before the floodwaters reached the smelting chamber. According to police reports, the president of the company and the head of the factory decided not to shut down the process when they were first warned of a possible flood. This facility had been struck by a flood in 2011 and is located in an area that is considered vulnerable to flooding. However, an awareness of these factors did not lead management to take the safe option in the decision-making process in July 2018. Such decision-making is often influenced by production pressures and normalcy biases. Production pressures have been discussed in the field of safety at work because they can lead frontline workers to engage in unsafe behaviour and pose a threat to safety. Safe working practices can be neglected when workers feel the need to perform their tasks quickly [42]. From the point of view of management, the concern is often over the economic consequences and their relations with external stakeholders. These pressures are not so much for quick performance, but more for continuing operations despite the risk of damage with thoughts such as “other areas might be subject to damage, but perhaps we won’t, ‘we had no damage on the previous occasions, so should be OK this time’, or ‘the situation won’t become any worse’. Such normalcy biases deter erring on the safety side in decision-making and delay activation of an emergency plan.

The decision can be particularly difficult when the demand for production is high. To combat this problem predetermined scenarios and values must be set to activate the emergency plan so that management responds responsibly to warnings of an acute and serious situation.
3.2. Case 2: the risk of a chemical reaction during shutdown

3.2.1. Identify slow developing and lagging Natech consequences

Public utilities such as gas, electricity and water supplies are all susceptible to natural disasters which can interrupt supplies and so cause extensive disruption in society which is highly dependent on the continuous supply of such utilities. Once an outage happens, it disrupts regular activities and can sometimes threaten even health and safety due to worsening hygiene. In a chemical plant, utilities are essential to maintain the safe operating conditions of processing units. They are necessary for maintaining operations including reaction, distillation, transfer, storage and so on by controlling valves, heating and cooling material and stirring substances. An electricity supply, in particular, is also essential to manage processes by monitoring or changing the condition of each unit in terms of temperature, pressure, level, and flow. An electricity supply is also essential for the safe shutdown of operations. Since the lack of an electricity supply can be catastrophic for production and safety, many chemical plants are equipped with private electricity power generators as a back up in case of an electricity power grid failure. For example, one chemical process facility faced an electricity outage immediately after the Great East Japan Earthquake in 2011, but the site was successfully shut down due to a prior impact analysis which had identified key equipment and the need for redundancy in nitrogen generation which was essential for a safe shutdown [43].

Maintaining conditions for continuous safe operation and storage is particularly important if a chemical facility stores unstable materials that can decompose above certain temperatures, so there is a need to ensure stable cooling. The chemical facility just mentioned kept an unstable catalyst on the site chilled by using a refrigerator vehicle and so avoided any decomposition. On the other hand, when the Arkema Chemical Plant in Texas was hit by Hurricane Harvey it struggled during the subsequent heavy flood to keep the organic peroxides which were stored on the site cool [44].

The rapid decomposition of an unstable chemical is often identified as a Natech risk, but a slow reaction can easily be neglected. Managers usually pay attention to unstable chemicals on site because they know the consequences of a cooling failure can result in an explosion and so understand the necessity of maintaining that process. However, the Osaka case described earlier highlights the danger posed by the slow development of a situation. A slow reaction may not cause an explosion, but it can gradually evolve and over time generate unexpected harmful substances.

In the Osaka case, the factory did not have enough knowledge of the consequences of unexpectedly halting a process and leaving the part processed material unattended for a long time. The part processed material gradually disintegrated generating hydrogen sulphide H₂S, which is lethal in high concentrations. Therefore, an understanding of the stability of all substances on the site is important, not only the reactive ones but also those that can slowly decay, including those which may exist only temporarily as a process progresses. This case highlights the fact that the impact of a natural disaster may appear much later even though the immediate response to the disaster was successful in avoiding any major problems. The Osaka facility had avoided the potentially damaging risks associated with flooding and strong winds during the typhoon. However, the toxic gas accumulated to lethal levels and was released half a year after the typhoon had passed.

This accident highlights the point that possible lagging effects of Natech disasters should also be incorporated into the Natech risk assessment. Many of the consequences of a natural disaster appear immediately and are obvious. However, in some cases, the consequences develop over a longer period of time and the impact may only become dangerous when it is assumed that all the problems have been dealt with. For example, cables damaged by an earthquake can ignite fires when the flow of current is due to a resumed. Maybe some of the damaged cables are not initially identified. After a while, when the other cables are repaired and the current flow switched back on, the damaged cables which have not been repaired can cause sparks which can ignite combustible materials in their vicinity and cause fires [45].

The Osaka case highlights the finding that the full impact of a natural disaster is not always immediately obvious. In response to a natural disaster, facilities may be shut down or operations partially suspended in a way that can hide a malfunction or the development of hazardous scenarios. In such cases, the full resumption of operations can be a dangerous process and needs to be done carefully. In addition to immediate consequences, latent, possibly delayed outcomes of natural disasters, which can cause danger later, should be investigated and then measures to avoid their occurrence should be incorporated into the emergency plan.

3.3. Case 3: the importance of mitigation prior to the onset of natural disaster

3.3.1. Prepare and intensify safeguards to avoid possible damage based on risk analysis

Since natural disasters are difficult to avoid, it is an essential safeguard to take measures which reduce the damage that might be caused. Since some safeguarding measures take time and resources to be implemented, they should be arranged well before any disaster arises. In the Osaka case, the reinforcement of embankments with mortar was a safeguard against possible landslides and the raising of the production facility was a safeguard against possible flooding. Although the severity of the disaster may have been greater than expected, the mitigation activities they had undertaken were prioritised in the order of the severity of any loss, particularly possible loss of life. Hence, the mitigation steps taken avoided any catastrophic damage to the factory. A president of the company told the author that he and all the employees knew of the predicted arrival of heavy rainfall from the weather forecast, but they had not foreseen the scale of damage it would cause. With the effects of global warming, natural disasters may well continue to increase in size, scale and frequency so that previous experiences of the impacts of natural disasters may not be a good guide to future ones. Therefore, mitigation measures to avoid or minimise possible damage and loss are of increasing importance.

3.3.2. Consider employees’ safety in returning to their homes, collect micro information and aggregate it

This case also highlighted attention to the safety of workers in returning to their homes. Some employers pay less attention to workers’ safety in their commuting than to their safety on the company premises. However, workers are an essential asset of a company and often form part of a community surrounding, say, a factory site. Since a natural disaster affects a large area which might well include both their factory and the workers’ homes, their commuting to and from their homes could well be impacted by a natural disaster. In fact, on October 13, 2019, a city government worker, who had set up a shelter for the community from a typhoon, was overcome by the flood on his way back home and drowned. He allegedly abandoned his car after the engine stalled due to the flood water and was then trying to walk home outside. While some staff may be required to remain to respond to damage caused to the factory, one of the options open to management when a severe natural disaster is forecast is to cease operations and isolate their facility, then give their workers days off. Or, if it is too late, let them stay in the premises to shelter from the harsh conditions outside. To ensure adequate safety for all employees, a sufficiently early decision to allow them to return home is important.

In the Etajima case, however, the severe local impact of the heavy precipitation was evident shortly after the release of the emergency warning by the meteorological observatory. The localised impacts of disasters might sometimes be at variance with the centralised official warnings, especially in terms of their timings. In such cases, a company might find it useful to collect local information provided by employees. Nowadays almost all employees have smartphones and can gather
information on their own by SNS and from other sources. Although false information may be circulated and the accuracy needs to be checked, information specific to a local area is helpful to clarify the situation. However, decisions relating to the operation of a factory and advice to employees must be made by the employers or those who have their authority. For good decision-making, a system of gathering information, verifying it and co-ordinating it should be established to make the most of specific local information gathered by and from individuals.

3.3.3. Provide current information about the situation to stakeholders

The factory management informed the relevant local government authority about the on-going situation so that the authority could post the information on their website reporting: the damage to the factory; the avoidance of an explosion; and details of the recovery plan. Compared to the Soja case in which all the employees abandoned the factory without informing the authorities or neighbouring residents of any danger, the Etajima factory communicated well with their stakeholders which contributed to building a good relationship with the authorities, customers, and the local people who read the information.

In any Natech case, an emergency response by the company without information about their facility and their activities makes the work of other emergency responders more difficult than in a conventional natural disaster. Since the company operating the facility handles chemicals and other technologies, they can provide information to stakeholders about their dangerous nature, possible damage to the local community, emergency actions if needed, and so on. Such information enables other emergency responders and residents to take early and appropriate action to deal with the situation.

In the chaos of a Natech disaster coupled with a natural disaster, it may be difficult to provide information to those who need it to respond to the disaster. Some normally preferred means of communication may not be available to residents in an area which may have already been affected by the disaster and so the most suitable communication media may vary depending on the situation. For example, in September 2019 a typhoon caused an electricity outage for several days which depleted the backup power of base stations for communications. It is important to consider various possible scenarios and prior to any disasters prepare more than one option to distribute information.

3.3.4. Plan resources required for recovery activities

During the recovery phase of a disaster, clearing damaged premises often requires heavy plant and machinery to remove debris, fallen trees, sediment or rocks. If the affected area is widespread, the machinery and equipment required for recovery tasks will be in high demand. The resources that may be required in the likely recovery activities should be carefully considered beforehand.

Compared to an industrial accident in a facility, a natural disaster often affects a widespread area, so many facilities and residents may require similar tools and machinery at the same time for remedial activities. In particular, in the affected area there may be limited availability of contractors who can operate the heavy equipment required to undertake the recovery activities and so the contractors may be spread thinly over many affected places. Since these resources may be restricted or unavailable, their possible limitations should be incorporated into the recovery plan.

4. The Lessons in Natech disaster management

The previous sections have described and discussed three cases in which manufacturing factories experienced problems and difficulties following heavy precipitation. From these experiences various lessons were drawn. This section aims to relate these lessons to the well-established natural disaster management phases and to recently proposed Natech risk management measures.

The well-established disaster management phases consist of four aspects which are shown in Fig. 2: mitigation, preparedness, response, and recovery [46]. As well as for natural disaster management these phases are also used for other types of emergency such as a terrorist attack. In the rest of this paper the term “preparedness” will be referred to as “preparation” as that gives a more active sense. In disaster management, preparation is defined as the activity of preparing to handle an emergency. Mitigation refers to steps taken to minimise the effects of a possible disaster. Response refers to the activities to be taken in reaction to an emergency and recovery refers to the actions taken to return an affected situation to a normal or an even safer situation after a disaster.

For Natech risk management, many researchers have explored key principles and essential features to facilitate better approaches to managing the risks. Since the characteristics of Natech risk include multiple occurrences across a wide area with limited resources to cope with the situation these pose many problems so suitable frameworks have been repeatedly discussed. In their recent paper Krausmann et al. drew attention to the problem that Natech risk often cuts across different domains and stakeholder communities that traditionally have not interacted much with each other. This led them to define important areas requiring measures as shown in Table 3 [47].

Table 4 lists lessons drawn from the cases presented in section 2 and shows the corresponding phases in disaster management and measures for Natech risk management proposed by Krausmann et al.

5. Extrapolation and exploration of the lessons – in the context of the COVID-19 pandemic

Just at this research was nearing completion, the COVID-19 outbreak shook the world. It continues to threaten our society and change our way of life. For most manufacturing factories, the beginning of this pandemic crisis was an external factor unless the disease spread in the facility. In that sense, the impacts of natural hazards and a pandemic have similarities in terms of external threats. The Emergency Events Database (EM-DAT, The International Disaster Database) [49] included “Biological” as a class of natural disaster as well as Geophysical, Meteorological, Hydrological, Climatological, and Extraterrestrial. They also share the similarity that business entities are faced with difficulties that stem from the uncertainty of the occurrence and the scale.

In this last section, we try to extrapolate from the lessons obtained

| Table 3 |
| --- |
| Important areas in Natech Risk Management (by Krausmann’s et al.). |
| Awareness |
| Risk governance |
| Legal infrastructure |
| Risk communication |
| Risk assessment |
| Guidelines |
| Data collection |
| Knowledge and skills |
| Cooperation and partnership |
Comparison among lessons in this study, phases in disaster management, and important areas in Natech Risk Management.

| Lessons | Phases in Disaster Management | Important areas in Natech Risk Management |
|---------|-------------------------------|------------------------------------------|
| (a) Undertake measures based on the hazardous conditions of materials and possible reactions | Preparation | Risk assessment |
| (b) Avoid normalcy bias for improved decision-making | Response | Awareness |
| (c) Identify slow developing and lagging Natech consequences | Prepared and intensify safeguards to avoid possible damage based on risk analysis | Awareness |
| (d) Prepare and intensify safeguards to avoid possible damage | Recovery | Risk assessment |
| (e) Consider employees’ safety in returning to their homes | Mitigation | Risk assessment |
| (f) Collect micro information and aggregate it | | |
| (g) Provide current information about the situation to stakeholders | | |
| (h) Plan resources required for recovery activities | | |

Lesson (a) Undertake measures based on the hazardous conditions of materials and possible reactions, is a lesson mainly relevant to chemical facilities handling potentially dangerous substances. Although the nature of their materials is basic information for manufacturers, the evidence from the cases presented suggests that the understanding of them may not be sufficient in some workplaces. The risk from their characteristics, reactivity, stability and so on should be reviewed and assessed in the context of possible natural disasters before they occur. Making appropriate arrangements, such as isolating the dangerous materials or moving them to a safer place, to avoid a Natech emerging when a natural disaster strikes is important preparation activities.

Lesson (b) Avoid normalcy bias for improved decision-making, falls into the “Response” category in disaster management and “Awareness” in Natech risk management. Many Natech disasters occur because the size of the impending natural disaster is underestimated or there is inappropriate anticipation of its arrival due to lack of awareness. It is not easy to make good decisions because only a few people have encountered a severe natural disaster before and had experience of making difficult decisions. Also, economic pressures can lead to wishful thinking. Well informed awareness of a natural disaster is essential and rich and reliable information on the situation is a good support for it.

Lesson (c) Identify slow developing and lagging Natech consequences, is required in risk assessment prior to a disaster. During preparation, the assessment should investigate possible consequences which may not be observable immediately after a natural disaster strikes. The results of such an assessment should be applied in the recovery process when the risk has actually occurred.

Lesson (d) Prepare and intensify to avoid possible damage based on risk analysis, is a typical example of mitigation. The Etauima case showed that carefully considered safeguards to overcome possible natural disasters contributed to the prevention of a Natech disaster. However, the Soja case highlighted the lack of sufficient safeguards when the dike let floodwater flow into the factory and caused a severe explosion.

Lesson (e) Consider employees’ safety in returning to their homes may be too specific. However, this aspect may have been neglected in some management frameworks focusing on disaster prevention, and the safety of neighbouring residents. In a factory, some employees must act as responders when there is an emergency because of their expert knowledge of the factory operation. As well as the appropriate utilisation of resources, their safety should be incorporated as a key element in the framework.

Lesson (f) Collect micro information and aggregate it, is categorised in both Preparation and Response because effective usage of information requires a well designed system which should be prepared prior to a disaster. Although reliable and official information is released by the responsible organisations such as government bodies and the national observatory via broadcasting media, nowadays instantaneous information is available on the internet. As a disaster approaches, employees sometimes communicate with each other via text messages or Social Networking Services often attaching photos to share information about the situation. Such communications should be utilised systematically particularly for decision making by the management of a factory in a disaster situation.

Lesson (g) Provide current information about the situation to stakeholders, is particularly important for industrial facilities because damage in their premises due to a natural disaster can trigger a Natech disaster. It is then necessary to provide risk information to stakeholders such as emergency responders and local people. Such information enables those people to understand the nature of the circumstances and take appropriate actions.

Lesson (h) Plan resources required for recovery activities, is thinking beyond a disaster. In previous research, awareness is sometimes seen to simply provoke fear and mental denial. But once good self-efficacy (one’s ability to perform the necessary behaviour) has been developed, people are able to face the risk [48]. Provision of suitable and necessary resources should contribute to self-efficacy. Since with current technologies it is difficult to avoid a natural disaster striking, planning for recovery is a realistic process to mitigate the consequences, particularly economic ones. Such a plan prepared prior to a disaster can lead to a more rapid resumption of normal activities. Since the recovery of a factory from a disaster may involve financial, engineering and other approaches, the support of other organisations or personnel, communication and collaboration with other stakeholders will be important in the process. Work load management and workers’ safety is also important, particularly for those workers who focus on early recovery or work hard in harsh condition or on unfamiliar tasks.

through our three case studies to challenges of Natech under a pandemic. This enables us to explore the wider generality and validity of the lessons in a way which was never envisaged at the outset of the research. With regard to a pandemic, Morens et al. discussed the definition of a pandemic when a new strain of the H1N1 influenza virus emerged in 2009 [50]. They considered diseases commonly said to be pandemic from several aspects: wide geographic extension, disease movement, high attack rates and explosiveness, minimal population immunity, novelty, infectiousness, contagiousness, severity. They noted that public health officials described infectious diseases as pandemic when they are contagious from person to person. Therefore, the term “pandemic”, in this section, will mean a contagious disease with high severity which drives people to keep a social distance. Explorations of the lessons in the context of Natech under a pandemic are now presented with consideration of whether any additional obstacles emerge or any expected difficulties are magnified.

Lesson (e) Consider employees’ safety in returning to their homes.

This lesson relates to the situation where employees’ safety is threatened by the onset of natural hazards, particularly when workers need to leave their facility. For ensuring workers’ safety when a natural disaster is coming, workers may travel as a team in case of contingencies. On the other hand, close contact must be avoided during a pandemic so although the onset is less sudden the problem with public or shared transport is more acute. Risk comparison is essential for decision-making because risks posed by natural hazards and ones posed by contagious disease vary depending on the circumstances such as location, the severity of the threat, and the extent of development of mitigation measures.

Lesson (f) Collect micro information and aggregate it.

For risk comparison, understanding the surroundings is important. Micro information around the area is helpful for a high resolution understanding of the situation. However, it may be difficult to obtain micro information about the spread of a disease at any time because micro information, in this case, involves personal information. The availability
of micro information will be variable because each cultural group or country has different attitudes to personal information. However, if it is available, local information relating to the natural hazard can be posted and browsed on the internet helping the public to know how to respond. The lack of such local information has hampered the efforts of some local authorities recently.

Lesson (c) Identify slow developing and lagging Natech consequences.

This lesson focuses on the risk of chemicals and technologies left unattended during a crisis. The recent disaster at LG Polymers in India increases the importance of this lesson because this company was preparing to restart a facility after the coronavirus lockdown and then toxic gas leaked killing 11 people and forcing hundreds of people to hospitals [51]. Although the disaster investigation found many technical and management defects in the plant, the stagnant storage period due to the business closure by the COVID-19 pandemic certainly contributed to the disaster.

A lockdown due to a pandemic can halt the operations of a facility for an initially unknown period of time as can a natural disaster. Moreover, the combination of natural hazard impact and the pandemic influence can extend the period further. Facilities should take into consideration lagging consequences created by a pandemic lockdown, and prepare for it, for example by increasing the storage of essential and unstable substances.

Lesson (b) Avoid normalcy bias for improved decision-making.

Lesson (g) Provide current information about the situation to stakeholders.

Both lessons are related to uncertainty. Lesson (b) warns against wishful thinking about the situation and encourages preparation for a worst-case scenario. Normalcy bias means some people or governments are overly optimistic and think that normal conditions will continue or soon return without much of a problem. However, by the time it becomes clear that a bad situation is developing, the bias may have delayed or prevented people from taking proper countermeasures. The worry that the countermeasures will not be effective is the main hindrance to taking countermeasures because the occurrence and size of the problem are uncertain. The Natech coupled with a pandemic would increase complexity. Then the situation would become difficult to forecast and optimism is dangerous. Lesson (g) aims to resolve the concern about the uncertainty perceived by stakeholders and/or provide input to enable stakeholders to make decisions properly concerning the facility. While a pandemic magnifies the chaos of a Natech disaster, communications with stakeholders per se would not change their importance and so a facility operator should continue to be concerned for communication.

Lesson (a) Undertake measures based on the hazardous conditions of materials and possible reactions.

Lesson (d) Prepare and intensify safeguards to avoid possible damage based on risk analysis.

Lesson (a) focuses on the behaviour of materials. It raises awareness of the possibility of catastrophic behaviour of materials in an unstabilised condition and the importance of understanding the lead time to stabilise them in a looming natural hazard. Lesson (d), encourages establishing safeguards to mitigate the physical damage which can trigger an industrial calamity. In that the threats illustrated in lesson (a) and (d) are physical and can only destroy objects, threats of a pandemic would not add severity. But we should keep in mind that undertaking measures in these situations may require human effort which can be disrupted by a pandemic.

6. Conclusion

Three cases of manufacturing factories experiencing natural disasters were described and lessons were drawn. In the first case at Soja in Okayama, the key decision to start cooling down the molten aluminium was taken too late and an explosion occurred. The second case in Osaka was less affected by the heavy rain, but part processed materials left idle in a tank slowly generated toxic gas with lethal effects and caused disruption in the surrounding area. The third factory in Etajima in Hiroshima managed to avoid any catastrophic results by a thorough system of safeguards.

The cases in this article indicate the sort of events that can be triggered by natural disasters and the lessons learnt are applied to the conventional disaster management framework and some measures in Natech risk management. The lessons are helpful examples, particularly for the private sector, which is often involved in Natech disasters and upstream of the chain of events in Natech disasters. Preventing escalation of disaster upstream is the first step of Natech disaster loss prevention. However, these cases do not include some characteristic features of Natech such as the simultaneous occurrence of damage to several facilities. That feature of Natech disaster management can be considered when further cases are gathered and analysed.

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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