Learning of the root factors of incidents potentially impacting the biofuel supply chains from some 100 significant cases

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Abstract

A biofuel is most often defined as a liquid or gaseous fuel used for transport purposes that can be produced from biomass substrates or bioresources. There are numerous potential supply chains for the production of biofuels, depending on feedstock, conventional or advanced processes, and final end use. All stakeholders involved in the promotion of more sustainable biofuels highly welcomed the area of industrialization of so called 2nd generation type of biofuels. However existing facilities producing 1st generation biofuels, i.e. bioethanol from sugar based or cereal plants and biodiesel from vegetable oils and fats, have sharply increased in number in recent years, allowing for a reasonable survey of safety issues from incidents.

Hazards have been identified throughout the entire supply chain from crop production until end use: these hazards are mostly linked to physical and chemical properties of products (feedstock, chemicals used at the conversion step, biofuels and their by-products...) as well as to some equipment. Incidents involve fire and explosion scenarios, equipment ruptures, steam release, derailment with leakage associated or not with fires and explosions, and environment contamination...

Significant accidents have occurred in recent past (Harper et al., 2008) (Marlair et al., 2008), triggering some interest on safety issues. INERIS initiated in 2006 a research work, BIOSAFUEL® (Marlair et al., 2006), more globally devoted to the analysis of safety-related issues with the main goal of appraising degree of risk control. Further survey of industrial and sanitary risks pertaining to biofuels are currently performed through contributions to two collaborative research initiatives. First, one is BIOMAP (Environmental and socio-technico-economic analysis and risks assessments of bioenergy pathways: Practical applications to several case studies) coordinated by IFP. The second, named ALFABIRD (Alternative Fuels and Biofuels for Aircraft Development) is piloted by the European Virtual Institute for Integrated Risk management. They are respectively funded by the French National Research Agency and the European Commission. A common tool for the performance of our contribution in those R&D projects is an incidents database, containing about 100 incident records which is the resource of this presentation.

In this paper, we propose to present the methodology employed to build this database and its contribution for the research programs aforementioned. The implementation of this incident database allows deriving appropriate information on safety issues pertaining to biofuel supply chains. In order to identify the root factors of incidents potentially impacting the biofuel supply chains, a statistical analysis (univariate and multivariate analysis) was applied on the database. This analysis is illustrated with several actual cases of accidents.

1. Introduction

Promoting the use of biofuels or liquid fuels produced from biomass is often considered as a key strategy to tackle climate change by decreasing greenhouse gas emissions in the sector of transport. The use of 'sustainable' biofuels also responds to other issues such as increasing energy security of supply, facing progressive rarefaction of petrol and relating increasing fossil fuel prices or contributing to new rural economy. Literature accounts numbers of papers concerning evaluation of environmental [Börjesson, 2009], energetic political, and economic impacts [Hill et al., 2006] of biofuels. By contrast, very limited scientific studies have so far addressed safety aspects of biofuel pathways (apart from material compatibility issues at end use stage) [Marlair et al., 2009]. Existing facilities producing first generation biofuels have sharply increased in number in recent years, reaching several hundred at least, and allowing for a reasonable survey of safety issues from incidents. INERIS (Institut National de l'Environnement Industriel et des Risques, France) initiated in 2006 a research work devoted to the overall analysis of safety-related issues of biofuels, including examination of past accidents. Learning on accidents required the preliminary implementation of an incidents database. The scope of this database was to collect all sorts of incidents (explosions, fires, spills, derailments, road accidents …) which occurred somewhere in the life cycle of biofuel production. This incidents database serves the goals of several research programs in which INERIS is involved. These programs are presented in section 2. Section 3 presents the incidents database and the methodology used to set it up. Section 4 of this contribution provides a statistical analysis of the root factors of incidents potentially impacting the biofuel supply chains, based on the use of the R software. Conclusions and perspectives of these works are given in section 5.

2. Research programs driving the examination of safety issues and relating contributions by INERIS

The implementation, updating and uses of a Biofuel incidents database are work packages serving 3 collaborative research programs in which INERIS is involved: BIOSAFUEL®, BIOMAP and ALFA-BIRD. The first one, BIOSAFUEL® [Marlair et al., 2006], initiated by INERIS in 2006 with funds coming from the Ministry of Ecology, is more globally devoted to the analysis of safety-related issues that may impact sustainability of the biofuel industry. The main goal was the identification of hazards and the appraisal of the degree of risk control of existing and shortly coming biofuels, from a life cycle perspective. The most outstanding deliverable of this project is a tool, named BIOSAFUEL®, allowing semi-quantitative evaluation and ranking of risks pertaining to 1st generation biofuel supply chains [Rivière et al., 2009]. The incidents database can be used to validate products hazards, identify typical accident scenario and rank risk significance. The second project, BIOMAP (Environmental and socio-technico-economic analysis and risks assessments of bioenergy pathways: Practical applications to several case studies) coordinated by IFP (Institut Français du Pétrole) and funded by the French National Research Agency, aims to further test and consolidate a multicriteria methodology implemented in the framework of a previous project ANABIO [Prieur, Bouvart, 2008], allowing for studying and comparing energy chains ex biomass, in terms of sustainability criteria. Indeed, the objective of the ANABIO project was to define a multi-criteria methodology to assess the various energy production chains from biomass, taking into account environmental, economic, societal, technological and safety criteria. The contribution of INERIS incidents database to BIOMAP deals more especially with the improvement of the methodology in terms of defining appropriate risk criteria and relating evaluation tools and in terms of ranking safety criteria.

The third project, ALFABIRD (Alternative Fuels and Biofuels for Aircraft Development) [Marlair, et al, 2007] is more prospective. Piloted by the European Virtual Institute for Integrated Risk management (Eu-Vri) and Airbus, it is an EU funded Research project addressing future needs to think about potential alternatives to kerosene, like XtL. The purpose of ALFABIRD is to study and compare a selection of alternative fuels (promoting among others biobased compounds) that could be used in blending with kerosene for aviation application (drop-in solutions). The implementation of the incidents database allows deriving appropriate information on safety issues pertaining to bio-based fuels supply chains.

3. Incidents database : procedure of implementation and lay-out

Incidents records considered for input in INERIS incidents database are those which unambiguously relate to the biofuel supply chains wherever they have occurred within the biofuel life cycle, from crop production to end-use. Thus, this database includes fire and explosion scenarios in stationary facilities, equipment failures (associated or not with missile effects), accidental steam release from ducts or containers, leakage in terrestrial transport (road and rail) associated or not with fires and explosions, following derailment, tank truck turnovers or crashes, and all sorts of environment contamination scenarios...
Information about incidents entered in the database were collected from regular survey of specialised literature, extracted from large accident database such as the BARPI one (Bureau d'Analyse des Risques et Pollutions Industrielles) in France. They were also identified from various web sites. Sometimes data were obtained from networking activities with colleagues working in agro-industries. Updating from regular survey of mentioned sources of information was an inherent part of the process of accident data collection.
The overall procedure of data collection thus encompasses:
a) Identification of new occurrences,
b) Hard-copy and electronic archiving of relating information (papers, videos, pictures if available, press releases, early reporting...),
c) Basic first order analysis of the incident record in order to identify supposed causes and sequences of events leading to the scenario.
Conceptualisation of the database, by describing each incident according to a list of pre-defined variables for the purpose of statistical analysis:
- date and localisation of incident
- plant data: name of plant, production capacity of plant, raw materials employed, particular condition of plant at moment of incident (maintenance, works…), year of plant opening
- assumed causes of incident: products involved, material or equipment implied, initiator event, localisation of incident
- known consequences of incident: number of fatalities of injured persons, of material damage, environmental damage, intervention features (evacuation of neighbours or not), etc.
Currently, the database lists 112 incidents that occurred between 2000 and July 2009. Year 2008 alone, 31 accidents were recorded.
As the database was supplied with information from websites and literature, it is likely that information about some incidents was not spread due to the modesty of consequences in some cases or due to potential barriers of political, linguistic or technical nature. It could lead to some bias in the data analysis but it should be reminded that these data essentially do not aim at making an exhaustive inventory of the accidents and essentially serves the objective of appropriately describing the main typologies of incidents. Table 1 illustrates several typical incidents that are recorded with pertinent information in our database:

Table 1: Some incidents recorded in INERIS incidents database

Port Kembla, Australia **28th January 2004** Explosion, followed with fire of a seven-million-litre ethanol tank. Maintenance works (welding) were performed before explosion. 2 persons were injured. The incident features also the extreme difficulty of tackling large ethanol fires	 
New Brighton, Pennsylvanie, USA. **22th October 2006** Derailment of train carrying 100.000 gallons of ethanol. No person was injured	 
Colorado, USA **May 2006** Explosion in a garage. A homeowner made biodiesel at home. He was gone for week end and forgot to switch off the tank heating system before departure. The garage was containing 600 gallons of biodiesel and recycled oils, and, in least significant quantities, glycerin, sodium hydroxide, sulfuric and phosphoric acids.	
Illinois, USA. **19th June 2009** Tank cars loaded with thousands of gallons of ethanol exploded in flames as a train derailed, killing one person and forcing evacuations of hundred of nearby homes. According to witnesses, the train faced hydroplaning behavior in standing water before derailment.	

4. Statistical analysis of database

In order to analysis the incidents database and identify the main typologies of incidents pertaining to biofuel pathways, we performed a Multiple Correspondence Analysis (MCA) followed by an ascendant hierarchical classification (AHC). All relating statistical analysis procedures were carried out making using the R software[1].

4.1. Methodology

Multiple Correspondence Analysis (MCA)
Our incident database includes categorical variables. MCA is a factor analysis method particularly suitable for the analysis of such variables. This method transfers a set of categorical variables into a small number of orthogonal variables called principal components, which optimally reflect primary data for statistical analysis purposes. MCA acts here as a useful technique for multidimensional analysis of categorical data. Moreover, MCA is a pre-processing step for classification purposes. Indeed, hierarchical classification requires quantitative values, and MCA provides quantitative values (coordinate values of incidents in the system of axes defined by the principal components) derived from categorical values of database.

[1] http://www.r-project.org/

Ascendant Hierarchical Classification (AHC)
Ascendant Hierarchical Classification is an iterative process which principle lies as follows: the algorithm starts with as many clusters as recorded data and progressively sort the data by building up a tree from successive merges of the two nearest clusters. The AHC procedure is often represented by a two dimensional diagram known as a dendrogram which illustrates the classification obtained at each successive stage of the analysis. The dendrogram is then cut off –at hand of the user- at a chosen level of clustering to obtain the final classification retained as more appropriate. In our study, the AHC process was performed by use of the AGNES (Agglomerative Nesting) [Kaufman et al. 1990] method.

4.2 Results

To implement the MCA followed by the AHC, 8 variables, called "active variables", describing incidents have been carefully chosen. These variables deal in our study with general information about each incident, supposed causes and circumstances of the event and consequences in terms of human, material and environmental losses. The results of the HAC are displayed as a graphical representation or dendrogram. (see figure 1):

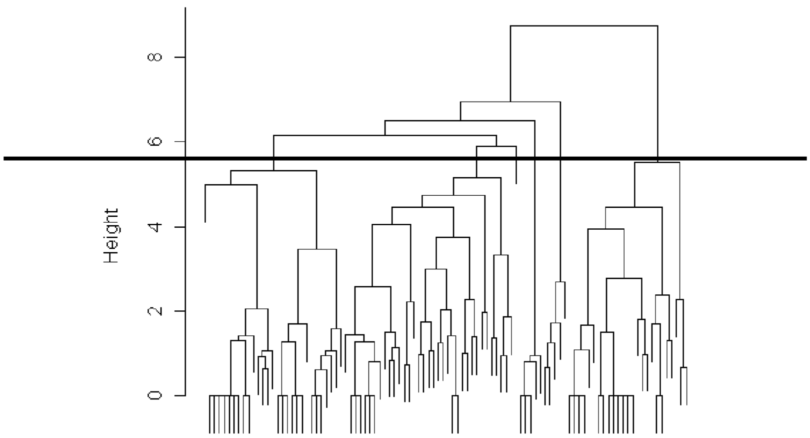

Figure 1: Dendrogram

Cutting this tree at various levels sorts the relating data in various partitions. The lower this dendrogram is cut, the more significant is the number of clusters and the less numerous are incidents in each cluster. Inversely, the higher this dendrogram is cut, the less significant is the number of clusters and the more numerous are incidents in each cluster. The more reasonable clustering in terms of overall significance, according to our expertise, was achieved when the AHC ended up with 5 clusters (cut off line is the red line shown on Figure 1). Figure 2 is a global representation of these clusters in the factor map:

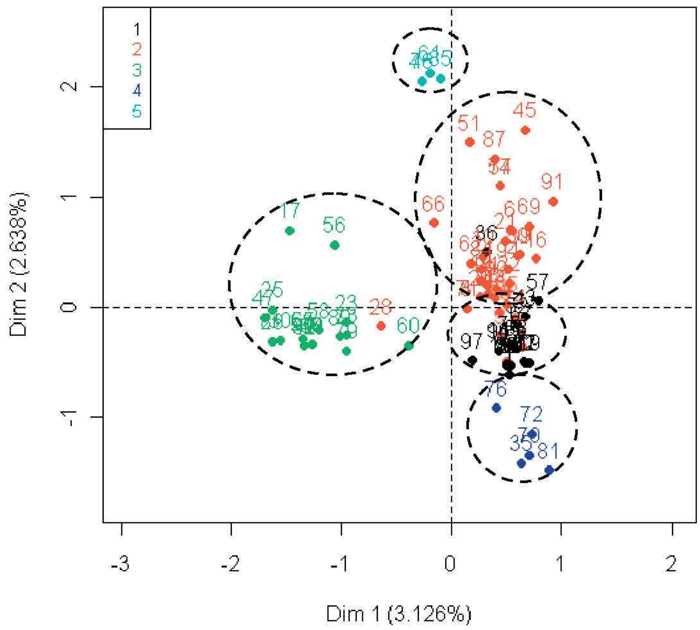

Figure 2: Biofuel incidents clustering in factorial map

Table 2 gives a technical description of each cluster (typology, number of incidents, composition) and a practical example of incident record representative of the cluster:

Table 2: Description of clusters and related typical examples of incidents

	Number of incidents	**Composition of cluster**	**"Real case" examples**
Cluster 1	29	- 57% of incidents of this cluster occurred in a **drying system** and 100% of database's incidents occurring in a dryer are in this cluster, - 89 % of incidents occurred in **plants under normal operation conditions** - The main event is an **explosion and/or fire** (100% of recorded incidents in this cluster), - 34% of incidents of this cluster involved **pulverulent** product and 59% of database's incidents involving pulverulent are in this cluster, - 86% of incidents of this cluster occurred during **bioethanol production life cycle.**	September, 2005, West Burlington, Iowa (USA): A grain dryer was the initial location of a fire in an ethanol plant. Roads around the plant were closed for about an hour. One plant worker and two firefighters were treated for minor injuries.
Cluster 2	36	- 61% of incidents of this cluster started in a **tank** and 100% of database's incidents starting in a tank are in this cluster, - 33% of incidents of this cluster occurred during **maintenance works** and accordingly, 80% of database's incidents occurring during maintenance are in this cluster, - 14% of incidents of this cluster occurred during **closing of the plant** (grouping all of database's incidents occurring during closing of the plant), - The main event is an **explosion and/or fire** for 89% of incidents, - 17% of incidents of this cluster involved **significant material damages** and 86% of database's incidents involving significant material damages are in this	April 2008, Calgary, Canada: an explosion occurred and killed a man working at a newly built biodiesel plant. The worker was welding on top of a 30-foot biodiesel tank when the tank exploded. The fire continued to burn in the tank for several hours after the explosion. Evacuation of the workers was processed.

		cluster.	
Cluster 3	25	- 88% of incidents occurred during **transport of materials,** - The product of concern is **ethanol** in 92% of this cluster's incidents, - The main event is a **spill of products followed or not with explosion and/or fire** (86% of the cluster), - incidents result from train **derailment** (40% of cases), or **tank truck turn over** or crash (32% of cases) or take place on **maritime/fluvial routes** (12% of cases), - 32% of incidents of this cluster involved **environmental risk** and relating 80% of database's incidents involving environmental risk are in this cluster, - 84% of this cluster's incidents did not injure anybody.	July 2008, Minnesota, USA: derailment of multiple carriages of a train carrying ethanol. The derailment caused an ethanol spill. The incident could be related to the failure of a wooden railroad bridge. No one was wounded and no evacuation was required dutring the emergency crisis management.
Cluster 4	5	- No identified product implied (100 %), - Not an explosion, nor a fire or a spill event (100%).	February, 2008, Austin, Minnesota (USA): a man died while working at an ethanol plant under construction. According to authorities, the man was pinned between a man-lift and a beam in the facilities.
Cluster 5	5	- 100% of incidents of this cluster occurred due to artisanal biofuel manufacturing at home (or in a garage), - 100% of incidents involved biodiesel.	May 2008, New York, USA: a garage explosion and resulting fire were the major consequences of a homemade biodiesel operation. The fire destroyed the garage, greatly damaged a house and another garage. Investigators found a large quantity of vegetable oil and 55-gallon drums of biofuels at the scene.

From the description of these 5 clusters, the following main typologies of incidents recorded in INERIS database may be developed in terms of scenarios as follows:

- ***Scenario series 1***: The scenario initiates by an explosion or/and fire in a grain dryer (overheating of equipment, self-heating of grains). This scenario mostly relates to bioethanol production supply chains.
- ***Scenario series 2***: The scenario essentially consists in an explosion or/and a fire starting in a tank storing a flammable product. This scenario occurs more frequently when the facilities are in maintenance phase or closed. Significant material damages follow up as a common consequence is such a case.
- ***Scenario series 3***: This scenario starts with a spill of ethanol during terrestrial transport (road, rail, less often from a boat) and may be followed by an explosion or a fire event. This scenario may correlatively lead to environmental contamination. This type of incidents generally involves limited casualties. Domino effects may also arise (as fire spread to other equipment of vehicles…)
- ***Scenario series 4***: In this series, the scenario comes from atypical incidents in which neither explosion / fire nor spill of hazardous product is involved.
- ***Scenario series 5***: This series of incidents deals with non professional (home-made) manufacturing of biodiesel. The lack of explosion- proof equipment or other safety devices is generally the root cause in this case.

These incident typologies, only based on the analysis of real accidental cases, highlight some safety issues as prominent, such as transport risk, storage risk or equipment risk. However, some cautions are needed for assessing the related risks in a more global way or for a given plant, according to local parameters. Additionally, as stated previously, some bias linked to data collection mode and performance may arise in the analysis. A better cover of incidents that may have occurred in South East Asia (bioethanol from a variety of crops and biodiesel ex Jatropha or ex palm oil) or in South America (sugar cane bioethanol, biodiesel ex soja…) is expected in the future.

5. Conclusions and perspectives

An analysis of more than 100 incidents that occurred after 2000 during biofuel production life cycle has been proposed. In order to highlight appropriate information and to learn lessons of this database, a multiple correspondence analysis followed by a hierarchical classification of data have been performed. This multivariate statistical treatment enabled to identify 5 main series of incidents typologies. These typologies outline some safety issues such as:
- the significance of the risk during drying of grains (scenario 1).
- the recurrent risk during storage of hazardous materials (scenario 2), such as ethanol, biodiesel or methanol, particularly during works in the facilities.
- the risk during batch transport of hazardous materials such as ethanol (scenario 3).
- the risk of artisanal biodiesel production (scenario 5). Produce biodiesel himself at home is increasingly popular, due to apparent ease of processing. However, consumers are rarely aware of hazards bound to this operation in an environment that is generally not appropriate, as recently recalled in a safety warning addressed on its web site by Health and Safety Executive in the UK [HSE, 2006].

This contribution concerns first-generation biofuel pathways, the only operational routes of production of biofuels today. However, many facilities are in project to produce so called 2nd generation biofuels (e.g. cellulosic bioethanol ex lignocellulosic biomass streams) and some demonstration units are already operating. Pressures and temperatures levels typically pertaining to some processes employed for production of 2G biofuel, such as liquefaction or Fischer-Tropsch synthesis, are significantly higher than with 1G products, that lead to specific safety issues. Other features of such facilities will require due attention in terms of safety. Given the globalization of the biofuel booming industry, it would be highly desirable to implement a common incident data reporting system. This could eventually facilitate and optimize the type of analysis performed in this study, by rendering it more widely applicable and less subject to potential bias. Safety issues could then be treated more consistently, thus bringing a valuable milestone to more sustainable biofuel production world-wide.

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