A review on Toulouse accident trials: can we learn the lessons despite uncertainty on direct causes?

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The 31st October 2017, the French Court of appeals condemned the former director of the AZF plant to suspended prison sentence of 15 months and 10 000 euros of penalty and sentenced the Grande Paroisse company to pay 225 000 euros, the maximum penalty. The lawyers of Total Group subsidiary claimed that it would require another appeal to the Cassation court.

On 21st September 2001, a powerful explosion killed more than 30 people, injured around 10 000 inhabitants and workers in the vicinity of the AZF fertilizer plant in Toulouse, France. The blast also destroyed 27 000 houses and flats causing approximately 1,5 to 2,5 billion euros damage. The explosion most probably took place in a warehouse at the AZF fertilizer plant where around 400 tons off-specification ammonium nitrate were temporarily stored to be recycled in another NPK fertilizer plant.

More than 16 years after the Toulouse disaster, for the matter of responsibility within the criminal litigation, direct causes are still challenged by the lawyers of Total and other experts and more generally have been a matter of debate in the 3 trials, and through numerous articles in the newspapers. The main assumption of the police and prosecutor is that the plant management failed in its safety management of the waste of ammonium nitrate fertilizer and technical grade manufacturing. It is assumed that likely some chlorinated compounds waste were by accident mixed with some waste of ammonium nitrate based materials. This error would have been committed by subcontractors in charge of waste management who lacked of risk knowledge.

As this scenario remains challenged despite the latest trial outcome, it could raise doubts on the relevance of the learning lessons process that lead to several changes in France and Europe. A key issue we want to discuss in this paper is how can we learn the lessons despite the direct causes' controversy? Therefore, we will recall some of the disaster damages, the main scenario assumed by the justice, the summary of trials and the related controversy on direct causes, the troubled history of ammonium nitrate manufacturing and characteristics of ammonium nitrate through accidents, the root causes of the disaster and an update on the changes in France and Europe in the aftermath of Toulouse disaster.

Keywords: Toulouse, accident, disaster, ammonium nitrate, fertilizer, explosion.

Introduction

With the purpose of better characterising the potential direct and root causes of accidents and derive key lessons to learn for accident prevention, the following elements are crucial in an accident investigation:

- knowledge about the potential chain of events, understanding what potentially happened,
- the underlying conditions and influence factors that set-up the accident, understanding how it happened,
- establishing the root causes, understanding why it happened (this way) and also an important question why it was not prevented.

These aspects are key aims in an event investigation for safety purposes but also for criminal investigation, though the fundamental purpose differs which in addition leads to an emphasis on the legal and moral responsibilities (CCPS, 2003, ESReDA, 2005, 2009, 2015, Dechy et al, 2012, Dien et al, 2012).

In the aftermath of the Toulouse disaster, five authorities carried out five separate inquiries with different perspectives:

1. The Inspection Générale de l'Environnement (IGE), in charge of oversight of the regulator, was ordered by the French Ministry of Environment, Yves Cochet to conduct an administrative inquiry into direct causes and some of the root causes, especially in the regulation and its enforcement; some technical investigations were led by INERIS and IPE, which is the Army branch in charge of explosives; the public report was issued a month after; ;
2. The Labour Inspection (Labour Ministry) made an investigation on the compliance to workplace and Labour regulation; the report was issued in march 2002;
3. The TotalFinaElf Group made also an investigation on the direct causes; the report was issued in march 2002;
4. The Police and Justice gave a preliminary press report on June 2002, and issued their final expert report in 2006 for the first trial in 2009;
5. The CHSCT (health, safety and working conditions committee) of the employees of the site subcontracted an investigation to Cidecos-conseil, a consulting company that issued a report in June 2002 to clarify working conditions, and organisation of the work.

Besides, two parallel actions were launched by the authorities to identify other generic lessons to learn for better regulation and oversight:

- A Parliament Commission (coordinated by deputies Loos and Le Déaut) that led a large number of visits and interviews at a national level issued a public report in February 2002, to address generic deficiencies in the risk management and governance, and their regulation;
- The Environment Ministry organised also a national debate on industrial and process safety after Toulouse accident in several cities with hazardous plants in the neighbourhood; the debates were led by Philippe Essig that issued a public report in February 2002, to collect complementary insights, especially on risk culture and acceptability.

These investigations revealed several findings and provided recommendations. Some of the changes were even integrated in both the French law on industrial risk prevention (Loi Bachelot 2003-699) and the European legislation, firstly with a change of classification criteria for ammonium nitrate fertiliser and off-specification materials in 2003, and later to some extent in Seveso III in 2013.

However, in 2017, more than 16 years after the Toulouse disaster, for the matter of allocating responsibility within the criminal litigation, direct causes are still challenged by the Total group lawyers and other experts. These urging issues became the major points in the debates during the three trials, which were depicted in articles in different newspapers. The main assumptions of the police and prosecutor are that the plant management failed in its safety management of the waste of ammonium nitrate fertilizer and technical grade manufacturing. It is assumed that waste containing chlorinated compounds was mixed by chance with waste of ammonium nitrate based materials. This error would have been committed by subcontractors in charge of waste management who lacked of knowledge of hazards associated with waste of ammonium nitrate based materials, downgraded or off-specification ammonium nitrate fertilizers.

As this scenario remains challenged despite the latest trial outcome, it could raise doubts on the relevance of the learning lessons process that led to changes in the legislation in France and Europe. A key issue this paper is aimed to depict is how the accident' lessons can or could have been learned despite the controversy among the direct causes?

Before the final discussion on this key question, the authors will recall the main damages caused by the disaster and the potential accident scenario assumed by the justice together with the summary of trials as a tool to address the controversy between the direct causes. The paper also reminds the troubled history of ammonium nitrate manufacturing and characteristics of ammonium nitrate via accidents. Finally, the study presents the root causes of the disaster and an update on the changes in the French and European legislation in the aftermath of Toulouse disaster.

The disaster damage

On 21st September 2001, a massive explosion occurred on a chemical plant called "AZF" where a 7 m deep crater (65x45m) was observed and a large cloud of dust and red smoke drifted to the north-west over Toulouse suburbs. The detonation, felt several kilometres away, corresponded to a magnitude of 3,4 on the Richter scale.

The explosion lead to a disaster as it officially killed 30 people according to the estimate of the Prefecture (the local state representative level) performed six months after the event. Some later controversies were brought by the newspapers with higher toll depending on how is attributed by the legists the lethal causality to the accident, if it occurred for instance within 24 hours or within a few days, or weeks or months after the event.

After the disaster, a health survey and monitoring system was established by the Institut national de veille sanitaire (InVS), the French institute in charge to collect and analyse the health effects and environmental impact of the accident (Lang et al, 2007). Indeed, the first estimate made six months after the event of 2242 injured by the Prefecture was given a different perspective three years after when InVS (Comité de suivi AZF, 2004) estimated (partly by records, parly by statistical extrapolation), that the blast may have approximately injured around 10 000 inhabitants and workers in the vicinity of the AZF fertilizer plant in the city of Toulouse in the south west of France. Also 14 000 people may have suffered of post-traumatic acute stress syndrome. The environmental impact has been estimated as moderate or low.

No domino effects occurred on storages and pipes of chlorine, ammonia, phosgene on the chemical plants of the industrial sector.

The blast also destroyed around 27 000 houses and flats causing approximately 1,5 to 2,5 billion euros damage. Concerning the local economy, 1 300 companies were damaged and 172 were severely damaged. Six months after, 29 companies employing 2 979 people would have been economically in danger. It damaged 17 schools, 26 high-schools and several universities. The public transportation company of Toulouse had 100 buses damaged on the parking between 300 to 500 m from the epicentre. Among 350 employees on site at the time of the accident, 322 were injured (Dechy and Mouilleau, 2004). 75 000 damages claims were notified to insurers which then ask for compensation to TotalFinaElf Group that has to insure itself. The group accepted to compensate all damages and indicated that it paid 2,5 billions euros.

During more than 6 months, the 6 companies of the chemical zone were stopped (1 100 direct employees and a total of 2 500 workers on sites) reviewing their safety studies in order to get another authorisation to operate from the local administration. However, in 2002, the TotalFinaElf group decided to close the AZF plant and the Prime Minister decided to close the two other highly hazardous plants under Seveso regulation (Tolochimie and SNPE).

The strength of the detonation was estimated by the Institut national de l'environnement industriel et des risques (INERIS) to 20 to 40 tons of TNT equivalent (Mouilleau and Dechy, 2002) and several other estimates were made by the Justice, Total, Technip and TNO (Dechy and Mouilleau, 2004). The explosion most probably took place in the warehouse No. 221 at the AZF fertilizer plant where an estimate of around 400 tons off-specification ammonium nitrate were temporarily stored to be recycled in another NPK fertilizer plant.

The accident scenario – what (potentially) happened?

At 10.17 a.m. on 21 September 2001 a severe explosion occurred in a temporary storage of downgraded ammonium nitrate (AN) fertilizer at the AZF industrial site in Toulouse, France. The plant had two main activities: the fabrication of nitrogen fertilizer and industrial nitrates, and the synthesis of chlorine-containing compounds. The factory synthesised ammonia that it transformed into ammonium nitrate, a part of which was then used to manufacture fertilizer, the rest being marketed directly in the form of industrial nitrates (used as explosives). The factory consisted of large dangerous material storage facilities, two cryogenic ammonia tanks (5,000 and 1,000 tons, 315-ton pressurised ammonia storage tanks, two 56-ton liquid chlorine tankers, 1,500 tons of oxidants, 15,000 tons of solid ammonium nitrate in bulk form, 15,000 tons in sacks and 1,200 tons of ammonium nitrate in hot liquor solution, as well as 2,500 tons of methanol (IMPEL, 2002)). The plant was therefore under French laws regulation for decades and Seveso regulations.

At the time of the accident, warehouse No. 221 stored around 400 tons of downgraded ammonium nitrate fertilizer (initial estimate of 300 to 400 tons was later narrowed to 390-450 range by the investigations of INERIS (Ayrault, Gaston, 2001)). From the various workshops, this material had been carried with buckets to an inlet area by three subcontractors and then taken by transport equipment into the warehouse. The stored material was periodically removed and transferred to be recycled to produce complex fertilizers.

On 20 September, 15 to 20 tons of AN with an additive in qualification phase was brought into the warehouse. On the morning of the explosion, products derived from the packaging and the production workshops were also transferred into the building. The last amount of material from another storage zone was transferred less than 30 minutes before the explosion.

Although this chronology scope could satisfy the prosecutor and process safety experts for deeper investigation into the direct causes of this scenario, several other "out of the scope" events occurred. These events triggered other assumptions and alternate scenarios were published in newspapers that contributed to increase the controversy.

Among them, some witness mentioned that they heard two distinguished explosions which was later proved by some acoustic scientist; this result could challenge the triggering factor of the AN waste storage explosion; some experts have investigated the possibility that a gas leak on one of the plant was the first explosion triggering the second one of large scale. Some witness mentioned electrical disturbances before the explosion; it oriented some external experts to the assumption of an underground electrical arc connected to an Electricité de France transformer. Another assumption considered the fact that the underground soil was contaminated by former chemical and military activities such as nitrocellulosis. Several victims and analysts claimed that those alternate scenarios should have required more attention and investigation to provide evidence, analysis and help to define the truth during the trials.

The trials and the controversy between the direct causes

First of all, it is important to recall some elements of the context. The disaster occurred ten days after the 9/11th terrorists' attacks. The just nominated prosecutor in charge, Michel Bréard declared the 24th of September to the Medias that "*it is likely an accident at 99% of probability*". This early statement generated many doubts on the justice litigation objectivity as 65% of the inhabitants of Toulouse thought in august 2002 that it was an attack.

Secondly, a key aspect is the choice of the French legal system framework in which the victims (2700 claimed to be and asked for litigation) require the inquiry and judgment to be performed. Indeed, several groups of victims and their lawyers choose to ask for criminal law litigation in order to be able to potentially condemn the key responsible persons in charge and the company (Grande Paroisse a subsidiary of TotaFinaElf group) as the moral actor. However to obtain the condemnation and sentence to jail for manslaughter, it is needed for the prosecution and victims to demonstrate the proof at 100% of certainty. This burden of proof is a challenge and the defence goal is to challenge the 100% certainty thesis by raising doubts on some causality evidence and on the exhaustiveness of the investigations with regards to other assumptions and scenarios. If the victims had chosen to seek for financial compensation into the civil law litigation, the most probable scenario would be enough.

Table n°1: the judicial steps

dates	Judicial steps
2001/09/21	The explosion at AZF plant in Toulouse leads to a disaster.
2002/06/14	11 employees (among them the director of the plant) and 2 subcontractors receive preliminary examination (indictment).
2006/05/11	Final report by the experts for the judicial inquiry that stand on the scenario of chemical accident due to an incompatible reaction between wastes of chlorinated compounds and waste of off-specification ammonium nitrate based fertiliser and technical grade. Some chemical tests have shown that a mixture between AN and DCCNa (SDIC, sodium dichloroisocyanurate) or AN and ATCC (trichloroisocyanurate acid) is strongly incompatible. In presence of small moisture content, the reaction is violent and starts as soon as the products come into contact, even at temperature close to ambient temperature. This reaction, in addition of the decomposition catalysis from chlorine ion, involves the production of a very unstable substance, trichloramine NCl_3, which is very sensitive and is able to explode. Other scenarios have been investigated, such as terrorist attack or malicious act, but excluded; 16 causes were investigated by the prosecutor but 12 were discussed during the trial, some others were not considered (though they were mentioned in newspapers).

2009/02/22	Beginning of first trial at the criminal court (*tribunal correctionnel*) of Toulouse for four months in a room that hosted 1200 people with 60 lawyers and 60 journalists. The case is made of 120 chapters and the trial was filmed. Several victims have testified. Several chemical experts have testified either about stability or instability of AN. Other experts in explosions, acoustic specialists for the two explosions discrimination, and electricians for the underground electrical arc have testified.
2009/11/19	Decision of the criminal court is a general acquittal for all parties in indictment due to benefits of remaining doubts on the evidence. The prosecutor and victims request an appeal with judgment by the court of appeal.
2011/11/03	Beginning of the second trial at the court of appeal (*cour d'appel*) of Toulouse. It was organised similarly, lasted also four months. The prosecutor indicated again a failure of management of the waste of AN and chlorine off-specification and a link between this failure, the fault and the damages.
2012/09/24	With similar findings, the sentence is however different as they considered other origins of the explosion that had been excluded previously. The experiments showed some explosion initiation delays were compatible with the chronology. The decision of the appeal court is summarised in a report of 682 pages. It condemns the former plant director to 3 years of suspended prison sentence and 45 000 euros of penalty and the *Grande Paroisse* company to 225 000 euros the maximum penalty. The company and the director request an appeal with judgment made by cassation court. The director was condemned for lack of adequate training of subcontractors on hazards, lack of coordination and oversight and the Grande Paroisse subsidiary for lack of cross-control of decisions made by the plant director. He was considered responsible as he did have enough margins of manoeuvre according to the Total Group and the prosecutor.
2015/01/13	The cassation court broke the appeal court sentence for procedural reasons due to lack of partiality of one judge that had helped victims association (she requested not to be part of the judges when she was ordered but failed to be replaced) and lack of evidence.
2017/01/24	Beginning of the third trial at the court of appeal (cour d'appel) this time in Paris which make the victims in Toulouse mostly unhappy. The trial lasted four months again but some other experts could also testified. The prosecutor finally abandoned the chemical assumption that could not be proved a 100% but chose finally to defend the law strategy considering that all conditions were there for an accident waiting to happen with failures in professional good practices, careful approaches and lack of compliance with the law. In the end, the three options for the court were either to condemn, to acquit or to seek further information (investigations) on other scenarios.
2017/10/30	Judgment of the Court of appeals condemned the former director of the AZF plant to suspended prison sentence of 15 months and 10 000 euros of penalty and sentenced the Grande Paroisse company to pay 225 000 euros, the maximum penalty. However, the Total group is acquitted. The lawyers of the Total Group subsidiary still claimed that it would require an appeal to the Cassation court, so did a few victims group as they requested more investigations. Indeed, the condemnation is obtained with a different law article and principle by indirect or default causality and renounced to sentence for a 100% certainty on the causality between management faults and homicides.
…	4th trial expected.

Among the critics that were made by some contributors and observers (e.g. the web blog of Daniel Dissy), is to recall, that the judges should tell the law, not the chemistry; and the judicial truth is not the scientific truth. In addition, Hubert Seillan, lawyer and former director of the Préventique magazine (one of the magazine that published some articles on alternate scenarios) recalled in 2017 that the inquiry to prove one theory with 100% certainty within criminal law often dominates the contradictory inquiry on several alternative scenarios. Another critics is the use of the indirect reasoning of cause by default of others, that is threatened by lack of evidence on causality on the assumed scenario and on the exhaustiveness of alternate scenarios identification for which plausibility should be assessed too (Montaron, 2013). In addition, Total lawyers but also other experts have criticized the realism of the tests made by the experts from the justice to show the chemical reaction that lead to the explosion after mixing off-specification AN and chlorinated compounds. Several victims considered that lawyer's role was to discuss evidence, raise doubts and bring other "crazy assumptions" (Le Monde journal, 2017, 31st October).

As a temporary conclusion established more than 16 years after the accident, no consensus on evidence and no scientific truth emerged from the trials and the controversy on direct causes remains open.

The troubled history of AN manufacturing and characteristics of AN via accidents

To better understand the failures of some elements of the risk analysis, safety management system, oversight and regulation and some difficulties of the prosecution during the investigation and to establish proof, it is important to recall first about the history of the most severe accidents that involved ammonium nitrate fertilizer. Notably, these past events were known, well-documented and available at the time of the AZF disaster. Yet, such devastating events still occur even after the Toulouse disaster. How can it remain possible?

Ammonium nitrate (AN) has an extensive history of industrial accidents that occurred in the last century. The first high visibility, historical event happened in 1921 in Oppau, Germany. On September the 21st 1921, two explosions occurred in a silo in the BASF plant, creating a 20 m deep, 90x125m large crater. At the time of the event 4500 tons of ammonium sulphate nitrate (ASN), ammonium nitrate and ammonium sulphate mix fertilizer were stored in the warehouse. The blast killed 507 people and injured 1917. The plant and approximately 700 houses nearby were destroyed (ARIA database, n.d.).

Findings showed that the company introduced a new spray process that could have been one of the reasons of the explosion. It was known before the accident that the explosivity of the ASN depended on the AN/AS ratio. However, it was not known that other parameters, such as the density and crystalline structure could also influence the explosive properties of the ASN fertilizer. Also, AN is hygroscopic and the storage in large quantity caused the ASN mixture clogged together under the pressure of its own weight. This solidified mass was extremely difficult to handle or transfer. Therefore, it was common practice to use cartridges to blast the clogged fertilizer, loosening it. However, the new process modified some physical parameters of the ASN such as the density, the crystalline structure and water content. Consequently, the ASN, dried with the new process had segments with higher AN content. This inhomogeneous mass was stored together with the ASN that was dried applying the old process. The higher content of AN with lower density and water content (reduction from 4% to 2% with the new technique) and changed crystalline structure the accumulated fine fraction was explosive. The anti-caking procedure was repeated 20 000 times with no large explosion before that day.

A highly devastating accident involving fertilizers occurred in 1947. In Texas City (Texas, USA) a ship carrying 2600 tons of ammonium nitrate exploded and set fire to a nearby vessel hold 960 tons of ammonium nitrate. 581 people were killed in the disaster (Stephens, Hugh W., 1997). The blast occurred when a small fire, perhaps caused by a cigarette, broke out on the ship Grandcamp. There were two additional factors that worsened the situation of the first explosion. First of all, the overlook of the threat of the fertilizer on the adjacent ship for almost twelve hours. Apparently, no officials responsible for transporting fertilizer from the dock were in place. They did not learn or considered additional potential risks from the first explosion, thus no further safety measures were taken to prevent the second explosion. The second factor that contributed to the high number of fatality was the fact, that a large number of people was allowed to stay in the close vicinity of the fire and became vulnerable to the subsequent explosion. In addition, another serious ship accident occurred in the French port Brest in 1947 (28th of July), after a large fire an explosion occurred killing 25 people. In both case, the AN was contaminated with organic materials during the fire which occurred in confined storages which induced the mass explosion (Fire Underwriters, n.d.).

Finally, the most recent event which claimed 13 lives occurred in West, Texas in 2013. On the evening of April the 17th of 2013, a fire of undetermined origin broke out at the West Fertilizer Company in West, Texas USA. After their arrival, firefighters started to fight the fire, when a detonation occurred. Although the firefighters were aware of the hazard from the tanks of anhydrous ammonia, they were not informed of the explosion hazard from the approximately 30 tons of fertilizer grade ammonium nitrate with a 34 percent total nitrogen content was stored in bulk granular form in a 7 m high bin inside the warehouse (White, 2014). As a consequence of the explosion, the shock wave crushed buildings, flattened walls, and shattered windows. Twelve firefighters and emergency responders were killed along with at least two members of the public who were volunteers and helped to fight the fire. At least 200 people were injured and more than 150 buildings were damaged or destroyed in the accident (CSB, 2016).

Detailed descriptions and lessons learned from these accidents can be found from many sources however it questions at large the knowledge management of accident lessons, of AN chemical properties and ways to make memory alive (Gyenes and Dechy, 2016, Paltrinieri et al, 2012, Ferjencik and Dechy, 2016).

Some root causes of the disaster

The explosion of off-specification AN was not prevented and turned into disaster due to several failures in risk assessment, management, governance, control and regulation (e.g. with failures at several levels of the sociotechnical system in Dechy et al, 2004).

Among them, one of the striking lesson is that the accident scenario was not included in safety case report of a Seveso plant. This failure of risk analysis occurred also at Buncefield, thus questioning abilities of classic risk analysis process and methods to identify relevant risks and “atypical” scenarios (Paltrinieri et al, 2012).

In fact, ambiguities of the behavior of ammonium nitrate, of past experiences of accidents in the last century, deficiencies in knowledge management, and fertilizer industry lobby allowed to consider that the “worst case scenario” for AN storage were fires with toxic fumes, because more likely, rather than massive explosion. In addition, the “envelope approach” of safety case studies lead to consider that there were other scenarios on the plant and in the neighbouring plants which were more severe (toxic cloud release) than an AN explosion.

Once approved in 1989, the land use planning (LUP) enabled local authorities to freeze the urban development, but it was too late as buildings and houses were close by, had no retroactive force to expropriate people. In addition, the safety perimeters were under-estimated because scenarios were rather incidents than worst cases. It occurred as an outcome of negotiation between the regulator and operator after Seveso I regulation, to find a way to value the financial investment of plants in prevention measures and value them in terms of safety gain.

Some root causes will remain unknown. Indeed, human and organizational factors investigations and organizational analysis were not the standard at that time (see developments after Columbia space shuttle loss in 2003 and Texas City refinery explosion in ESReDA, 2009, and Dien et al, 2012). However, some weaknesses are assumed in the integration of workers, subcontractors, stakeholders in the risk assessment, management and governance as well as in subcontractor management especially in competencies in safety and chemical properties of AN.

Some changes in the aftermath of the disaster

Since then, the new French law n°2003-699 of July 30^{th,} 2003 on technological risk prevention has contributed to include the first lessons from AZF accident such as (Dechy and al, 2004, Merad and Dechy, 2010):

- A need for a better governance of land-use planning around the existing and future plants. State, mayors and operators will be in charge to cooperate, prepare, negotiate and define land-use planning restrictions based on Technological Risk Prevention Plans (PPRT). Land use planning restrictions rely on the safety perimeters established on effects distances of several scenarios that are extracted from the safety case report. At the end of 2016, the ministry in charge mentions 394 PPRT defined with 90% approved, on 825 cities urban area, that lead to exclude inhabitants or buy 1000 houses.

- A need for a fair compensation of protection measures to enhance robustness to known scenarios. Constructive measures issued from the PPRT to reduce the vulnerability of the stakes (e.g. blast proof windows) are declared by citizen living within the PPRT perimeter to benefit from a tax deduction. The cost would be shared by the 4 stakeholders: the inhabitants, the town, the company and state. 20 to 30000 houses or flats have been requested to protect their homes in France.

- A need to improve insurance mechanism to foster the recovery of the territories around the Seveso II plants. An insurance mechanism is activated to help citizen by reducing the time of compensation after a major technological accident as performed for natural disaster.

- A need to improve risk governance around Seveso II plants. Local committee for information and dialogue (CLIC) are implemented to contribute to facilitate the dialogue and information sharing between citizen, operators, local State representative, employee and labor representative and mayors, to participate to the PPRT and to discuss and share information on incidents, accidents and emergency plans.

- A need to extend the emergency plan to the worst scenario potential impact zone.

- A need for a more balanced risk mitigation strategies. Risk assessment has moved from a semi deterministic approach (with reference scenarios as reasonable worst cases including some probabilistic considerations) to a semi probabilistic approach (where some ranges of likelihood are estimated rather than a number). 2000 new safety case report were produced under the new regulation. 200 to 300 millions of euros were invested by industrials (1000 to 1250 Seveso plants in France according years with around half were high tier and regulated by the new French law) to reduce risk at source.

- A need for more regulation enforcement with the raise of inspectors' staff from 700 in 2001 to 1400 in mid-2000s.

Discussion: can we learn the lessons despite direct causes' uncertainty?

First of all, from a rigorous scientific point of view, it looks not really satisfying to learn some lessons while uncertainties remain on the causal chain especially on the direct causes. Indeed, the causal chain lacks its foundations. In other words, this could lead to build a house of cards. Indeed, to us, it could lead to two risks: (1) to act on some influence factors and levers in safety management and governance that are not relevant for the purpose and (2) to inaction on issues more relevant for accident prevention.

However, let's take a closer look to both risks. For the alternate scenarios rose by various experts with more or less evidence (terrorist attacks, underground electrical arc…), that were not investigated or rejected by the justice litigation, it is true that no specific learning loops aimed at correcting these direct causes. So no measures for their risk prevention were implemented. This is probably the main safety issue raised by the trials that receive little or no action to date or that are publicly known. One should notice that it happens for some accident investigation, that it becomes impossible to exclude some scenarios during the assessment of the plausibility of some initiators and fragments of causal chains. In such situation, there remains a few alternate scenarios that remain plausible. The perspective of risk analysis should lead analysts to consider all remaining plausible scenarios with the need to take proportionate measures according to their estimated criticality (probability, severity and vulnerability of the stakes).

For the chemical incompatibility scenario, this disaster potentially recalled the risk of manufacturing such materials on the same plant. The risk perception, knowledge and safety awareness of workers in those high risk industries is a requisite and the reliance on the compliance to procedures is not enough. This remark echoes to one lesson learned from the nuclear accident of Tokaï-Mura in 1999 in Japan (Furuta et al, 2000). In a period of reduced budgets, the company management chose a strategy to rely on the compliance to procedures, as a way to suppress some training on the complex phenomena of criticality. Thus not ensuring proper training for high risk activities is an accident waiting to happen and trapping safety into rules is not enough (Bourrier and Bieder, 2013). So in a risk prevention perspective, despite the lack of certainty for the occurrence of this scenario at Toulouse, it is relevant to learn this lesson and seek to avoid chemical incompatibilities and to implement proper training for workers in-house or in subcontracting companies.

For other root causes of the AZF accident, the lack of certainty on the direct causes and chemical scenario assumed by the justice litigation is not jeopardizing the lessons learning that lead to changes in France and Europe. First, the off-specification ammonium nitrate risks were found to be underestimated, poorly managed and not regulated. If the chemical scenario was finally judged irrelevant, another accident or event could sooner or later reveal those fundamental vulnerabilities. The complex behaviour of off-specification AN polluted by several compounds and degraded in real conditions did not receive enough attention in safety studies, daily risk management and research.

Similarly, for instance, the land-use planning vulnerabilities that are the result of the historical competition between plant territories and urban areas during the 20th century have been illustrated by Toulouse accident but are not specific to it. They are widespread and were known before the accident. Enschede accident in 2000 in the Netherlands already provided such lessons (Ham et al, 2006). Changes to reduce vulnerability of urban areas of cities can only been managed on the long term on several decades. Therefore, such root causes should be considered as vulnerabilities of risk management and governance and the Toulouse accident only provided a picture of it, or in other words, was a form of audit to these vulnerabilities. The Toulouse accident generated a shock and provided the "window of opportunity" (Kingdon, 1984) to trigger some organisational and regulation changes against political and economic constraints. Indeed, that is why we consider accidents as being catalysts for changes.

More generally, rigorous science can hardly match complex and constrained business reality. Knowledge generation is continuous and non-linear, and can be considered as always incomplete when it is time to interpret, decide and act in real time operations. In the real complex world, the time and resources needed to produce rigorous and verified knowledge are hardly coherent with human, business and regulation time. Learning is dynamic (ESReDA, 2015) and should be performed with a critical perspective towards the knowledge it deals with. Similarly, a learning update should be triggered when later information and knowledge become available. The practical implication for instance is that after a first wave of changes are implemented to make Seveso plants and their neighbours safer with first findings and lessons of Toulouse disaster, a long term learning loop should reconsider the latest lessons to be implemented, and organise updates in a critical perspective.

Conclusions

More than 17 years after Toulouse disaster, its third trial (second in appeal) in 2017 led to sentence the former director of the plant and the Grande Paroisse Company, a subsidiary of Total Group. However the result is mixed with the lack of confidence on evidence for the chemical scenario supported by the prosecutor and for any other scenarios. Moreover, the main assumption of the justice litigation is under jeopardy as it failed to provide 100% certainty needed to condemn for manslaughter under criminal law. The lawyers of Total raised doubts on it and other experts challenged causality and lack of investigation in other scenarios (terrorist, other complex chemical and underground electrical arc). Thus, the story is not over still as it seems that the lawyers from Total group mentioned they would seek a new trial in appeal, as well as some groups of victims which called for more investigations and expertise to provide evidence and truth about direct causes of the accident.

Thus, the controversy of direct causes remains active. After three trials, the judicial truth is still challenged and is not supported by a "scientific truth" and the expertise conducted for the judicial inquiry failed to provide it, for the time being, and are also challenged. In this context, AZF disaster is another example that illustrates how judicial time differs from the regulation, business and professional times. While it is clear, it is not worth waiting for "the truth" to take actions, the doubts on direct causes and potential alternate scenarios should question us on the relevance of the learning processes from the disaster.

The conclusion by the authors is that to the exception of some alternate scenarios where no real preventive measures were taken to reduce the likelihood of similar risks (underground electrical arc,…), the relevance of taking actions on the main assumed direct causes and other root causes is validated. Indeed, many vulnerabilities found in land use planning, regulations, human and organisational factors, risk analysis and worst case scenarios definition were waiting for an accident to happen that would show bright light on them. Toulouse disaster played an "audit" role revealing the vulnerabilities as could have other accidents with different scenarios and direct causes. It played a role of catalyst for changes with some changes, that could have been initiated earlier, but that found with the accident a window of opportunity to be addressed and implemented.

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