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A Practical Three-Dimensional Tool for Real-Time Safety-Security Risk Assessment of Process Facilities

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Plants that process and store significant quantities of hazardous substances can become targets of malicious attacks, potentially leading to major accidents, e.g., fires, explosions, and toxic dispersions, which could also lead to domino effects toward neighbouring units. Despite the rising interest in the security of process facilities, current tools offer at most semi-quantitative evaluations based on simplifying assumptions. Moreover, intentional attacks escalate quickly, so they are not well represented using conventional risk tools. The aim of this work is to show the progress in the development of a tool for Integrated Safety-Security (ISS) risk assessment and related domino effects. The graphical interface of the tool is made by the 3D reconstruction of the plant. Real-time data are then associated with critical assets. The tool evaluates the probabilities and 3D consequences of accidents given real-time and/or user-input data, e.g. meteorological conditions; moreover, the performance of safety and security barriers is included in the evaluation. The tool allows for the real-time and 3D calculation of risk. In the present contribution, we provide an application of the tool to showcase its potentialities. We show how tracking real-time changes in process parameters is essential to map the risk of the areas surrounding the plant. Possible weaknesses can therefore be highlighted using this tool, which could guide technical response measures and investments to reduce the vulnerability of industrial installations.

1. Introduction

As technological systems grow more complex and interconnected, more advanced tools for risk estimation, communication, and management are required (Jones, 2019). Namely, real-time data acquisition and simulation align with the current European digitalization trend of automation in the framework of Industry 4.0 (Wahlster, 2012). In this context, process plants storing hazardous materials face unique challenges. Beyond internal process upsets, these facilities are increasingly exposed to external events, such as intentional attacks, which introduce complex dynamics that conventional risk analysis tools often fall short in capturing. Additionally, these events could escalate and propagate among neighbouring units, generating the so-called domino effects. Consequently, understanding the real-time dynamic evolution of external attacks is essential to protect people, assets, and the environment.
Several works have dealt with dynamic and real-time analyses of conventional process safety. Among those, Vairo et al. (2022) developed a predictive decision-making tool based on Deep Neural Networks and Hierarchical Bayesian Networks to assess indicators of the overall safety level for process plants. Lee et al. (2019) developed a dynamic risk approach by combining the concepts of Systems Engineering and Digital Twins. However, there are no works focusing on developing a tool to comprehensively evaluate safety and security risks. Thus, the LIFE20 ENV/IT/000436 LIFE SECURDOMINO project aims at addressing the challenges that come with the Integration of Safety and Security (ISS) through the development of a tool for Three-Dimensional (3D), Real-Time (RT) risk assessment.
This work deals with the developed methodology to design and operate the tool, which is presented in Section 2. The 3D reconstruction of the plant serves as the graphical interface of the tool, which has different features.

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Firstly, the tool quantitatively evaluates 3D-RT-ISS scenarios and associated risks. Additionally, the tool is designed to efficiently store process documentation, administration, and logistics in order to ensure a comprehensive management of an industrial facility. An application of the tool to a case study is presented in Sections 3 and 4, while Section 5 discusses the results and future perspectives.

2. Methodology

The methodology for real-time 3D mapping is the result of an interdisciplinary effort bridging expertise in chemical engineering, computer science, visual design, and the humanities. Originally developed in a previous work (Marroni et al., 2023), it consists of five steps, which are hereby recalled:

1. Preparatory phase: plant documentation is gathered and analysed to determine critical assets to map in the tool;
2. Plant inspection: drone photogrammetry is used to survey the plant;
3. Development of the graphical interface of the tool: three-dimensional reconstruction of the plant and coupling critical assets with information and real-time data;
4. Implementation of real-time evaluation of consequences and risks of an accidental or intentional release.

Each step is discussed in the following sub-sections.

2.1 Preparatory phase (Step 1)

The preparatory phase aims to understand how the facility under analysis works. Hence, data on the facility should be collected; the collaboration of the tool-development team with the staff of the plant, e.g., process engineers and plant managers, is essential for optimal execution of this phase. For the sake of clarity, the documentation to be retrieved has been grouped into three categories: plant technical documentation, plant security documents, and context analysis. Plant technical documentation includes but is not limited to: Piping and Instrumentation Diagrams, Process Flow Diagrams, heat and material balance, plant layout, control systems logic, safety barriers, emergency plans, manning levels, hazardous substances inventory, and safety datasheets. Then, plant security documents should be available. They include a list of all security measures, a map of their placement, and information on the response times and location of the emergency team. Additionally, reports on compliance with security legislation should be supplied if they exist. Lastly, the socio-economic and political analysis of the context where the plant operates should be conducted. The documentation retrieved supports the screening of the critical assets to be analysed. In this work, a chart-based screening methodology is used. More specifically, five levels of criticality, ranging from 0 (lowest) to 5 (highest), can be assigned by intersecting on a reference chart the type of equipment with the physical state of its inventory. This score considers both the inherent hazard posed by the asset and its visibility, which reflects how attractive the asset might be to potential attackers. Full details on the chart are available in (Marroni et al., 2023).

2.2 Plant inspection (Step 2)

After the completion of the preparatory phase, the team inspects the plant by flying a drone. The pilot must obtain all required permits and licenses, as drone flight is subject to restrictions according to the flight zone. The tool-development team is then admitted to plant grounds, escorted by plant staff. The drone is flown above the plant, capturing photos and videos. The images contain information on the latitude, longitude, elevation, and inclinations, which are used in Step 3 to create the graphical interface of the tool (see Section 2.3). Extra attention is dedicated to capturing all relevant details on the critical assets identified in the preparatory phase of the methodology. For indoor areas, such as warehouses, a camera is used instead of the drone. The camera is also used to shoot in the outdoors to capture distinctive graphical elements, such as patterns and textures.

2.3 Development of the graphical interface of the tool (Step 3)

The graphical interface of the tool is constituted by the 3D reconstruction of the analysed plant. It is obtained by processing the information from the images obtained in Step 2 of the methodology using Agisoft Metashape. This tool, developed by Agisoft LLC, uses aerial photogrammetry to create 3D models (Agisoft, 2024). This technique exploits photographs taken from different angles to extrapolate data and recreate 3D models of environments; this technique is adopted in many fields by different actors, like tech giant Google (Google, 2019). Once the reconstruction is complete, post-processing techniques are applied to improve the visual aspects of the tool's interface; specific sub-models for equipment are created by the computer science and visual design experts of the team. An example of the graphical enhancement is shown in Figure 1a: the right side of the picture shows the photogrammetry model, while the left side shows the manually enhanced model. Once the interface is complete, data are associated with critical assets and barriers, which are clickable and interactive. Technical details, sketches, and documentation for assets are stored in dedicated tabs for easy retrieval during third-party inspections.

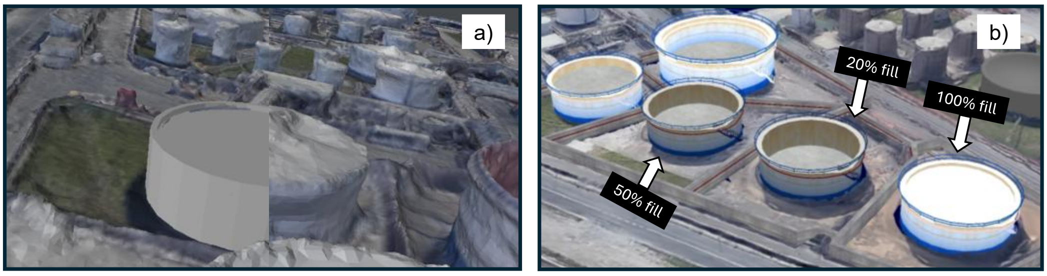

Figure 1: a) Comparison between the photogrammetry model (right) and manually enhanced model (left); b) graphical representation of real-time data (filling level) of an atmospheric floating roof tank in 3D interface.

The tool is also equipped to store and process RT data. RT data include meteorological data, which can be obtained through a weather station; of particular interest for 3D-RT ISS risk assessment are wind speed, wind direction, relative humidity, and ambient temperature. Moreover, process parameters can also be stored, such as storage temperature, pressure, and level. The graphical models in the interface of the tool dynamically represent the variations of these parameters. For instance, as the liquid level changes, the height of the floating roof inside the tank adjusts accordingly, as illustrated in Figure 2b.

2.4 Implementation of three-dimensional real-time consequences and risks (Step 4)

The final step of the methodology is the development of ISS algorithms. The tool operates in two different modes, a 'default' and a 'custom' mode. The default mode does not allow the change of significant ISS parameters and is hence intended for less experienced users. For example, release diameters from American Petroleum Institute (2008) have been adopted for safety releases and adapted to intentional releases. Conversely, more experienced users can use the custom mode to change the parameters. If available, the tool processes real-time weather data; if no RT data are available, then default 2F and 5D conditions are used, in accordance with conventional safety analyses. The frequency f_{FO} of final outcomes is evaluated using the Event Tree Analysis (ETA). Namely, the methodology developed by Landucci et al. (2017) was used to integrate the performance of security barriers with the ETA conventionally used in safety analyses as also exemplified by Casson Moreno et al. (2022). More specifically, the synergistic performance of safety and security barriers is obtained using specific decisional gates, tailored to different functions and working principles. More details can be found by the Reader in previously mentioned references. The modelling of physical effects follows a practicality principle. Namely, this tool should be able to support emergency operations after a major accident. For this reason, it was necessary to find an optimal compromise between accuracy and computational time. For example, point and multi-point sources were used for flame modelling.

Table 1: Compatibility matrix used for risk assessment, adapted from Laurent et al. (2021); LFL = Lower Flammability Limits, LC50 = Lethal Concentration for 50% of exposed population (30 minutes), IDLH = Immediately Dangerous to Life or Health

Impact zones →	High lethality	Starting lethality	Irreversible injuries	Reversible injuries
Pool/jet fire [kW/m^2] →	12.5	7	5	3
Fireball [kJ/m^2] →	Fireball radius	350	200	125
Flash-fire →	LFL	½ LFL	-	-
Overpressure [mbar] →	200	140	70	30
Toxic dispersion →	LC50	-	IDLH	-
Frequency f_{FO} ↓				
$f_{FO} < 10^{-6}$	DEF	CDEF	BCDEF	ABCDEF
$10^{-6} < f_{FO} \leq 10^{-4}$	EF	DEF	CDEF	BCDEF
$10^{-4} < f_{FO} \leq 10^{-3}$	F	EF	DEF	CDEF
$f_{FO} > 10^{-3}$	F	F	EF	DEF

The tool displays the final results as risk and vulnerability contours, depending on the users' choice. The Italian compatibility matrix for land-use planning is used in this work for risk assessment, and it is shown in Table 1. A territorial category (ranging from A, densely populated to F, industrial grounds) is assigned to each combination of frequency and impact zone; the Reader is referred to (Laurent et al., 2021) for more details. As this risk representation is scenario-based, tool users can browse through different scenarios coming from the ETA analysis. On the other hand, the overall vulnerability is obtained through the cumulation of all probabilities of attack success in the ETA, thus allowing users to visualize which areas of the plant are less protected from an intentional attack. More details on barriers, physical models for consequences, risk, and vulnerability contours are available in the open repository of the project (Securdomino, 2024).

3. Case study

To demonstrate the tool's functionality, the methodology was applied to a petroleum depot, shown in Figure 2. The depot has been active for 70 years and is located in a mild socio-economic and political context. The plant stores petroleum products (gasoline, diesel fuel, jet fuel) in floating and fixed-roof tanks.

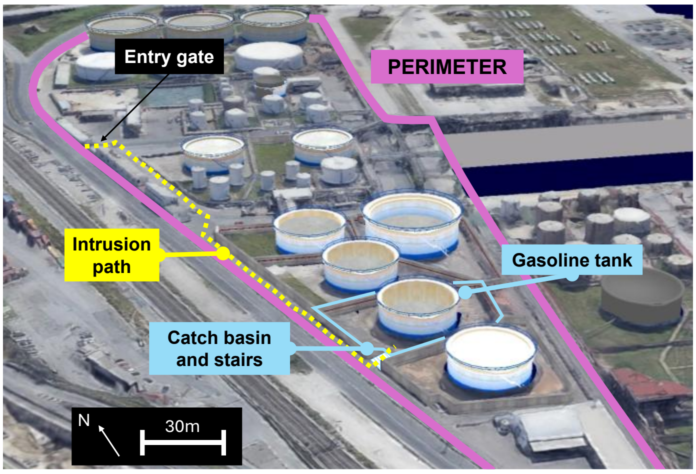

Figure 2: Layout of the analysed facility, and intrusion path (dotted line)

Figure 2 also shows an example of an attack path: an attacker passes the entry control gate during the day, runs to the gasoline tank (capacity: 8000 m³), which is 50% filled, and detonates 10 kg of TATP (Triacetone triperoxide, an improvised explosive device) inside the catch basin. The gasoline tank is protected by a sprinkler system. If the attack is successful, a simplified case of a catastrophic release with immediate ignition is considered, leading to a pool fire.

4. Results

The results of the ETA analysis are shown in Figure 3. The frequency of the attack scenario was assumed to be once in the lifetime of the facility, i.e., 1.43E-02 1/y.

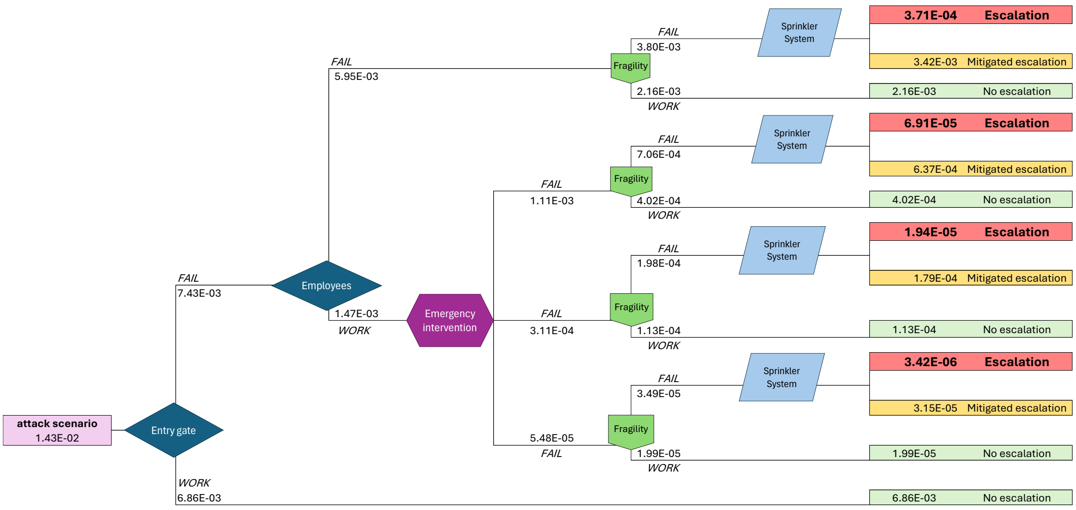

Figure 3: Results of the ETA analysis implemented in the tool.

The attacker could be either detected at the entry gate or by employees (dark blue gates in Figure 3). The fragility of the equipment, i.e., its physical resistance to the attack mode, is represented by the green gate, while the light blue gate is the sprinkler system. The emergency team is represented by the purple gate: in this case, the attacker is quicker than the emergency response in performing the attack, hence it cannot be neutralized. The full probabilistic model is detailed in (Casson Moreno et al., 2022), to which the Reader is referred to for more details. The final scenarios can be divided into three types: Escalation takes place if the equipment is damaged and safety barriers fail, represented by red branches in Figure 3; a mitigated escalation takes place if equipment fails but the safety barriers are effective (yellow branches in Figure 3); finally, no escalation takes place if either the attacker is detected or the equipment resists the overpressure generated by the explosive (green branches in Figure 3).
In the following, we will focus on the escalation scenario: the cumulated frequency of the pool fire from the escalation is f_{FO} = 4.63E-04 1/y, which is obtained by summing all the red branches in Figure 3. The pool fire model detailed in (Securdomino, 2024) is then used to assess the physical effects. Gasoline has been simulated as n-hexane, and the presence of the catch basin was considered by modelling a confined pool in case the liquid reaches the catch basin walls. Two different meteorological conditions in the time-span January-November 2024 are investigated: i) case A using the average wind speed and most frequent (0.72 m/s @ 10 m coming from east), and ii) case B with the maximum wind speed and its associated direction (2.90 m/s @ 10 m coming from west). Figure 4 shows the obtained risk contours.

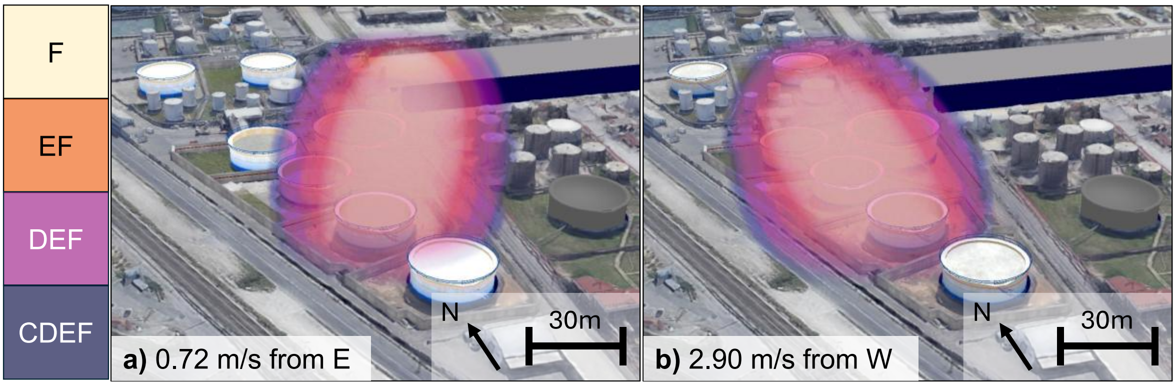

Figure 4: Risk contours in different meteorological conditions in: a) average and b) maximum wind conditions; for territorial categories, see (Laurent et al., 2021)

For both cases, the territorial compatibility is respected. Namely, the plant is located in an industrial landscape and risk contours slightly impact the road only in case of higher wind speed (Figure 4b). This is also due to the fact that the real-time amount of substance in the tank is considered, which is lower than the full capacity (50%). However, the potential targets impinged in the pool fire change. If only the average wind speed and direction are considered, no other tank is involved in the fire (Figure 4a); instead, the neighbouring tank is impacted in the case of maximum wind speed and associated direction (Figure 4b).

5. Discussion and future perspectives

The results in Section 4 showed how 3D-RT data influences plant risks. Even for a simple scenario, such as a pool fire, the risk contours change to a noticeable degree. Wind speed and direction play a critical role, as they determine how the flame tilts and which targets are affected. For instance, targets at certain heights may either be impinged or not, depending on the wind conditions. Additionally, wind direction dictates where the flame is tilted, impacting the specific areas at risk. While these physical effects are well understood, conventional risk analyses often overlook them by using only two representative wind speeds (2 m/s and 5 m/s) and assuming equal probabilities for all wind directions. This can lead to overestimating or underestimating risks for certain targets. Incorporating 3D-RT data provides a clearer view of risk distribution. This enhanced risk representation has multiple practical applications. It can assist in daily plant operations by increasing staff awareness of localized risks. It also has value for employee training, offering a straightforward tool to visualize plant documentation and better understand ISS scenarios. Furthermore, the tool's computational efficiency allows first responders to quickly simulate specific scenarios in emergency situations using the "custom" mode described in Section 2.4. Despite these advantages, some improvements are still required. Firstly, the influence of other RT-3D parameters should be investigated, such as the equipment's physical conditions, including level, temperature, or pressure. Then, other risk metrics should be implemented. This is necessary because domino effect chains, while already implemented in the tool, are not efficiently represented using a compatibility matrix. On the other hand, the Local Specific Individual Risk (LSIR) would allow a combined view of all intentional and accidental scenarios, as well as their domino effects. Finally, a comprehensive investigation of the influence of 3D-RT-ISS parameters on the LSIR should be carried out, in order to identify the parameters most influential on the risks of the plant. This could support plant managers in better identifying technical response measures, thus reducing the overall vulnerability of the plant.

6. Conclusions

External attacks represent a new challenge for process plants treating hazardous substances. Among those, intentional attacks are especially critical: their dynamic nature makes the use of conventional risk tools difficult and inaccurate. Moreover, integrating intentional attack scenarios with conventional process upset is necessary for efficiently managing the overall safety of the plant. In this context, the LIFE20 ENV/IT/000436 LIFE SECURDOMINO project aims at developing a tool to visualize a three-dimensional, real-time, integrated safety and security (3D-RT-ISS) risk assessment. This work presents the methodology behind the tool, which was developed by our interdisciplinary team. The tool was applied to a case study to show its potentialities. The results highlight how real-time conditions of the plant allow for a more precise visualization of risk, which could be used in different settings, from employee training to emergency response. Moreover, the possibility of storing process documentation in the tool allows for an easier retrieval in case of third-party inspections. The tool will be improved by including other risk indexes, such as the LSIR, which allows a complete vision of all possible scenarios in the plant (including domino effect chains). We believe that the tool developed could help in understanding the nature of intentional attacks and boosting a more effective and integrated management of risks in process plants.

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