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Resilient Safer Approach to Cope the Oily Waste Generation in Industrial Facilities: Lessons Learned from Cuban Installations

David Javier Castro Rodríguez[a, *], Omar Gutiérrez Benítez[b], Jelvys Bermúdez Acosta[c], José Poma Rodríguez[b], Dayana Rabassa Rabassa[d], Orlando Viera Ribot[b], Enmanuel Casals Perez[b], Fulvia Chiampo[a], Alberto Godio[e], Micaela Demichela[a]

[a] Department of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy.
[b] Department of Eng. and Environ. Management, Centro de Estudios Ambientales de Cienfuegos, Ciudad Nuclear, Cuba.
[c] Greeng S.R.L., Cerro Porteño C/ Próceres de Mayo No. 1258, Asunción, Paraguay.
[d] Department.of Chemical Eng. and Metallurgical, Universidad de Sonora, Blvd. Luis Encinas J, Sonora, Mexico.
[e]Department of Environment, Land and Infrastructure Eng., Politecnico di Torino, Duca Degli Abruzzi 24,Torino, Italy
david.castro@polito.it

Nowadays, huge quantities of oily wastewater and oily solid wastes are associated with different industrial activities, which not only may harm the environment and human health but also a performance worsening of the installation. The goal of this study was to establish a resilient approach to cope with oily waste generation in industrial facilities. Several lessons learned from Cuban installations studied separately for ten years in the municipality of Cienfuegos were the cornerstone for the model definition. The approach included the development of a novel methodology to address integrated features of loss prevention in the operation of petroleum transport, storage, process, handling, and use. This methodology was designed and improved using the principle of convergence to integrate engineering procedures, standards, technical and management tools. The results from the methodology implementation generated a list of findings translated into industrial failures modes, that can impact both environment and human health. Then, a set of general and specific causes associated including the incidence of the natural events were deployed in different orders. The environmental monitoring around the plants offered a significant sample of points that allowed the spatial representation of how hydrocarbon pollution constitutes a complex network of permanent stress rooted in the territory of Cienfuegos. Moreover, a package of inherently safer solutions was generated as primary prevention, integrating the waste management hierarchy concept. At last, this iterative approach generated a research project to develop a bioremediation technique for the treatment of oily sludge from maintenance operations, which can be neither eliminated for the inherently safer solutions nor disposed to the environment. The lessons learned from Cuban installations enabled the conception of this resilient approach, which represents a framework to improve industrial safety performances contributing to the release reduction of oily waste. In addition, it represents a contribution to increasing the awareness of industrial vulnerabilities in the territorial resilience analysis.
Keywords: Inherently safer solutions, oily waste, industrial facilities, resilient approach, territorial resilience.

1. Introduction

It has generally accepted that industrial development has brought with it an increase in the amount of oil used. Due to this wide application of oil as an energy source for transportation, electricity generation, and heating (Bosco et al., 2019), huge quantities of oily wastewater and oily solid wastes are annually generated in numerous industrial installations involving petroleum oils and lubricants (Shahryar, 2017). This kind of pollutants not only represents harm to the environment and human health but also a performance worsening of the installations (Shahryar, 2017).

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Moreover, it is growing public concern about the large volume of toxic petroleum hydrocarbons that are inadvertently emitted into the environment. For instance, Johnston and Cushing (2020), have recognized the occurrence of acute exposures resulting from inadvertent industrial releases, including those triggered by natural events. With regret, despite several environmental regulations becoming more stringent and great care for operational safety, there is still the possibility of the uncontrolled release of petroleum products (Kaczorek, 2021). Substantially, the hydrocarbons pollution from industrial activities happened due to leakages, leaching, accidental spills, and improper behaviors in waste treatment and disposal (Bosco et al., 2019).

On the other hand, given the potential impacts that hydrocarbons pose on the environment and human health, it is necessary to adopt strategies to ensure safer processes (Mohammad et al. 2018). In good agreement with this statement, the efficacy of inherent safety design for shaping friendlier chemical processes has been demonstrated in simultaneously augmenting safety, health, and environmental performance for identifying more compelling process options (Xiaoming, 2021). Inherent safety interventions have been considered at the top of the hierarchy for process safety strategies and constitute a central direction for loss prevention in the process industry. In addition, inherent safety is based on the proactive concept of preventing hazardous processes aiming to unearth permanent solutions for loss prevention (Amyotte and Khan, 2021).

Although inherent safer designs refer to hazard avoidance from the planning phase, there remains a difficulty for existing plants. Indeed, absolute safeness is rare in the process industry because the risks linked to chemical process operations are most often than not inseparable from it (Amyotte et al., 2018), such as the release of hazardous (e.g., hydrocarbons pollution). Regarding this issue, Kletz and Amyottes (2010) stated that if the processes are already working, before hazard avoidance and risk reduction can be done, the current hazards need to be identified and understood. Hence, understanding hazards can be achieved through a risk-based approach including the application of tailored assessment tools. Furthermore, for existing plants, some layers of protection are frequently required to mitigate the risks which cannot be eliminated with primary prevention (Abedi and Shahriari, 2005). Therefore, the environmental protection options (Shahryar, 2017) offer a valid safer alternative as secondary prevention integrable in a systemic approach. This paper established a resilience safer approach to cope with the oily waste generation in industrial facilities.

2. Methodology

This section offers an overview of the industrial and maintenance installations which were selected as a multiple case study, including a brief description of the origin of the oily waste generation during their operations. Furthermore, a methodological description of the approach adopted, and its details are provided.

2.1 Case study

The case study corresponded to fifteen installations rooted in the territory of Cienfuegos province, Cuba. These facilities were studied indistinctly for approximately ten years. Firstly, a group of ten generation power plants was analyzed. Specifically, the generation of oil sludge and liquid oily waste in the generation power plants, come from the purification (centrifugation) of fuel, purges of storage tanks, accidental spills during the loading and oil transfer operations, breakdowns, handling of used oils, among other activities (Castro et al., 2021b). Secondly, four transport workshops were analyzed, three of them belonging to a local construction company and the other one to an electric enterprise. The function of the beforementioned workshops is to repair and maintenance the fleet of light and heavy equipment. These workshops offer to scrub and greasing services to the fleet, from which both liquid and solid oily waste were generated. Finally, a workshop whose function is to carry out the maintenance and repair of electrical transformers in the central region of the country was analyzed, the implications with oily residuals are wastewater and solid components and clothes smeared with dielectric oil.

2.2 Framework overview

Beforehand, the established approach was designed to prevent and mitigate oily waste release in industrial facilities. The basic design methodology was partly based on the general method for problem-solving. Later, the community resilience concepts as the ability to anticipate, recognize, adapt to, and learn from variations and disturbances that might cause harm to human beings and the environment, were incorporated as transversals stages in the methodology. In addition, a conception that combined risk and resilience approaches adjusted from Schauer et al., (2021) was used as a parallel process to consider both industrial and territorial contexts. There were introduced steps that considered the vulnerabilities in the territory according to Cozzani et al. (2014). In advance, some steps from the methodology described by Amyotte and Khan (2021) were considered to introduce the inherent safer design as primary prevention. Lastly, the environmental protection options were included as described by (Shahryar, 2017) as a layer that ensures secondary prevention. Figure 1 shows a flow chart with the architecture of the proposed resilient approach.

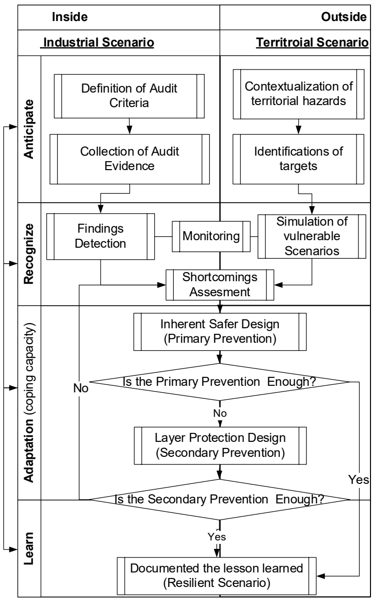

Figure 1: Flow chart of the resilient safer approach to cope with the oily waste generation in industrial facilities.

2.2.1 To anticipate

Firstly, this stage is related to the necessity that having proactive installations facing uncertainties disruptions as an asset. These disruptions could be associated with both industrial and territorial contexts. The environmental audit was included as a cornerstone to assess the unsafe situations associated with the oily waste generation within the industrial installations. In consequence, both the definition of the audit criteria and collection of audit evidence were the steps developed during the anticipation stage focusing on the industrial scenario. These two steps were implemented identically as was previously described in Castro et al., (2021b).
On the other hand, according to Cozzani et al. (2014), the starting point for the territorial scenario was the assumption that data of all the primary territorial hazards and sources present in the layout of concern was available. Then, the next step consisted in the identification of the targets (safety-critical equipment or infrastructure), which may fail because of the natural event. According to the aim of this research and the climatic conditions of the territory under analysis, the scope of the study was limited to the contribution of the hydric factor and its storm drainage system interactions, on the generation and diffusion of oily runoff within the industrial contexts. For this purpose, the determination of the intensity of rainfall in the province of Cienfuegos was carried out as explained by Gutiérrez et al. (2019) while the considered elements to evaluate the storm drainage system are detailed in Gutiérrez et al. (2018).

2.2.2 To recognize

The second stage pretends to recognize dynamic complexity and the interdependencies between the inside and the outside of the system in question, which needs a function that monitors and assesses the impacts of all those events had. Within the industrial scenario, as for the previous stage, the audit findings were determined following the steps detailed in Castro et al. (2021a). Furthermore, likely scenarios of how the rainfall behavior interacted with the targets of the industrial drainage system were forecasted.
Moreover, an intermediate step within this stage, which integrates information from both the industrial and territorial context was the environmental monitoring around the installations. The monitoring was carried out quite similarly as reported in Castro et al. (2021b). The installations studied in this research offered a representative number of points from the complex industrial network rooted in Cienfuegos territory. This sample joined to some other major accidents (oil spills) reported in the territory, were addressed in the spatial modeling of vulnerabilities by hydrocarbons pollution in the territory. Finally, the Environmental Impact Assessment (EIA) as part of the shortcoming assessment was applied according to the criteria of Conesa (2010).

2.2.3 Adaptation

The third stage encompassed the different order strategies for prevention from a systemic perspective that integrates both industry and territory. As primary prevention, an engineering plan tailoring the criteria given in Eini et al. (2015) was developed. It consisted of a package of the following inherent safer solutions: i) reducing the generation of oily waste in the source (minimization of chemical inventory); ii) replacing inputs in the processes with less hazardous ones or eliminating them as far as reasonably possible (substitution), iii) conducting processes under safer conditions (attenuation); iv) designing simplified processes for the reduction of human errors (simplification). Moreover, the environmental protection options such as waste-management hierarchy plans (cleaner productions, and circular economy principles as reuse and recycling), the improvement of waste management practices, the certification of disposal processes, and the employee training, were included as secondary prevention.

2.2.4 Learnt

Finally, the fourth stage allows the system to learn from the experience as a continuous planned process focused on the system functions and location, the links between causal analysis in the findings, and their interdependencies with vulnerable scenarios including industrial and territorial contexts. Moreover, a systematization of how the system absorbs and reacts from the beforementioned scenarios to a safer performance throughout the resilient approach implementation was summarized in a group of lessons learned.

3. Results

In this section some results from the implementation of the previously described framework on the multiple study cases are presented. Table 1 summarized the frequency of findings between evidence collected and established audit criteria in the industrial context in each generic industrial facility.

Table 1: Frequency analysis of findings studied industrial facilities.

Industrial facilities	Findings Frequency	Industrial facilities	Findings Frequency	Industrial facilities	Findings Frequency
Power Plant 1	24	Power Plant 6	23	Transport workshop 1	73
Power Plant 2	30	Power Plant 7	31	Transport workshop 2	32
Power Plant 3	26	Power Plant 8	17	Transport workshop 3	24
Power Plant 4	27	Power Plant 9	95	Transport workshop 4	36
Power Plant 5	23	Power Plant 10	58	Transformer workshop	33

More than 200 independent causes totaling all the industrial facilities analyzed, which were immediately deployed throughout the failures modes, and effects analysis obtained the most critical causes according to the risk priority number (RPN). The results are consistent with those reported in (Castro et al. 202a). Moreover, Figure 2 presents the results obtained for Transport workshop 4, as an example to illustrate the simulation of scenarios of rainfall interacting with different runoff sectors in the drainage system and the EIA.

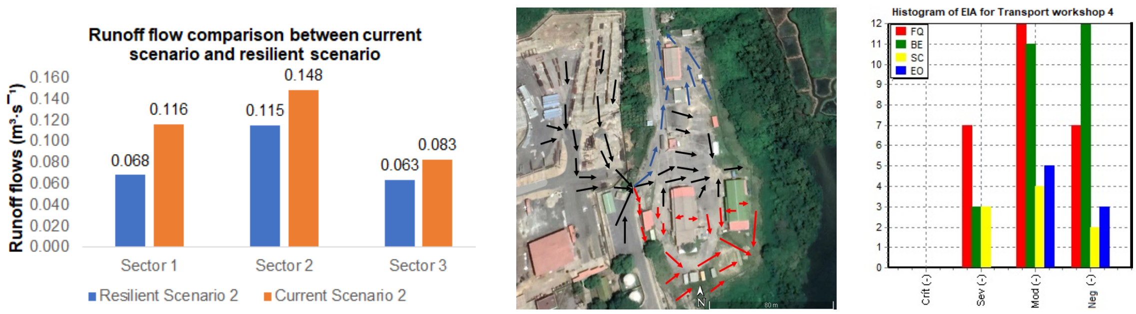

Figure 2: Some results corresponding to Transport workshop 4. a) Simulation of rainfall scenarios. Flows estimations in the defined runoff sectors (1, 2, 3) before and after measures. b) Representation of the directions of runoff surface for main runoff sectors (sector 1, sector 2, sector 3 corresponds arrows in red, in black, and in blue respectively). c) Histogram of EIA.

The estimation of rainfall intensity (Figure 2a, red bars) and its behavior in the plant surface (Figure 2b) have enabled the understanding of how this factor, in interaction with the previously aborded failure modes, has historically increased the contaminant load for the wastewater treatment system or acted as a mechanism of diffusion of oily wastes. Moreover, Figure 2c presents how there were environmental impacts on the physical-chemical (FQ), biological-ecological (BE), socio-cultural (SC), and economic-operational (EO) dimensions negatively evaluated as moderate and severe. The most relevant impacted factors were marine waters, soil contamination, the health of workers, and the internal image. Figure 3 plotted the concentrations of total petroleum hydrocarbons (TPH) obtained from the monitoring program carried out around all the facilities.

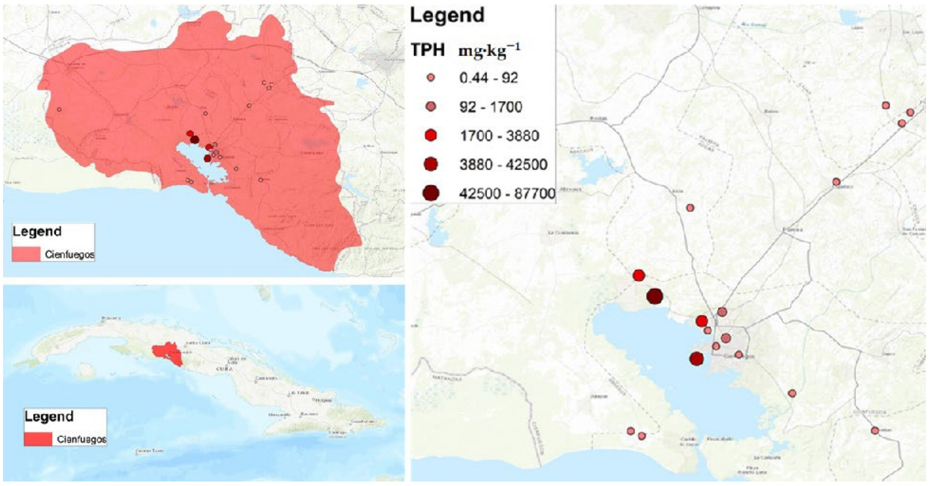

Figure 3: Concentrations of TPH in the environment surrounding industrial facilities of Cienfuegos, Cuba.

As can be appreciated, the density of points represented how a complex network of points rooted in the territory is conformed, principally in the northeast of the bay, where the urban life and economical activities are developed.

More than 400 measures were proposed totaling all individual industrial facilities. These intervention packages were comprised by organizational solutions and inherent safer solutions and have constituted a guideline for the industrial stakeholders. For illustrative purposes, as an example of primary prevention, to reduce the increment of liquid oily waste, a group of hydraulic measures was implemented to reduce the flow of water that arrives to the three runoff sectors represented in the Figure 2b. Consequently, a significant water flow rate was avoided (see Figure 2a blue bars), in line with the results described by Gutiérrez et al. (2019). Additionally, part of this water was recovered and reused for industrial purposes.

On the other hand, as an example of the use of secondary prevention, applying the hierarchy of waste treatment, the oils used or recovered during the different processes, were proposed as fuel to be burned in the furnace of a cement company in the territory. The proposal was based on the Cuban national policy of import substitution related to the inputs of the industrial energy matrix. In parallel, a research project to develop a bioremediation technique for the treatment of oily sludge was generated. This project has developed a resilient technique for the degradation of solid oily waste in situ. It consists of the evaluation of different treatments of biopile ecotechnology, supplementing different renewable industrial organic or agricultural wastes from the local industry. The project have been developed in the period 2017-2021 and was composed of the following five phases: i) Quality Function Deployment to determine the conceptual configuration of the specific experimental units of biopile ecotechnology at bench scale; ii) Evaluation of soil petroleum biodegradation using local and different treatments with heterogenic organic wastes in the biopile ecotechnology; iii) Evaluation of the operating variables optimal range in the selected treatment as the best candidate for the bioremediation of petroleum wastes; iv) Establish a prototype of biopile with the selected and optimized treatment (scale-up); v) Technical, economical, and environmental evaluation for the final substratum disposal and reuse. These phases have been disseminated in previous and further research.

The implementation results of the stages anticipate, recognize, and adaptation have allowed to iteratively learn several lessons. The first lesson was that the system should be firstly studied by the physical area, then stratified by functional targets and after that analyzed each target downstream the process. This structured sequence allowed the determination of the findings simplifying the complexity of the system.

The second lesson was that a set of common causes with a higher RPN were identified in all the facilities. They could be clustered in the following principal categories: i) the wastewater system design requirements; ii) technical status; iii) functional performance; iv) the operating conditions; v) maintenance factors; vi) bad practices of operation. The third lesson consisted in the importance of incorporating the factors of the natural events which can influence the sensitive elements of the infrastructure. Moreover, the increasing of the territorial vulnerability taken into account each singular industrial contribution constituted the fourth lesson learned. The fifth lesson was that primary and secondary prevention not only contribute to the system adaptation but also add value to both the industry and the territory, throughout the application of the circular economy concept and the preservation of resources. Finally, the sixth lesson was the convenience of developing an in-situ bioremediation technique for the treatment of the oily sludges, which can be neither eliminated for the inherently safer solutions nor disposed to the environment because of its hazardous properties.

Conclusions

A resilient safer approach to cope with the oily waste generation in industrial facilities was established and systematically updated for ten years throughout the state-of-the-art and the lesson learned during its implementation in industrial installations from Cienfuegos Territory, Cuba. This framework has ensured to the fifteen industrial installations studied to path from a vulnerable scenario to a resilient one, focusing on oily waste generation. Further research would be testing the effectiveness of this framework implementation considering other industrial risks factors and integrating multi-hazards belonging to diverse natural conditions.

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