Energy-related Severe Accident Database (ENSAD): cloud-based geospatial platform

Wansub Kim, Peter Burgherr, Matteo Spada, Peter Lustenberger, Anna Kalinina and Stefan Hirschberg

ABSTRACT
The Energy-related Severe Accident Database (ENSAD) is the most authoritative resource for comparative risk analysis of accidents in the energy sector. Although ENSAD contains comprehensive, worldwide data, it is a non-spatial database in Microsoft Access format. Therefore, spatial characteristics of the data cannot be fully utilised as well as analysed directly. Based on these premises, a new web-based version of ENSAD with GIS-capabilities – named ENSAD v2.0 – is designed and developed using state-of-the-art, open source technologies. The ENSAD v2.0 consists of two main components, i.e. a spatial database and a responsive web application. For the spatial database, the current accident data are georeferenced and migrated from Microsoft Access, using a tiered approach. The responsive web application can be accessed from desktops as well as mobile devices, and provides both a 2D and 3D mapping platform that is developed on cloud-based, serverless architecture. ENSAD v2.0 also allows assigning different user roles with specific access rights, and a public version with advanced visualisation capabilities has also been developed. Lastly, a case study was carried out using a spatial analysis to visualise the potential impact radius of a natural gas pipeline explosion and to assess its consequences in terms of economic damage and casualties.

ARTICLE HISTORY
Received 29 November 2018
Accepted 18 February 2019

KEYWORDS
Energy-related severe accident database; web-based GIS; resilience; cloud computing; risk assessment

1. Introduction
The ideas of energy security and resilience have been increasingly adopted in national security, energy policy and urban planning to make critical energy infrastructure more resistant to disruption caused by natural disasters, and international terrorism (Burgherr, Giroux, & Spada, 2015; Coaffee, 2008). Furthermore, the safety performance of energy infrastructure is strongly linked with its sustainability and the availability aspect of energy security, which requires that a wide range of energy technologies is analysed and compared based on the objective expression of accident risk (Burgherr & Hirschberg, 2014). Thus, comparative risk assessment in the energy sector plays an important role for a comprehensive evaluation of energy security.

CONTACT Peter Burgherr peter.burgherr@psi.ch Laboratory for Energy Systems Analysis (LEA), Paul Scherrer Institut (PSI), Villigen PSI, Switzerland

© 2019 The Author(s). Published by Taylor & Francis Group and Science Press on behalf of the International Society for Digital Earth, supported by the CASEarth Strategic Priority Research Programme. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
In order to support the assessment of accident risks in the energy sector, a number of databases have been developed collecting and managing information in the past. For example, Sovacool et al. (2016) compiled a database with 686 accidents for the period 1950–2014, which cumulatively resulted in 182,794 fatalities and $265.1 billion in property damages. The Major Accident Reporting System (eMARS) is the official system for submitting reports to the European Commission (EC), containing about 700 accidents and near misses at so-called Seveso facilities that were collected since 1982 by the EC member states (JRC, 2018). The Failure and Accidents Technical Information System (FACTS) is an industrial accident database that collected 25,700 industrial accidents worldwide, which happened during the past 90 years (FACTS, 2018). Finally, the Analysis Research and Information on Accidents (ARIA) database comprises about 46,000 accidents from France and the world, and covers many activities and sectors (ARIA, 2018).

The ENergy-related Severe Accident Database (ENSAD) has been developed by the Paul Scherrer Institut (PSI) since the 1990s (Hirschberg, Spiekerman, & Dones, 1998). It currently contains 32,963 accidents for all major energy chains (i.e. fossil, hydropower, nuclear, new renewables), covering complete energy chains from exploration through transportation to end use (Burgherr et al., 2017). Generally, ENSAD has been continuously updated and extended both in scope and content to keep up with the changing and emerging needs of different stakeholders (e.g. risk analysts, policy makers, industry, etc.), and the database has also been used in many studies to provide tailored data for risk assessment (e.g. Burgherr, Eckle, & Hirschberg, 2012; Burgherr & Hirschberg, 2014; Burgherr, Hirschberg, & Spada, 2013; Cinelli, Spada, Miebs, Kadziński, & Burgherr, 2017; Hirschberg et al., 2016; Kalinina, Matteo Spada, Burgherr, Marelli, & Sudret, 2016; Spada, Burgherr, & Rouelle, 2018).

Compared to other databases, ENSAD has a number of advantages: (1) it focuses on accidents in the energy sector; (2) it provides detailed information for individual accidents that is in many cases verified by two or more primary information sources; (3) it considers full energy chains; (4) it has a global coverage that allows comparisons across different world regions, country groups and/or countries; (5) it specifies severity threshold for different types of consequences (e.g. numbers of fatalities, injuries, evacuees, economic damage, material released) (Burgherr et al., 2017).

ENSAD was originally developed in Microsoft Access format, which means that the database is based on a non-spatial data model and it runs as a desktop application. Thus, multiple users cannot access and edit the database concurrently, and spatial characteristics of the accident data cannot be fully utilised. To improve the limitations of the current version of ENSAD, an interactive, web-based Geographic Information System (GIS) named ENSAD v2.0 is designed and developed based on state-of-art technologies. The actual implementation was carried out within the Future Resilient Systems (FRS) program of the Singapore-ETH Centre (SEC). FRS is a research programme under the SEC, established by ETH Zurich and Singapore’s National Research Foundation, in partnership with Switzerland-based Paul Scherrer Institute (PSI), and Singapore-based Nanyang Technological University (NTU), National University of Singapore (NUS), and Singapore Management University (SMU) (FRS, 2018).

The main objectives of this study are: (1) defining a semi-automatic process for georeferencing accident data utilising advanced technologies; (2) designing a spatial database that is optimised for accidents in the energy sector, operated on cloud computing, i.e., Docker; (3) developing a web-based GIS that visualises maps of accidents on different devices and dimensions; (4) implementing a user management system that allows access to specific
accident information and level of detail depending on the user role; (5) adopting an analytics platform to monitor user activity. First, we analyse user requirements that lead to the definition of the specific functionality of the new accident database. Based on this analysis, we evaluate available technologies to design an architecture for both hardware and software. Then, a spatial database is designed to migrate all the non-spatial data to ENSAD v2.0 with an approach of hybrid georeferencing that is specially devised for ENSAD v2.0. With the functionality and spatial database designed, three different versions of client viewers are implemented, namely a desktop viewer and a mobile viewer supporting 2-dimensional (2D) and 3-dimensional (3D) maps, and a public viewer offering limited accident data detail. To monitor the user activity on the web application, an analytics platform is adopted between the client viewers and the server. Lastly, a case study example is presented that applies a spatial analysis to determine the potential impact radius (e.g. fatalities) of natural gas pipeline accidents using ENSAD v2.0.

2. Development of the new accident database

A structured, multi-phase approach was applied to transform the static, standalone ENSAD v1.0 into an optimised, spatial database – named ENSAD v2.0 – that builds upon a web-based GIS. First, a requirement analysis was conducted to identify the main shortcomings of the current ENSAD v1.0, and to compile a list of new features to meet the various user needs. Second, available technologies were screened for their feasibility of implementation. Third, the general system architecture was designed, including specification of the main features and pre-defined user roles.

2.1. Requirement analysis

The requirement analysis comprised the identification of a broad range of user requirements, which are then grouped into categories. Afterwards, these requirements were translated into specific system functionalities. Table 1 summarises the user requirements in seven categories that were compiled as the outcome of several meetings with different types of potential future users of ENSAD v2.0. The category ‘General’ includes basic requirements such as interactive online application and GIS capabilities, but also availability on multiple devices (e.g. desktop vs. mobile). The categories ‘Map’ and ‘Table’ concern the treatment of accident records within the database. Naturally, accurate geocoding is another important aspect of a GIS-database. The corresponding requirements are primarily relevant when adding new accidents to the database, and can be integrated as a geocoding assistant in the accident record registration wizard. The categories ‘User Role’, ‘History’ and ‘Management’ allow the administrator to invite and coordinate users according to their specified role, to keep track of changes made to individual accident records, to make changes to the GIS server, and to monitor and analyse the use of the database.

According to the findings of the requirement analysis, the primary expectation is that the new database is developed as a web-based, interactive GIS application, which can be accessed from desktops as well as mobile devices such as tablets and smartphones. Therefore, responsive web design is adopted, which is an approach to develop a website that can provide the same contents regardless of the size of the screen and the type of device. Another key requirement is that stakeholders need a simple process and registration form to add new
| Category     | User requirement                                                                 | Functionality                                      |
|--------------|-----------------------------------------------------------------------------------|---------------------------------------------------|
| General      | Web-based, interactive application                                                | Responsive web application                        |
|              | Built-in GIS capabilities                                                          | Web-based GIS and Spatial database                |
|              | Visualisation on 3-D map                                                           | 3D Viewer                                         |
|              | Accessibility from mobile devices                                                 | Responsive web application                        |
|              | Simple process to add a new accident record                                       | Registration Wizard                               |
| Map          | WGS84 map projection                                                              | EPSGS: 4326 (WGS84)                               |
|              | Print map of selected area and selected layer(s)                                   | Print Map (PDF format)                            |
|              | Basemaps (country boundaries, infrastructure facilities, population, etc.)       | Display basemaps, Add/Remove layers               |
|              | Pan/Zoom-in/Zoom-out                                                               | Map Tool Bar                                      |
|              | Possibility to edit map (geometry and attribute)                                  | Modify Map                                        |
| Table        | Spatial database tables comprise four types of attributes; polygon, line, point or non-spatial. | Spatial database                                  |
|              | Option to export table                                                             | Export Table (CSV Format)                         |
|              | Search function to query database content                                          | Query by Attribute or map extent                  |
|              | Table and Map are interactively connected                                          |                                                   |
| Geocoding    | Geocoding options: 1) manually input coordinates, 2) automatically find coordinates using address, city or country, 3) semi-automatically find coordinates using infrastructure maps | Registration Wizard                               |
|              | Geocoding index assigned to each accident record that describes how coordinates were obtained and their accuracy. | Registration Wizard (geocoding index)             |
| User Role    | Admin – all rights, restricted number of persons                                   | User Management                                   |
|              | Editor – can create new records and modify existing records, export table and map. |                                                   |
|              | Basic – can query database, display selected maps and tables.                     |                                                   |
| External User| Public – can only query and display limited information                            |                                                   |
| History      | All changes to an accident record are logged (e.g. record creation, modification date and modified field(s), User Name). | Data History                                      |
| Management   | Online access and activities of users are monitored                                | Analytics Platform                                |
|              | Turn on-/off map server                                                            | GIS Server                                        |
|              | Possibility to change map style                                                   | Layer Styler                                      |
|              | Assign a role to user                                                             | User Management                                   |
|              | Register map layers                                                               | GIS Server                                        |
accident records to the database. Thus, it was decided to develop a registration wizard (see Section 4.2) that guides the user when adding new accidents to ENSAD v2.0.

2.2. Evaluation of available technologies

In the first step, commercial and Open Source GIS systems were compared. The advantages of commercial systems such as ArcGIS (ESRI, 2018a) are the following: (1) they are stable and fast for a large-scale system; (2) they provide many ready-to-use web templates and tools; (3) it is straightforward to implement geoprocessing using pre-defined tools for spatial analysis. However, there are also disadvantages that include: (1) the high costs for purchasing and maintaining of the packages; (2) the core engine is a black box; and (3) the main functionality of the system cannot be modified freely.

In contrast, open source GIS offer (1) sufficient performance and functionality for a small to medium scaled system; (2) even the core engine of the system can be modified for performance tuning; (3) additional functionality can be added; and (4) there is no cost of purchase and maintenance. With regard to its complexity and size (33,000 accident records), the requirements of the current ENSAD v1.0 are easily satisfied by the above-mentioned criteria one to three. Therefore, it was decided to use open source GIS to develop the new ENSAD v2.0.

Table 2 shows the various server- and client-side GIS components that were evaluated and selected to develop ENSAD v2.0. On the server-side, GeoServer (2018) was selected as the GIS server, and PostGIS+PostgreSQL (PostGIS, 2018) as the spatial database. Furthermore, an analytics platform (Matomo) (Matomo, 2018) was added to monitor the activities of the users online. For instance, access information (e.g. accessed time, location, IP address) as well as device information (e.g. type of device, browser) can be analysed. Although Google analytics (Google, 2018a) was considered as an alternative, it is not completely free and open source compared to Matomo.

On the client side, a 2D and 3D web client for the desktop version and a mobile client for the mobile version of ENSAD v2.0 were chosen. Boundless SDK (2018) was selected as the 2D client because this SDK provides a user interface comparable to typical GIS desktop software like ArcMap (ESRI, 2018b) and QGIS (QGIS, 2018), so that a user can easily adopt to the new ENSAD v2.0. For the 3D web client, the 2D client was integrated with Cesium (CesiumJS, 2018), a 3D map platform. Unlike the Google Earth plugin, Cesium does not require installation of additional plugins, since it is based on WebGL (Web Graphic Library) (WebGL, 2018).

Once the various system components of ENSAD v2.0 had been chosen, it was necessary to find a suitable server-hosting provider. The criteria for this decision included scalability, GIS capability, available databases, maintenance scheme, physical server location and costs. Table 3 shows a comparison between four different providers of server hosting with regard to these criteria. WebFaction (2018) is not a cloud server service, which means that it is not possible to control or tune the scalability of the server once the system is set up. Although AcuGIS (2018) is a cloud server with full support of GIS packages, its smaller market share and lack of technical documents are significant drawbacks. In contrast, Amazon EC2 (Amazon, 2018) and OpenShift (RedHat, 2018) are widely used and provide many references and documents. Between OpenShift and Amazon EC2, it was decided to use OpenShift because it has a simpler architecture than Amazon EC2, which results in
| Category        | Component            | Role                                                                 | Selected product | Alternatives                  | Reasons for selection                                                                 |
|-----------------|----------------------|----------------------------------------------------------------------|------------------|-------------------------------|---------------------------------------------------------------------------------------|
| Server-side     | GIS Server           | Manages maps and their publication                                   | GeoServer        | MapServer                     | Connects external map services; can easily extract and manage external maps.          |
|                 |                      | Map share and edit                                                    |                  |                               | Advanced log configuration                                                           |
|                 |                      |                                                                     |                  |                               | Customisable user and role management.                                               |
| Spatial database|                      | Stores and manages both generic data (strings, numbers, etc.) and spatial data types (vector and raster) | PostGIS+         | PostgreSQL                    | Stable and fast, full support for spatial data management and manipulation           |
|                 |                      |                                                                     |                  | MySQL + MySQL + spatial extension       | GeoServer only integrated with GeoWebCache                                          |
|                 |                      |                                                                     |                  | MapCache                       | Comprehensive feature for user monitoring                                            |
|                 |                      |                                                                     |                  | Google Analytics               | Customisable functionality                                                           |
|                 |                      |                                                                     |                  | MapCache + GeoExt              | Well-integrated with PostGIS and GeoServer                                          |
|                 |                      |                                                                     |                  | Google Analytics               | Full support not only for internet map services such as Google Map, Bing map, but also for OGC (OpenGIS Consortium) standard maps |
| Map cache       |                      | Caches map tiles to improve performance                              | GeoWebCache      | Google Analytics               | GIS-friendly components.                                                            |
|                 |                      |                                                                     |                  | MapCache                      | Well-integrated with Openlayers and OGC services                                     |
| Analytics platform|                    | Monitors user access and activities                                  | Matomo           |                               | Easily converts map mode between desktop and mobile                                  |
| 2D Web client   |                      | Displays maps published by GIS server on the web browser             | Openlayers + GeoExt | MapBuilder, MapFish           | Client-side web GIS library                                                            |
|                 |                      |                                                                     |                  | Google Earth plugin            | Displays map on a 3D globe                                                          |
|                 |                      |                                                                     |                  | Cesium                        | Displays map on mobile devices                                                       |
| 3D Web client   |                      | Displays map on a 3D globe                                           | Openlayers Mobile |                               | Client-side web GIS library                                                            |
| Mobile client   |                      | Displays map on mobile devices                                       |                  |                               | GIS-friendly components.                                                            |

Table 2. Overview of selected technologies and components for ENSAD v2.0.
Table 3. Comparison of four server providers according to six evaluation criteria. GB = Gigabyte, RAM = Random Access Memory, CPU = Central Processing Unit, SSD = Solid State Device, Pod = Hardware resource unit, Instance = Hardware resource unit, Package = Hardware resource unit.

|                | Webfaction\(^a\) | OpenShift\(^b\) | Amazon EC2\(^c\) | AcuGIS\(^d\) |
|----------------|------------------|-----------------|------------------|--------------|
| Scalability    | Low scalability  | High scalability| High scalability | Medium scalability |
| GIS capability | Support for GeoServer | Support for GeoServer | Supports only ArcGIS server | Built-in PostGIS and Geoserver |
| Database       | PostgreSQL (as a built-in database) | -Hourly backup | -Hourly backup | -Daily backup |
| Maintenance    | -Weekly backup   | -Support by email | -Support by technician | -Support via phone, email |
| Physical location | USA, Netherlands, Singapore | USA, Ireland | Germany, Ireland, USA, Asia | UK, Germany, USA |
| Monthly cost(USD) | 60               | 150–200         | 200–300          | 200          |
|                | (90GB SSD/4GB RAM/4 CPUs) | (80-90GB SSD/7–8 pods) | (80-90GB SSD/7–8 instances) | (100GB SSD/4 packages) |

\(^a\)https://www.webfaction.com/
\(^b\)https://www.openshift.com/features/
\(^c\)https://aws.amazon.com/solutions/global-solution-providers/esri/
\(^d\)https://www.acugis.com/geoserver-hosting.htm
more efficient operation of the server. Moreover, OpenShift provides a grant for academic use of the server, which considerably reduces the cost of maintenance.

2.3. System architecture

Based on the requirement analysis and subsequent selection of technologies and components, the system architecture of ENSAD v2.0 was designed as shown in Figure 1. A standard web browser is used as client-side software to access ENSAD v2.0. An up to date version of a web browser is required to ensure full use of state-of-the-art technology such as HTML5 and CSS3. For the different types of viewers, various libraries and APIs of JavaScript are adopted such as GeoExt, OpenLayers, Google Map API, Cesium, OpenLayers Mobile and D3. A detailed description of each library and viewer is given in the subsequent sections.

As shown in Figure 1, the spatial database is the core of ENSAD v2.0, which consists of a spatial data handler and a generic Data Base Management System (DBMS). It is connected with the GIS server to publish maps as a web service that follows the protocol of the Open Geospatial Consortium (OGC), i.e. Web Map Service (WMS) described in the following sections.

2.3.1. Cloud server

OpenShift is a Platform as a Service (PaaS) provided by RedHat. A PaaS provides resources of both infrastructure (hardware) and software (e.g. operating system, database, middleware, web application) as a service, primarily targeting developers (Zhang, Cheng, & Boutaba,
The hardware resource (i.e. CPU, RAM, and SSD) acts as a unit and is called ‘Pods’, which is roughly equivalent to ‘Instances’ in Amazon EC2 or ‘Packages’ in AcuGIS, and the software resource also acts as a unit and is called ‘Container’. Pods are one or more containers deployed together on one host, and a container is a lightweight, stand-alone package of a piece of software that contains everything, i.e. code, runtime, database and web server (RedHat, 2018). OpenShift’s container is built on the Docker platform that is an initiative driving the container movement and the most commonly used platform in the cloud computing (Docker, 2018). The main advantage of PaaS is that a user can easily setup a server using pre-defined servers and components with a one-click process. Furthermore, the performance and capability of the server can be freely scaled-up and -down according to variable resource needs, depending on the actual number of users. The usage of Docker also provides several benefits such as agility, portability and security.

2.3.2. GIS server and spatial database
In ENSAD v2.0, GeoServer is adopted as a GIS server, and PostGIS with PostgreSQL for a spatial database. PostGIS stores and manages typical GIS data formats such as vector and raster as well as generic (non-spatial) tabular data in the database. GeoServer can directly access maps stored in the PostGIS to publish the maps on the Internet. ENSAD v2.0 uses the Geoserver for map processing (i.e. WFS, WMS, WPS), while generic database processing (i.e. Create, Remove, Update and Delete (CRUD)) is executed by the Java Server Page (JSP). In particular, the query by map extent and query by attribute are implemented by using the built-in query functionality of GeoServer that relies on Web Feature Service (WFS). WFS is a web service that extracts and visualises information from vector maps based on the OGC protocol. Furthermore, Web Map Service (WMS), which is a web service to deliver map tiles, is used to display maps with JavaScript libraries that consume WMS on the client-side. In order to improve the performance of the WMS, a tiling server called ‘GeoWebCache’ is installed between the GeoServer and the web application server. GeoWebCache pre-generates tiles of maps with pre-defined configuration, thus allowing a user to access map tiles directly without waiting for the generation of the tiles. Finally, the Web Processing Service (WPS) is adopted to conduct geo-processing. For example, a spatial join between country boundaries and an accident location map or the interpolation of an accident map are executed by the WPS. In addition to these OGC services, the Representational State Transfer (REST) API of GeoServer is adopted to change symbols or to display label features on a map dynamically.

2.3.3. Analytics platform
In order to track and monitor the activities of the ENSAD v2.0 users, the open-source analytics platform Matomo is adopted on the server-side. The analytics platform analyses the user data statistically, e.g. how and when a user accessed to the system, and what menu or feature a user used. Matomo allows not only customising the data to be analysed, but also the structure of the table and system can be adapted in accordance with the requirements of the administrator. The platform can extract the following data:

- Access information: time, geographical location, IP address, type of device, type of software, etc.
- User activities: selected menu, downloaded data, etc.
- Referrers: search engine and keywords that a user utilised to access ENSAD v2, etc.
• Log of visits: number of unique visitors, average visit duration, number of page views, etc.

2.3.4. SSL and google reCAPTCHA
The Secure Socket Layer (SSL) and Google reCAPTCHA (Google, 2018b) technologies are applied to improve the security of ENSAD v2.0. SSL encrypts data shared between a client and a server. It protects the data from being potentially forged or modified by a hacker. Every web page in ENSAD v2.0 is secured by the SSL. Furthermore, Google reCAPTCHA is used to prevent robots to hack the login or the signup system of ENSAD v2.0. The process of verifying a user is usually just done with one click, and sometimes it requires a user to choose some pictures to allow judging whether the user is a robot or not, depending on how frequently a user accesses the system. After the successful login of a user with reCAPTCHA over SSL, the user can access to the ENSAD v2.0’s desktop version, mobile version or the ENSAD Visual Explorer (EVE), according to the type of device used, and the defined user role.

2.3.5. 2D/3D and mobile viewer
ENSAD v2.0 is developed as a responsive web application so that users can access it from a desktop as well as a mobile device. The desktop version of ENSAD provides both a 2D and a 3D viewer. The 2D viewer displays maps on a 2D plane, which is developed based on the following JavaScript libraries: Boundless SDK integrated with GeoExt and OpenLayers, and the Google Maps API. The main user interface of ENSAD v2.0 is implemented as a 2D viewer similar to the user interfaces of a typical desktop GIS software (e.g. ArcGIS, QGIS). Therefore, users who have experience with GIS software packages can quickly handle ENSAD v2.0. Furthermore, the panels in the 2D viewer are easily resized and folded so that a user can adjust the interface according to its preferences. For the 3D viewer, the Cesium engine does not require the installation of a plugin, and it is not dependent on a specific web browser. This means that it runs with most commonly used web browsers, including Google Chrome, Firefox, Internet Explorer and Safari. The 3D viewer displays maps on the 3D surface of the Earth, which is developed based on the Cesium JavaScript library for 3D maps. The accident locations are dynamically mapped on the terrain of the Earth. The altitude of an accident location is extracted in meters by the Google Maps API. The user can switch between the 2D and 3D viewer modes with just one click.

2.3.6. ENSAD Visual Explorer
Accident data on ENSAD v2.0 are collected from a broad range of commercial and freely available primary information sources. Therefore, raw data and complete accident record information cannot be provided to every interested person or organisation. To overcome this drawback, a separate, public version of ENSAD was developed. This so-called ‘ENSAD Visual Explorer’ (EVE) has restricted functionalities and contains only limited accident information that can be shared. During the sign-up process, every user is automatically assigned to the role ‘public’, and redirected to it after a successful login. Similarly, each user registered to ENSAD v2.0 can also access EVE. Since EVE focuses on attractive visualisation of accident data with limited information its main functionality includes: (1) to display accidents on a world map; (2) to display charts that show the trends of the numbers of accidents or different types of accident consequences over the years; and (3) to display specific subsets of accidents by using pre-defined attributes to filter the database. The D3.js Java Script library was chosen as the client-side technology, whereas the server-side technology is the same as for ENSAD v2.0. D3.
js is a JavaScript library specialised on visualisation of data. This combination of technologies is most suitable to meet the above-mentioned visualisation and data query goals.

3. Design of the spatial database

First, we look into the structure of the current ENSAD v1.0 (section 3.1), and then design a new spatial database – i.e. ENSAD v2.0 – that can store georeferenced data migrated from the current ENSAD (section 3.2). The georeferencing process is embedded in the overall accident data migration, and referred to as so-called ‘Hybrid georeferencing’ (Section 3.3).

3.1. Structure of ENSAD V1.0

The current ENSAD v1.0 is a non-spatial database based on Microsoft Access (Burgherr & Hirschberg, 2014; Burgherr et al., 2017; Hirschberg et al., 1998). Figure 2 shows the main elements of the database structure of ENSAD v1.0. Even though the database has been continuously updated in content, scope and functionality since its first release, several shortcomings can be identified. First, it is a standalone desktop application that cannot be accessed by multiple users at a time. Second, it is a non-spatial database, hence there is no direct connection to GIS and its capabilities to visualise, process and analyse complex data. Third, the interface has become too complicated over time because of the many structural changes and addition of new features. Fourth, although the accident information is organised in well-structured tables, it is not optimal for large amounts of data. The current structure of an accident record is not adapted to the specific needs of individual energy

![Figure 2. Schematic structure of ENSAD V1.0 (compare also Burgherr et al., 2013).](image-url)
chains, so a data record can contain redundant and unnecessary fields or information. The complicated data record structure also affects the effectiveness of data handling, e.g. complex queries are executed very slowly.

### 3.2. Structure of the new spatial database

ENSAD v2.0 is developed as a spatial database that can fully use GIS capabilities. The design of the spatial database was driven by two aspects, namely simplification of the accident record and database structure compared to ENSAD v1.0, and scalability to make the database overall more flexible, also in view of potential future extensions. The simplification is achieved by reducing the number of tables and columns, but also by simplifying the table structure to adopt several energy chains that manage different information. On the other hand, the scalability of the database is implemented by designing independent tables for each energy chain, which allows adding or removing an energy chain without affecting the others.

As a result, the database and accident record structure in ENSAD v2.0 consists of six main categories:

1. General accident information: accident date, location (incl. geographical coordinates), energy chain, energy chain stage, etc.
2. Accident consequence information: fatalities, injured persons, evacuees, monetary loss, involved material(s), abstract, data source etc.
3. Infrastructure-dependent accident information: particular information that is relevant for the affected infrastructure.
4. Infrastructure maps: countries and administrative boundaries, storage facilities, refineries, power plants, etc.
5. User information: user role, user ID, last access date and time, organisation, etc.
6. Data history: accident ID, date, time, user ID, table name, changed field values, etc.

The overall structure of the database is depicted in Figure 3. The three main tables forming an accident record include general accident information, accident consequence information and infrastructure-dependent information. Compared to ENSAD v1.0, certain accident record fields are generated dynamically, based on spatial characteristics. For example, location information such as latitude and longitude can be extracted from a geometry field, and address information of accidents can be extracted by spatially joining accident locations with administrative boundaries. Additionally, infrastructure-dependent information is stored in separate tables for each infrastructure type (e.g. refinery, pipeline, etc.). Infrastructure and boundary maps are used as reference data. Finally, the user and data history information tables provide important information about who created or modified an accident record, and what changes have been made over time to which fields.

The tables are dynamically linked to be used as a GIS map layer. Each energy chain is managed as a specific map layer in ENSAD v2.0. Therefore, the table of consequences and accident information are combined with/without a selected infrastructure information table (i.e. infra-dependent table in Figure 3). The core table, i.e. the general accident information, is linked through a 1:N relationship to the consequences information ensuring that information from different primary information sources is stored individually in the consequence table. The infra-dependant table is then linked through a 1:1 relationship to the core table.
As indicated in Figure 3, the infra-dependent tables store data that is relevant for a specific energy chain. Thus, the database can be easily expanded if a new energy chain is required by simply adding a new infra-dependent table. In other words, the infra-dependent table can be removed without affecting the relationship with the other tables.

Figure 4 shows the conceptual structure for a hydropower accident. Using this structure, any type of accident map or an energy chain can be formed by simply changing infra-dependent information that belongs to specific energy chains. In order to implement this conceptual structure, the ‘View’ feature in PostGIS is used to generate a virtual table by combining several tables using SQL. The advantage of using this ‘View’ feature is that a map layer can be easily created according to the actual user role. For example, according to different user roles three different versions of the hydropower accident map layer need to be provided. A Basic user of ENSAD v2.0 can display and query the full database content, whereas the editor and admin user roles also allow creating, modifying and exporting accident record data; the admin role has more privileges than the editor to manage and track users’ sign-up/login-in and activities. In contrast, a public user has only access to limited accident information, and can select from pre-defined choices. This provision of user-specific content can simply be achieved by switching versions of the general accident and consequence tables as shown in Figure 4. Consequently, a map layer can be scaled vertically to compose a map that contains complete information for a specific energy chain as joining three (or two) tables. Each accident layer can be scaled horizontally as well with different information according to the different user roles as we query different information from each table. More specifically, a new map layer for
different energy chains (e.g. hydropower, natural gas) can be created as the general accident information is simply queried with a specific energy chain. Moreover, in order to provide different levels of information according to the user role, one can query and select from different columns in the consequences information table.

### 3.3. Data migration

The migration from a generic, relational database to a spatial database is the key change in ENSAD v2.0. In order to convert the non-spatial ENSAD v1.0 to the spatial ENSAD v2.0, full georeferencing of all accident records is needed. Depending on the available level of detail for a specific accident record, a different type of georeferencing is required. Therefore, a semi-automatic process called ‘Hybrid georeferencing’ has been developed as shown in Figure 5.

This process can be applied either when a new accident record is added or when multiple accident records are migrated in batch mode. For the first case, a specific User Interface (UI) the so-called ‘Registration Wizard’ is used (see Section 4.2). According to the level of detail of location-specific information, the most appropriate method of georeferencing can be selected. If the actual coordinates of the accident location are known, they can be entered directly. If the address of the accident location is known, then it can be directly geocoded to specific coordinates. In the case that the name of the infrastructure where the accident happened is known, the user can search for it and if it is found, its coordinates are automatically assigned as the accident location. Otherwise the user can zoom-in on the map and manually identify and select the correct infrastructure, and the infrastructure coordinates are then automatically assigned as the accident location coordinates. If only limited information are available about

---

**Figure 4.** Conceptual structure of hydropower accident: three (or two) tables are vertically and virtually joined to form a map layer to provide different levels of information, i.e. different columns in a table according to a user role, each table can be horizontally replaced and joined.
the accident location, then coordinates of the closest geographic place (e.g. city), administrative unit (e.g. state, county) or country are chosen. Independent of the georeferencing method choice an ‘Accuracy Index’ is assigned to the final coordinates of every accident to describe the accuracy level and to keep track of the geocoding method applied.

For the second case, when multiple accident records are geocoded in batch mode, the actual process remains mostly the same, but instead of the registration wizard a geocoding software (e.g. ArcGIS or QGIS) is used. However, the results then need to be cross-checked, and accidents to which no coordinates could be assigned still require manual geocoding.

4. Implementation of ENSAD v2.0

Compared to the current, standalone ENSAD v1.0, the new, web- and GIS-based ENSAD v2.0 is available in three dedicated versions. The desktop version combines access to full accident record information with the most comprehensive interface and functionality, including a data registration wizard, 2D and 3D map viewers and a layer styler among others (see Section 4.1). The mobile device version has a simple interface, limited query functions and no data analysis tools because it focuses on displaying accident data only due to the limited screen size. Finally, the interface of the public ENSAD Visual Explorer (EVE) provides the graphically most sophisticated user interface because it was designed by a specialist user experience team, focusing on visualisation of complex data from a user’s perspective. Although each interface is developed with different JavaScript libraries, the backend system is based on the same platform, using PostGIS, GeoServer and Java 8. Furthermore, the accident data are centrally managed and updated, which means that for each interface the same number of accidents is provided, although with different levels of details.
4.1. Functionality and user interface

Table 4 provides an overview of the functionality of the desktop, mobile and EVE interfaces of ENSAD v2.0, grouped by category, menu item and a short description of its functionality. The Desktop Viewer consists of management menus, viewers and panels for typical GIS processes, whereas EVE provides map clustering for intuitive visualisation with charts and graphs. The mobile viewer can also display 2D maps as well as 3D maps with terrain without installing a 3rd party library on the user’s device.

Figure 6 shows a screenshot of the main interface of the desktop viewer, which is developed using Boundless SDK (Boundless, 2018). The interface has a similar layout to a typical GIS software (e.g. ArcGIS, QGIS). The layer panel is located on the left, and the preview panel for information sources is on the right of the map. The main menus and buttons are placed on the top, whereas the query form and attribute table are on the bottom.

Figure 7 shows the interface for mobile devices, which is developed using Boundless mobile SDK. The main interface consists of three buttons at the bottom of the screen (left panel), i.e. (1) ‘Search’ to search for a location, (2) ‘Locate’ to show a map with accidents around the current location of the user, and (3) ‘Layers’ to select the desired accident and base maps (middle panel). When the user selects an accident on the map by touching the respective symbol, the corresponding attribute information for this accident is displayed in a popup window (right panel).

Figure 8 shows the EVE interface. The filtering panel on the left has three tabs which allow choosing energy types (chains), damage types and energy chain stages. If at a certain location more than one accident occurred, they are displayed on the map as a pie chart with one slice per energy chain, and the total number of accidents is also indicated. The user can also select from several predefined chart options to generate summary graphs. Lastly, the period of observation, for which accidents are displayed, can be adjusted (upper right corner).

4.2. Data registration process

The full life cycle of data management can be carried out with the Desktop interface, using a standard web browser. After a new accident record has been registered to the database, both the accident data and its geometry can be subsequently modified and visualised by combining them with selected infrastructure and background layers. The ‘Registration Wizard’ is intended to simplify the registration of new accident data, provide a user-friendly interface, and to guide the user step-by-step through the whole process, ensuring that all necessary data are collected. The ‘Registration Wizard’ is composed of several steps (or forms) as shown in Figure 9.

First, the accident location is determined using a hybrid georeferencing as described in section 3.3 (Figure 9(a)). If the location is identified by choosing the affected infrastructure from an available infrastructure layer, then the available infrastructure information is directly filled in the respective fields of the location and infrastructure forms. The final coordinates with altitude information is then displayed at the bottom of the form. In the second step, main accident characteristics, such as energy chain, energy chain subtype, energy chain stage and event chain steps, are assigned (Figure 9(b)). Then generic accident (e.g. date, failure time) and consequence information are collected (Figure 9(c)). Since consequences can be reported by
### Table 4. Functionality of ENSAD desktop, mobile, and EVE viewer versions.

| Category          | Menu item                                  | Functionality description                                                                 |
|-------------------|--------------------------------------------|------------------------------------------------------------------------------------------|
| **Desktop Viewer**| Data management                            | - Registration Wizard                                                                    |
|                   | Modify                                     | ● Register new accident data                                                             |
|                   | Query                                      | ● Modify existing data                                                                   |
|                   | Table Export                               | ● Search data by attribute                                                               |
|                   | ENSAD Data history                         | ● Search data by map extent                                                              |
|                   | Management User Role                       | ● Export the query results to csv files                                                 |
|                   | Viewer                                     | - Modify existing data                                                                   |
|                   | 2D/3D Viewer                               | ● Record and track all changes made to an accident record                                |
|                   | Google StreetView                          | ● Assign a new role to a user                                                            |
|                   | Preview of source file                     | ● Display user information                                                                |
|                   | Layer management                           | - Layer on/off                                                                           |
|                   | Layer Styler                               | ● Add or remove layers from GeoServer or external WMS server                             |
|                   | Help                                       | ● Change order of layers                                                                  |
|                   | About ENSAD v2.0, Send Feedback             | ● Change symbol of map                                                                   |
|                   | Mobile Viewer                              | ● Change display label                                                                   |
|                   | Map                                        | ● Classify map attribute                                                                  |
|                   | Search                                     | - Search for location by name or address                                                 |
|                   | Locate                                     | ● Map handling by touch gesture                                                         |
|                   | 3D viewer                                  | ● Display information for a touched accident                                             |
|                   | Search                                     | ● Display information for a selected layer                                              |
|                   | Locate                                     | ● Search data by attribute and zoom-in to a selected data                                |
|                   | EVE Map                                    | - Turn on/off layers                                                                     |
|                   | Filter                                     | ● Switch between 2D and 3D viewer                                                        |
|                   | Search                                     | ● Search for location by name or address                                                 |
|                   | Locate                                     | ● Show map and accidents around a user’s current location                                 |
|                   | EVE Map                                    | - Basic map handling                                                                     |
|                   | Map clustering                             | ● Group points of accidents within certain distance using so-called ‘pie chart’         |
|                   | Filters                                    | ● Filter accidents by energy chain                                                      |
|                   | Charts                                     | ● Filter accidents by energy chain stage                                                 |
|                   |                                            | ● Filter accidents by region                                                             |
|                   |                                            | ● Filter accidents by year                                                               |
|                   |                                            | ● Filter accidents by consequence type (e.g. # of fatalities or injured persons)       |
|                   |                                            | ● Display the cumulated numbers of accidents, fatalities, injured persons or evacuees   |
|                   |                                            | for selected years, regions or energy chain stages                                      |
several primary sources, it is possible to enter detailed consequence information for each source, and to attach a PDF file of every source. In the last step, specific infrastructure details are

**Figure 6.** Main interface elements of the desktop viewer: the interface adopts a similar layout to typical GIS software consisting of a layer panel, map panel and attribute table.

**Figure 7.** Interface of mobile viewer. (left) Main interface, (middle) Layer selection, (right) Attribute table.
registered (Figure 9(d)). If the affected infrastructure has already been identified in the location step, then available information is already inserted in the respective fields, but missing
information needs to be complemented manually. Finally, the user can register the new accident record by clicking the ‘Register’ button, which subsequently stores the new accident record in the spatial database. Afterwards, both its geometry and attributes can still be modified using the ‘Modify’ feature.

According to the data availability, a user can select from one of four options: geographical coordinate, address, infrastructure name or other spatial category (e.g. ocean boundary). If the user enters the coordinates in latitude and longitude, then an address that matches the coordinates is automatically extracted using a technology called ‘Reverse Geocoding’, i.e. coordinates are converted to an address. Furthermore, the altitude of the location is obtained as well using Google’s Elevation API. If the user needs to check the area visually, clicking the ‘Go To XY’ button will zoom-in to the area. Then, the user can select a corresponding infrastructure manually. The ‘Address’ option uses auto completion so that a list of candidate locations is displayed when the user enters the first two letters of the address or name. Selecting one of the suggested candidates returns the geographic coordinates of this location using a technology called ‘Geocoding’ that converts an address to the corresponding coordinates. The ‘Infrastructure’ option allows searching for a corresponding infrastructure from an infrastructure map (e.g. dams, power plants, etc.), and then the coordinates of this infrastructure location are extracted. Lastly, the option ‘Other Spatial Category’ supports georeferencing of accidents for which no coordinate or specific address or infrastructure information is available. For example, ‘Ocean boundary’ can be selected if the user only knows the approximate marine area, and then available ocean boundary maps such as Exclusive Economic Zone (EEZ), Marsden Square and Large Marine Ecosystems (LME) can be used to determine coordinates. If there is a corresponding infrastructure or other spatial category in the map, firstly the coordinates are extracted, and then a matched address is obtained by the reverse geocoding using the coordinates in the same manner as for the ‘Geographic coordinates’ option.

If an accident record is added, modified or deleted using the ‘Add Accident’, ‘Modify’ and ‘Delete’ buttons, respectively, the system automatically stores which record is affected, including date and time, user name and modified fields. All these changes can be viewed by clicking the ‘Data History’ button (Figure 10). The history shows the id of each table that has been changed, and also the specific fields and values. The user can also search the history by accident id, user id, name of table, date of change, and so on.

### 4.3. Analysis of user activity

Collecting and analysing users’ activity is essential for ENSAD v2.0 in terms of security as well as to improve the User Experience (UX) of the web application. Data security is an important factor, since ENSAD v2.0 partially includes licensed and/or sensitive data. A second aspect for the successful operation of the web application is the consideration of the actual UX, which is essential to attract new users and to ensure that users keep visiting the ENSAD v2.0 after registration.

For these reasons, ENSAD v2.0 has adopted the Matomo analytics platform. Figure 11 shows the user interface of Matomo. The overview page provides a general report on the number of page views, unique visitors, etc. (Figure 11(a)). The visitor log then includes a detailed analysis for individual users, e.g. IP address, ID, Country of the access,
type of browser, device, and the pages accessed (Figure 11(b)). Lastly, the event log (Figure 11(c)) displays the activities of the user with respect to which menus or buttons were clicked, and the duration and the frequency of the usage of each menu.

Figure 10. The history of data changes is tracked for each accident and its consequences information with relevant infrastructure information.

Figure 11. Interface of Matomo: the analytic platform tracks and monitors users’ activities.
It is also possible to analyse how users found the web application, i.e. through search engines or a web site that included a link redirecting to ENSAD v2.0. First, this information is valuable to customise the specific content of the web application such as title, metadata, keywords, etc. to ensure that ENSAD v2.0 is ranked on top in relevant web engine searches. Second, the analysis of user preferences concerning data and functionality of ENSAD v2.0 offers important insights to further improve the application. Finally, if a user tries to access or use functionality that does not conform to its role, then this is tracked and the account can be blocked if necessary.

5. ENSAD v2.0 case study: potential impact radius of gas pipeline explosion

ENSAD v2.0 accident data have already been used in a broad range of analyses and case study applications, which highlight its usefulness and versatility. Examples include Bayesian hierarchical modelling to assess the risk of dam accidents for hydropower and other purposes (Kalinina, Spada, & Burgherr, 2018), rough set analysis (Cinelli et al., 2017) and complex network analysis (Lustenberger et al., 2018) of accidents in the natural gas chain, and comparative risk assessment of hydrogen and selected fuel cells (Spada et al., 2018), among others. All these analyses rely on accident data specifically extracted from ENSAD v2.0, which subsequently were analysed using advanced statistical methods. However, in the remainder of this section a case study example is presented that has been implemented in the database, demonstrating the potential to add analytical features that can be directly applied by the users.

In order to fully use the spatial characteristics of ENSAD v2.0, the Potential Impact Radius (PIR) model for gas pipeline explosions was implemented. The PIR model was developed to determine the area potentially affected by a rupture of a natural gas pipeline (Stephens, 2000). This model considers two factors, namely the pressure and the diameter of a pipeline:

\[
r = 0.685 \sqrt{pd^2}
\]

where \( r \) = potential impact radius (ft);
\( p \) = pressure of pipeline (psi);
\( d \) = diameter (in).

IHS Markit data (IHS, 2018) was used to gain information on the pipeline’s diameter. As the operational pressure of natural gas pipelines can vary, a lower and upper operation pressures were introduced for each pipeline diameter according to literature (Stephens, 2000). With this information the PIR can be estimated once for the upper and once for the lower operation pressure. When a user in ENSAD v2.0 clicks on a gas pipeline on the map, the PIR of this location is automatically calculated and displayed as a circle around the selected pipeline (Figure 12). Additionally, the potential economic damage of assets and casualties are displayed with a StreetView around the area for the cases of maximum pressure and minimum pressure of the respective pipeline.

The potential economic damage and casualties (fatalities and injured) within the PIR are calculated using the Global Exposure Database (GED) that was developed for the global Assessment Report 2015 (GAR15)(De Bono & Chatenoux, 2015). The GED provides economic values of the exposed assets, and population estimates on a map with 5 × 5 km grid
Figure 12. Example of PIR analysis: two circles of PIR are drawn with minimum and maximum radius that is calculated based on minimum and maximum pressure of the pipeline respectively. StreetView displays the potential economic damage of assets and casualties for minimum PIR and maximum PIR.

Figure 13. Data processing of server-side: GED of 20 m size grid within PIR are extracted (green triangles).
size that covers the whole earth. The PIR of a pipeline rupture is usually not more than 1 km so that it was necessary to scale down the GED to 20 m spatial resolution. Therefore, the original values of the 5 km grid are distributed evenly over the 20 m grid cells. For instance, if the original 5 km grid cell has a value of 1000 USD (economic asset) and 1000 people (population), then each 20 m grid cell is assigned to a value of 0.016 since a 5 \times 5 \text{ km} grid cell contains 62,500 grid cells of 20 m. Figure 13 shows an example using the downscaled 20 m grid, and how the data are processed on the server-side. Based on the circle of the PIR the server (PostGIS) extracts from the GED those 20 m grid cells that are within the circle (indicated by green triangles), and then all grid cell values are summed up for the total economic damage and casualties for this location.

This case study is a first step towards the future implementation of dedicated analysis tools in ENSAD v2.0. The range of potential applications for this kind of tools in ENSAD v2.0 is large, and it includes all energy chains and infrastructure types as well as different types of accident consequences. For example, effects of refinery configuration and geographic location on outcome risk levels (Burgherr et al., 2018) or visualisation of spatial risk assessment of oil spills (Spada and Ferretti, 2018) are two cases currently considered for implementation.

6. Conclusions

The newly developed ENSAD v2.0 provides an interactive, GIS and web-based platform to manage, visualise and analyse the comprehensive, worldwide database of energy accidents that has been compiled by PSI for more than two decades. It is based on state-of-the-art GIS, web and mobile technologies and cloud computing. The data migration from the current ENSAD v1.0 to the new ENSAD v2.0 was carried out in several distinct steps. First, the old database structure was reviewed and subsequently optimised to meet current user needs and to take advantage of available cutting-edge technologies. Second, the process of hybrid geocoding was designed to improve the efficiency of the data migration process. A geospatial architecture for ENSAD v2.0 was designed to run on both desktop and mobile devices with 2-D and 3-D maps. To ensure a simple and intuitive registration of new accident data, a registration wizard was developed, using several mapping APIs, such as Elevation API, Reverse Geocoding API, etc. The addition of an analytics platform allows analysing individual user characteristics, their use of the system, and to track and block potential malicious activities. Finally, a spatial analysis tool (Pipeline Impact Radius, PIR), was developed to demonstrate the analytical capabilities of ENSAD v2.0 by combining accident data with specific infrastructure and other information layers. It is important to note, that all these components and features work in a cloud-computing environment which is stable and easily scalable. Overall, ENSAD v2.0 is not just a database or web application, but rather an integrated platform that covers the whole process from data migration, through data registration to data visualisation and data analysis for complete energy chains at a global scale. Planned future developments of ENSAD v2.0 include adoption of a new data structure like NoSQL, native app versions for Android and iOS and implementation of a diverse set of geospatial analysis tools.
Acknowledgments

The research was conducted at the Future Resilient Systems (FRS) at the Singapore-ETH Centre (SEC), which was established collaboratively between ETH Zurich and Singapore’s National Research Foundation (FI 370074011) under its Campus for Research Excellence And Technological Enterprise (CREATE) programme.

Specific tasks of the work (e.g. conceptual design, preparation of ENSAD v1.0 data for data migration, update of dam and hydrogen accidents) have been carried out within the Swiss Competence Center for Energy Research (SCCER) Supply of Electricity (http://www.sccer-soe.ch) and the National Research Programme (NRP70) ‘Energy Turnaround’ of the Swiss National Science Foundation. Further information on the National Research Programme can be found at www.nrp70.ch.

The development of the ENSAD Visual Explorer (EVE) was a joint effort with the Collaborative Interactive Visualization and Analysis Laboratory (CIVAL) of the Future Cities Laboratory (FCL) in the Singapore-ETH-Center (SEC). We are particularly grateful to Shiho Asada, Dr. Wei Zeng, and Dr. Remo Burkhard.

Data availability statement

The data referred to in this paper is not publicly available at the current time. ENSAD v2.0 will be available in the second half of 2019 at the URL: www.ensad.ch

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Wansub Kim http://orcid.org/0000-0003-4921-0853
Peter Burgherr http://orcid.org/0000-0001-6150-5035
Matteo Spada http://orcid.org/0000-0001-9265-9491
Peter Lustenberger http://orcid.org/0000-0003-4055-5265

References

AcuGIS. (2018). AcuGIS. Retrieved from https://www.acugis.com/geoserver-hosting.htm
Amazon. (2018). AMAZON EC2. Retrieved from https://aws.amazon.com/solutions/global-solution-providers/esri/
ARIA. (2018). ARIA database. Retrieved from http://www.aria-database.com/
Boundless. (2018). Boundless SDK.
Burgherr, P., Cinelli, M., Spada, M., Blaszczyński, J., Słowiński, R., & Pannatier, Y. (2018) Risk assessment of worldwide refinery accidents using advanced classification methods: effects of refinery configuration and geographic location on outcome risk levels. In S. Haugen, A. Barros, C. van Gulijk, T. Kongsvik & J. E. Vinnem (Eds.), Safety and Reliability – Safe Societies in a Changing World. London, UK: CRC Press, Taylor & Francis Group.
Burgherr, P., Eckle, P., & Hirschberg, S. (2012). Comparative assessment of severe accident risks in the coal, oil and natural gas chains. Reliability Engineering & System Safety, 105, 97–103.
Burgherr, P., Giroux, J., & Spada, M. (2015). Accidents in the energy sector and energy infrastructure attacks in the context of energy security. European Journal of Risk Regulation, 6, 271–283. doi:10.1017/S1867299X00004578
Burgherr, P., & Hirschberg, S. (2014). Comparative risk assessment of severe accidents in the energy sector. Energy Policy, 74, 545–556.
Burgherr, P., Hirschberg, S., & Spada, M. (2013). Comparative assessment of accident risks in the energy sector. In R. M. Kovacevic, G. C. Pflug & M. T. Vespucci (Eds.), Handbook of Risk Management in Energy Production and Trading. International series in Operations Research & Management Science (Vol. 199). New York, NY: Springer Science+Business Media. doi:10.1007/978-1-4614-9035-7_18

Burgherr, P. M., Kalinina, S. A., Hirschberg, S., Kim, W., Gasser, P., & Lustenberger, P. (2017). The Energy-Related Severe Accident Database (ENSAD) for comparative risk assessment of accidents in the energy sector. European Safety and Reliability of Complex Engineered Systems, ESREL 2017. Portoroz, Slovenia.

CesiumJS. (2018). Cesium.js. Retrieved from https://cesiumjs.org

Cinelli, M., Spada, M., Miebs, G., Kadziński, M., & Burgherr, P. (2017, December 14–16). Classification models for the risk assessment of energy accidents in the natural gas sector. The 2nd International workshop on Modelling of Physical, Economic and Social Systems for Resilience Assessment, Ispra, Italy, 120. Publications Office of the European Union.

Coaffee, J. (2008). Risk, resilience, and environmentally sustainable cities. Energy Policy, 36(12), 4633–4638.

De Bono, A., & Chatenoux, B. (2015). A global exposure model for GAR 2015. UNEP-GRID, GAR.

Docker. (2018). Docker platform. Retrieved from https://www.docker.com/

ESRI. (2018a). ArcGIS. Retrieved from https://www.arcgis.com/features/index.html

ESRI. (2018b). ArcMap. Retrieved from http://desktop.arcgis.com/en/arcmap/

FACTS. (2018). Failure and accidents technical information system. Retrieved from http://www.factsongline.nl/

FRS. (2018). Future Resilient System. Retrieved from http://www.frs.ethz.ch/

GeoServer. (2018). GeoServer. Retrieved from http://geoserver.org/

Google. (2018a). Google Analytics. Retrieved from https://analytics.google.com

Google. (2018b). Google reCAPTCHA. Retrieved from https://www.google.com/recaptcha/

Hirschberg, S., Bauer, C., Burgherr, P., Cazzoli, E., Heck, T., Spada, M., & Treyer, K. (2016). Health effects of technologies for power generation: Contributions from normal operation, severe accidents and terrorist threat. Reliability Engineering & System Safety, 145, 373–387.

Hirschberg, S., Spiekerman, G., & Dones, R. (1998). Severe accidents in the energy sector. Villigen: Paul Scherrer Institut.

IHS. (2018). IHS markit midstream essentials EDIN 2018.

JRC. (2018). Major accident reporting system. European Commission - Joint Reseach Centre. Retrieved from https://ec.europa.eu/jrc/en/scientific-tool/major-accident-reporting-system

Kalinina, A., Spada, M., & Burgherr, P. (2018). Application of a Bayesian hierarchical modeling for risk assessment of accidents at hydropower dams. Safety Science, 110, 164–177.

Kalinina, A., Spada, M., Burgherr, P., Marelli, S., & Sudret, B. (2016, September 25–29). A Bayesian hierarchical modelling for hydropower risk assessment. Risk, Reliability and Safety: Innovating Theory and Practice: Proceedings of ESREL 2016, Glasgow, Scotland, 412.

Lustenberger, P., Kim, W., Schumacher, F., Spada, M., Burgherr, P., Hirschberg, S., & Stojadinović, B. (2018). Network analysis of the European natural gas infrastructure to identify potential bottlenecks. In S. Haugen, A. Barros, C. van Gulijk, T. Kongsvik & J. E. Vinnem (Eds.), Safety and Reliability – Safe Societies in a Changing World. London, UK: CRC Press, Taylor & Francis Group.

Matomo. (2018). Matomo. Retrieved from https://matomo.org/

PostGIS. (2018). PostGIS. Retrieved from http://postgis.net/

QGIS. (2018). QGIS. Retrieved from https://qgis.org/

RedHat. (2018). OpenShift. Retrieved from https://www.openshift.com/features/

Sovacool, B. K., Andersen, R., Sorensen, S., Sorensen, K., Tienda, V., Vainorius, A., … Frans, B.-T. (2016). Balancing safety with sustainability: Assessing the risk of accidents for modern low-carbon energy systems. Journal of Cleaner Production, 112, 3952–3965.

Spada, M., Burgherr, P., & Rouelle, P. B. (2018). Comparative risk assessment with focus on hydrogen and selected fuel cells: Application to Europe. International Journal of Hydrogen Energy, 43(19), 9470–9481.
Spada, M., & Ferretti, V. (2018). Toward the integration of uncertainty and probabilities in spatial multi-criteria risk analysis: An application to tanker oil spills. In S. Haugen, A. Barros, C. v. Gulijk, T. Kongsvik & J. Vinnem (Eds.), Safety and Reliability – Safe Societies in a Changing World. London, UK: CRC Press.

Stephens, M. J. (2000). A model for sizing high consequence areas associated with natural gas pipelines (C-FER Report 99068). Edmonton, Canada: C-FER Technologies.

WebFaction. (2018). WebFaction. Retrieved from https://www.webfaction.com/

WebGL. (2018). WebGL. Retrieved from https://developer.mozilla.org/en-US/docs/Web/API/WebGL_API

Zhang, Q., Cheng, L., & Boutaba, R. (2010). Cloud computing: State-of-the-art and research challenges. Journal of Internet Services and Applications, 1(1), 7–18.