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Evaluating the safety operations procedures of an LPG storage and distribution plant with STAMP

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Abstract

System thinking concepts and simulation tools are used to model the risk prevention plan and operational modes designed to enforce safety constraints at a French liquefied petroleum gas (LPG) storage and distribution facility. In France, such facilities are classified and the subject of special legislation and safety regulations. Their supervision is the responsibility of a control and regulatory body. A technological risk and prevention plan is provided, where all the dangerous phenomena likely to occur in addition to the safety control measures are listed in the safety report. Safety is therefore addressed through rules, and control mechanisms ensure that the system complies with safety constraints. Taking this facility as a case study, we use the STAMP theoretical framework together with AnyLogic simulation software to model technical elements and human and organizational behavior. We simulate how the system evolves over time and the strategies that are deployed in a loss of control scenario. The aim is to assess whether the prescribed safety program covers all of the system's phases; namely operations and audits. The results enrich other research that focuses on the contribution of system dynamics to risk analysis and accident prevention.

Peer-review under responsibility of the organizing committee of STAMP EU 2015

Keywords: LPG; STAMP; AnyLogic; Safety;

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1. Introduction

Industrial facilities are classified according to the hazard or nuisance that may result from their activities. These classifications are regularly reviewed and updated. The Seveso disaster that occurred in Italy in 1976 was a determining factor that pushed European states to adopt a common policy for the prevention of major industrial risks and accidents. Subsequently, the sector noticed multiple international agreements, directives, standard procedures and regulations for the protection of the environment and human health. Since 1982, the Seveso Directive has provided the framework for European legislation that aims to prevent major on-shore accidents involving dangerous substances, and limit their harmful consequences for humankind and the environment. "Seveso establishments" are subject to inspections by regulatory and control authorities. European member states have adopted the Seveso guidelines into their laws, regulations and decrees at national level, and regulated facilities are classified into various tiers. The French regime is consistent with the Seveso directives and requirements [1].

Classified installations (*Installation Classée Pour la Protection de l'Environnement*) are subject to environmental protection monitoring, and authorization to operate is given subject to a demonstration of public utility (*autorisation avec servitude d'utilité publique*). Installations such as refineries, chemical facilities and liquid petroleum gas (LPG) storage sites are 'upper tier' the Seveso establishments, and safety studies are mandatory. These high-risk installations fall under the remit of the French law on the Prevention of Technological and Natural Risks and Compensation [2] that provides for the preparation of a Technological Risks Prevention Plan (TRPP). The main objective of a TRPP is to protect the neighboring population against any technological hazards resulting from the plant. By law, it must comprise a zoning plan that delineates regulated areas, the regulations to be applied to each area, and a report that explains the zoning and any controls to be enforced. This paper presents a case study of an LPG storage plant in France. The approach is based on the System-Theoretic Accident Model and Processes (STAMP) model that is integrated into the simulation tool AnyLogic. The tool is used to dynamically simulate control actions and directives prescribed in the official safety report intended to secure routine operations and activities.

1.1. Accidents related to LPG exploitation

The principal hazards are directly related to the presence of LPG, which is extremely flammable. LPG is stored in liquid form at ambient temperature and in pressurized reservoirs. Daily activities associated with LPG storage concern loading and unloading from mobile rail and road tanks and its transportation through pipelines [3].

The flammable - explosive range refers to the concentration of a gas or vapor that will burn or explode if an ignition source is introduced. The lower percentage for LPG is 2.4% (i.e. 47.3 g/m^3 concentration) and while the upper limit is 9.3% (187 g/m^3 concentration). One of the most devastating accidents that can occur with LPG substances is the boiling liquid expanding vapor explosion (BLEVE), which creates a highly destructive blast wave. In most situations it is accompanied by a fireball, a toxic cloud of gas and debris [4]. The Major Accident Reporting System (eMARS) is a database of major industrial accidents and was established under the Seveso Directive 82/501/EEC in 1982. The purpose of the eMARS database is to share experience of accidents and near misses involving dangerous substances, in order to improve chemical accident prevention and mitigate potential consequences. Many authors have analyzed the contents of the MARS database in relation to major accidents, substances used in the petrochemical industry and LPG in particular [5, 6]. The analysis of 330 domino-effect accidents concluded that LPG was the most frequent culprit [6].

Similarly, the Analysis, Research and Information on Accidents (ARIA) database operated by the French Ministry of Ecology, Sustainable Development and Energy lists accidents that (could) have affected public health or safety, agriculture, nature or the environment. The principal cause of these events are industrial or agricultural facilities that have been classified as hazardous. A secondary cause is the transportation of hazardous substances, followed by other relevant events. Together, these databases list over 40,000 accidents and incidents, of which about 37,000 occurred in France. Accidents in other countries are included either because of the seriousness of their consequences, or their value in terms of feedback from experience. The ARIA database lists 512 accidents in France linked to LPG.

2. The case study

The case study focuses on an industrial LPG storage and distribution site in France, covering an area of 18,000 m^2. The site's main activity is to store LPG in an underground reservoir with a capacity of 400 m^3. LPG is supplied to the site by road or rail in tanks with a storage capacity of 20 tons, which are unloaded into the underground reservoir. The LPG in the reservoir is loaded into small 6–9 tons' tanks to supply households that are not connected to the national network. The site carries out 20 loading operations (i.e. LPG is loaded into small tanks) and 4–5 unloading operations per day (i.e. LPG is transferred from large tanks into the reservoir). The plant is a typical high-risk industrial installation; operational accidents may lead to dangerous situations (e.g., explosion, fire or clouds of toxic gas) whose consequences may extend beyond the site boundary. The local population may be adversely affected in three ways: first, clouds of toxic gas may be inhaled; second, the combustion of inflammable substances may burn people or destroy buildings; and third, an explosion may generate overpressures that injure the exposed population. In the next section we outline the databases of technological accidents at the Seveso establishments. Then we explain the legal context, and the sociotechnical system that is responsible for the operation and supervision of the plant. Finally, we provide a brief description of the facility and its technical equipment.

2.1. Legal and industrial context

In 2008, the installation and the operator's safety report was subject to inspection. As a result, the operator was instructed to implement additional mandatory risk control measures in order to protect the population and reduce the impact of an uncontrolled, harmful scenario. They were required to prepare a TRPP with the objectives of: limiting future urbanization around the site; strengthening the protection offered by the existing infrastructure; and limiting any harmful impacts. However, the company decided that the implementation of the prescribed measures was not cost effective and experts were tasked with finding exemptions that would avoid their application. The solution they found was to reclassify the site from the "AS" to the "A" regime. This meant that the authorized quantity of LPG held by the site was limited to 50–200 tons. In order to achieve this change in status, the company had to optimize LPG unloading by improving the management of trucks entering and leaving the site, based on a needs assessment. It also had to decrease the storage capacity of the reservoir. Calculations showed that a decrease in capacity, which would allow the company to change regime could be achieved without affecting activity levels (20 loads, 4–5 unloads/day). Given these real-life constraints, our models and simulations had to ensure that the level of activity did not change and that the amount of dangerous substances stored on-site did not exceed 200 tons. Our comprehensive model therefore included the elements and parameters found in a real-life risk prevention analysis (maintenance interventions, equipment use, wear and tear, etc.).

2.2. The sociotechnical control system

The sociotechnical control structure included the French Minister of the Environment, urban, industrial and environmental organizations, public health inspection and protection authorities, and regulatory bodies. More specifically, the actors involved in the application of the prescribed TRPP measures included: the French government through its local representative; specialist services represented by classified installation inspectors; the departmental directorate responsible for public works; local authorities represented by elected officials and technical services; the operator; the local coordination committee; and other local actors such as associations. In France, the Regional Directorate of Environment, Planning and Housing (DREAL) hold responsibility for ensuring that safety directives are enforced. Risks must be reduced at source, which involves identifying all dangerous phenomena and implementing all necessary safety measures. Emergency plans must be in place that protect and assist the population, and they must be tested on a regular basis to ensure their effectiveness. Information must be provided to the public on potential risks and the procedures to be followed in the event of an alert. Finally, measures such as strict controls on urban development around sites must be implemented.

2.3. The facility

This section describes the logistics and design of the LPG storage and distribution facility. The installation consists of an underground reservoir with a storage capacity of 400 m^3. It is supplied by tanks loaded onto trucks that access three, self-service stations supervised by an attendant. Two stations are dedicated to loading operations and each is equipped with an LPG transfer arm with a two inches' diameter. The third station handles both loading and unloading operations and is equipped with an LPG transfer arm and a gas transfer arm, both two inches in diameter.

LPG is transferred via two pumps each with a flow rate of 50 m^3/hour, and a compressor with a flow rate of 110 m^3/hour. The station is equipped with a second compressor designed for purging. The facility includes detectors coupled to an alarm, a protection system and dedicated firefighting systems. The site is also equipped with 26 gas, and 5 flame detectors distributed throughout the installation (Fig. 1.). Feedback from these detectors is processed by one or more centralized systems. Motorized valves are installed on the pipeline infrastructure and coupled to an interlock system that provides additional safety measures. This system consists of a deactivating pump and compressors, and valves automatically, which close when heat, gas or flames are detected.

In order to protect truck drivers, the station is equipped with a device that requires from the driver to press a button every 30 seconds, during the time allocated for loading (approximately 10–18 minutes) or unloading (approximately 19–29 minutes). If the operator does not press the button, an alarm sounds 15 seconds later and the LPG transfer operation stops. Loading or unloading can resume if the button is pressed again in the following the two minutes, otherwise steps are taken to ensure safety of human and infrastructure (the intervention plan is launched, power is automatically cut off, all valves are closed, pumps are stopped, etc.). Other alarms alert operators for malfunctioning of the central fire and gas detection system, unauthorized entry and activation of motorized firefighting pumps. The control room operator can manually shutdown the system in an emergency. All these alarms extend across the site. Power to the whole installation is cut off with the exception of devices needed to secure the perimeter, and valves on safety devices are automatically closed. In the event of a power shut down, the compressed air system is purged; this leads to the closure of valves on the reservoir filling the transfer lines and truck facility, while firefighting pumps are automatically activated.

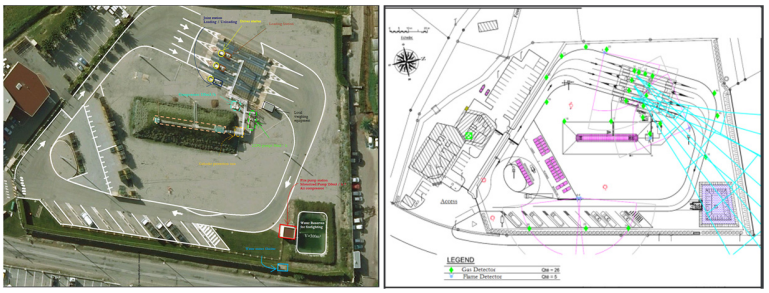

Fig. 1. Overviews of the LPG plant

3. The STAMP approach

In order to understand an accident process in a technological system, it is necessary to take into consideration the complexity of the underlying feedback structure. In highly complex sociotechnical systems such as those encountered in the petroleum industry, new types of safety issues and disastrous failure modes cannot be addressed within the traditional approach of accident analysis. Indeed, accident analysis cannot rely solely on the cause-effect approach, but must also take into account the safety control structure in addition to the enforcement of safety constraints in the system. STAMP is a model developed at the Complex Systems Research Laboratory of the Massachusetts Institute of Technology by Leveson [7, 8]. The basic concepts in STAMP are constraints, control loops, process models, and levels of control. The model has been applied to several studies in the oil and gas domain [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. The steps in STAMP are sequenced as follows:

- Identify risks and hazards at system-level.

- Enforce safety directives, measures and procedures to avoid threats.
- Model the static control structure to prevent or mitigate the threats.
- Assign constraints to the system components responsible for implementing those constraints.
- Define the control actions for the components that prevent or mitigate the threats and hazards.
- Capture the behavioral dynamics with System Dynamics Modeling.

3.1. STAMP applied to LPG distribution and storage facility

The case study began with an evaluation of the plant's safety report. We identified potential hazards, described the site's environment and its external boundaries, reviewed accidents and incidents, and made a preliminary risk assessment of potential accidents and associated hazards. We also highlighted hazards associated with the site's activities, and the preventive measures implemented to eliminate sources of risk related to LPG manipulation and the plant's operations. The purpose of these measures was to minimize the potential impact of an accident on property, people or the environment. The case study sought to evaluate the contribution of STAMP as a tool for the management of loading and unloading operations. We modeled a control structure for each of the system's actors involved in loading or unloading operations. The objective was to understand the interaction between system components and map structures related to the enforcement of safety directives.

Our aim was to understand the dynamic behavior of an agent over time by implementing a STAMP-based control-mapping model in a simulation tool. Control mapping in STAMP consists of representing control rules (i.e. safety constraints, directives and measures), and control actions that are continually adjusted as a result of feedback from the controlled process. To enforce a command, controllers rely on a process model that reflects the status of the controlled process, and a control algorithm. On-site, operators are trained to execute written procedures; however, the simulation tool made it possible to identify scenarios where the written guidance was inconsistent with recommended practice and safety directives. Operators perform sequences of tasks; in the simulation environment, feedback about the behavior of the system or a potential failure is provided following a control action.

The STAMP model simulated loading and unloading operations, and for each task, the operator received feedback on the system's status. For example, if they did not execute the command within the time allocated for the task, then the control sequence indicated that the process was not completed within the scheduled time. In the model, operators can optimize their performance over time to meet a variety of goals. As time pressure increases, they try to become more efficient and productive, and deviations from specified tasks or prescribed sequences of actions can occur. If the operator suspects that something has gone wrong during (un)loading operations, they try to diagnose it and determine the correct response. While performing a control action, human error can be viewed as a deviation from normal procedure or as a deviation from a rational and effective procedure given the workload and timing constraints for the tasks that must be performed. In the STAMP model, we assume that the controller is the truck driver who executes the LPG transfer process (Fig. 2).

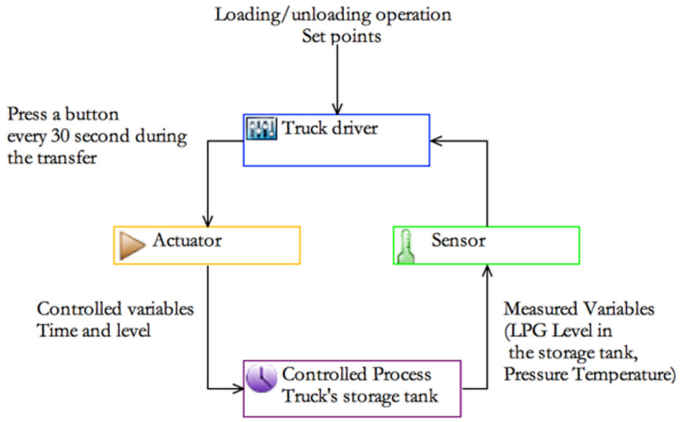

Fig. 2. Control structure

3.2. Control structure: a sensor installed on the underground reservoir

At the plant, LPG is stored in an underground reservoir and safety measures prevent any loss of containment. These safety measures are enforced by a sociotechnical control structure. In the case study, we modelled the level of LPG in the underground reservoir. Detectors are coupled with an alarm. Visual and audible alarms are triggered if levels fall below 7.5% and loading operations stop (i.e. pumps shut down and safety valves close). Similarly, visual and audible alarms are triggered if levels reach 10%, 84.5% or 89%. In the latter two cases, LPG transfer operations to fill the reservoir stop (i.e. compressors shut down and safety valves close). If the level of the reservoir reaches 94% a general alarm sounds that automatically activates safety devices across the site, notably the closure of safety valves (Fig. 3).

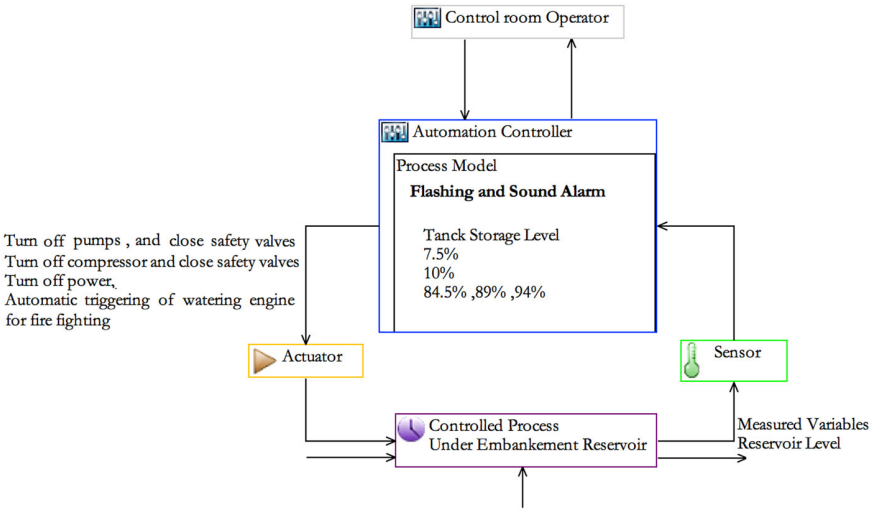

Fig. 3. Simulation of reservoir level detector

4. STAMP implementation in AnyLogic software

In this section, we present the integration of STAMP into the simulation tool. We assume that the controlled process is an LPG plant and that a human controller carries out control actions. Control actions consist of commands executed by the operator on the physical installation. AnyLogic software was used to simulate each sequence of control actions, while feedback allowed the operator to update the process model and control algorithm. This approach allowed us to understand the behavior of the system over time.

4.1. AnyLogic software

AnyLogic is a multi-method simulation–modelling tool developed by AnyLogic [9]. It includes a graphical modelling language and allows the user to extend simulation models using the Java programming language. The software implements various constructs: stock flow diagrams are provided for system dynamics modelling; state charts are mostly used in agent-based modelling to define agent behavior and in discrete event modelling (e.g. to simulate machine failure); action charts are used to define algorithms and in discrete event modelling; process flowcharts are the basic construct used to define processes in discrete event modelling. The language also includes low-level modelling constructs (variables, equations, parameters, events etc.), shapes (lines, polylines, ovals, etc.), analytic tools (datasets, histograms, plots, etc.), connectivity tools, standard images and experimental frameworks. Qian and Yahui [10] used the tool to evaluate an accident emergency pre-plan enforced after a gas pipeline leakage. Mercantini, Loschmann and Chouraqui [11] used the tool to simulate the execution of the emergency plan imposed on a chlorine stripping plant in Marseille, France. Feng, Chao and Hui [12] used the tool to model a gas emergency dispatch system in an urban environment.

In this case, the model simulated the behavior over time of a joint emergency command system for an urban gas emergency command center and other departments. The system provided communication, decision-making, command and emergency dispatch functions. It was capable of rapidly drawing up the most effective emergency plan, and was widely used in simulation exercises. We used a combination of STAMP and AnyLogic software to model, simulate the actions of operators at the site, and detect possible deviations. In the following example, the Discrete Event (DE) paradigm made it possible to simulate the movements of a truck that is stopped by an operator who carries out identification and control procedures. After these checks, the truck enters the site and reaches the LPG transfer station. Unloading was simulated for a 20-ton tank, while a loading operation was simulated for a 6–9 tons' tank.

4.2. Modelling and simulating operator control actions

A multi-method paradigm was used to model (un)loading operations. Three approaches, System Dynamics (SD), Agent Model (AM), and Discrete Event (DE) simulations represented the performance of operators over time. SD simulated LPG transfers to/from the reservoir and tanks. The AM simulation represented the driver's level of training and operational competence. This model also showed the availability of resources, tanks, attendants and (un)loading stations. The DE simulated the movements of mobile agents (i.e. drivers, trucks and attendants) and transfer procedures. The first simulated procedure was the identification of drivers and tanks at the site entrance, and the granting of an authorization to perform the transfer. This procedure takes 2–3 minutes and verifies the following points:

- The driver is allowed to operate and has followed the training related to safety and prevention of the risks inherent in handling LPG.
- The tank has been authorized and is compliant with the prescriptions of the European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) [13].
- The tank compliance with regulatory controls, and the condition of the vehicle are checked.
- The transaction has been authorized and quotas are respected.

If all of these points are validated, an (un)loading authorization is issued and the driver moves to the transfer station. Otherwise, the driver is directed to the exit. In terms of safety, it is crucial to check that what enters the system complies with standards and legislation. Nevertheless, this is not a sufficient condition to ensure that the transfer operation will be uneventful. Assuming that all of the above conditions have been met, the following scenarios can occur:

- If the driver is trained and experienced, they undertake the transfer operation themselves.
- If the driver is trained but inexperienced, the attendant supervises them.
- If the driver is untrained, the attendant undertakes the operation and the driver watches.

If the attendant is occupied or absent, an inexperienced driver may undertake the operation unaccompanied. This scenario corresponds to a loss of control over the system due to lack of resources. In practice, attendants are both agents and resources for drivers. This scenario as explained later in detail corresponds to a defect mode. The software tool models the system and its potential outputs. Depending on the outcome of the identification checks, attendants/resources and the transfer station are included, while other parameters (i.e. the probability of an error and the time the error is corrected) can vary.

The multi-agent system can differentiate drivers according to their level of training; the drivers can be linked to a system of discrete events that simulate the movements of trucks on the site. The link between the two paradigms is generated by an 'Identification' function allocated to attendants who are either agents or resources. The goal is to link the DE and AM simulations through a functional paradigm. The simulation assumes that a truck enters the site and waits at the stop sign. Four potential scenarios can follow: the driver operates alone, the attendant supervises the driver, the attendant operates alone, or the driver exits and no operation takes place. Consequently, the model redirects the driver, with or without the attendant, towards either the (un)loading station, or the exit. If the attendant is busy and cannot accompany the driver, the driver is able to access the transfer station alone. This represents a negative, loss of control scenario.

4.3. Model development

The solutions applied by the site were modelled by combining these three paradigms (SD, DE, MA). The site is the same in all scenarios, while a relay of tanks is (un)loaded.

Simulation of the LPG transfer procedure

The transfer procedure specifies the tasks that must be carried out under the supervision of the attendant. The following loading procedure must be respected: calibrate the vehicle; verify the position of valves; ensure that the surge control system is ready; connect the truck to a grounding device in order to prevent the risk of electric shock, and wait for a visual confirmation that the connection is established; connect a device that controls levels in the tank; connect the safety device that couples the truck to the facility; connect the nozzle to the fluid fill port; open the filling valve of the truck's tank; check that connections are sealed; open the valves on the loading arm; start the pump; and press the charging button for loading. Finally, the loaded weight is displayed. The loading procedure ends when the set point is reached, and an automatic shutdown is initiated. Valves close and pumping stops; this marks the beginning of the disconnection phase. The operator closes the tank's internal valve and the valve on the loading arm, and disconnects other devices.

The DE simulation models the tasks executed by the operator and automated controls in the three major phases of the operation: the loading procedure, the end-of-loading procedure and the disconnection procedure. It simulates the time spent performing each task, together with control weaknesses resulting from operator error (e.g. task monitoring, scheduling or issuing an unsafe control command). The SD simulation (see the stock flow diagram shown in Fig. 4) models the transfer of LPG from the reservoir to the small transport tank. More precisely, the DE simulation models tasks, while SD simulates flows. Two AM simulations are used for the loading operation (Fig. 4.). The first provides a notification of the status of the operation. The second provides information about that status of the station after each procedure (e.g., operational, subject to wear and tear, damaged or undergoing maintenance). The simulation assumes that there are a large number of (un)loading operations and unsafe control commands can be issued, including mistakes by the operator. This made it possible to link the scenarios used in the model to an agent.

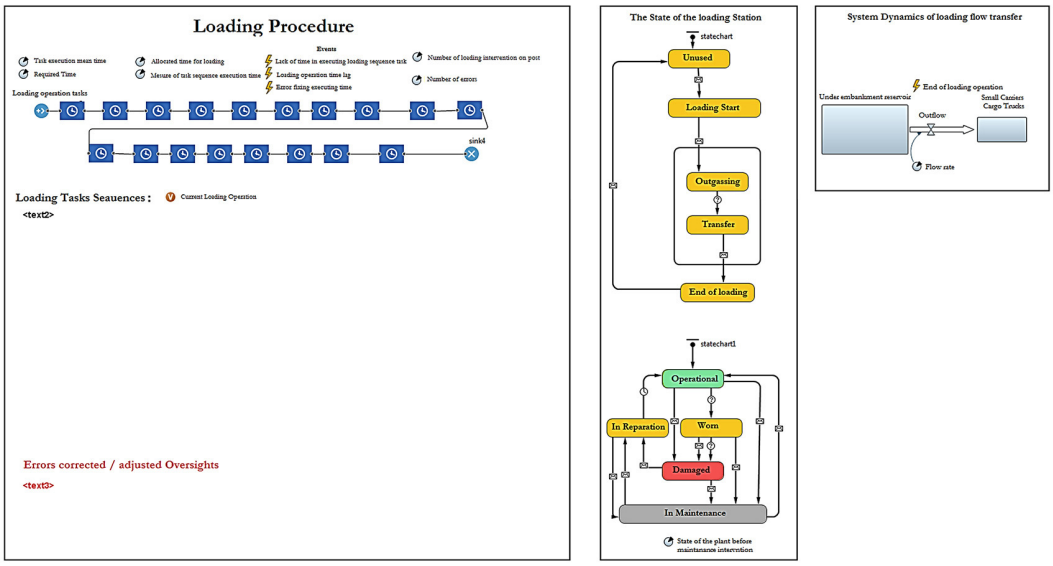

Fig. 4. SD, AM and DE simulation paradigms

Process control simulation model

One of the major problems is to maintain control of the physical process. The STAMP model assumes that both the process and environment are dynamic and, consequently, complex. This complexity is addressed at the level of the organization (e.g., the design of working environments, social structures and technological objects) and the individual. The model simulates various loss of control scenarios suggested by STAMP (i.e. incorrect or unsafe commands are given, corrections are not made, commands are given too early or too late, or a control is stopped too soon or applied for too long). The operator perceives information about the controlled process either directly or indirectly via sensors, notifications and alerts. A lack of information is modelled by a probability that alerts are not triggered, meaning that important information is not received at the appropriate time; this corresponds to the types of feedback failures included in the STAMP model.

We also simulated a scenario where identification and authorization procedures are not properly followed, and the operation is performed in degraded conditions. In this scenario, an unidentified driver accesses the transfer station. Consequently, information such as the driver's level of training and tanker compliance may be missing, which may lead to inappropriate control actions. Another scenario takes into account time constraints for (un)loading operations; operators are expected to take 10–18 minutes to load, and 19–28 minutes to unload. However, mistakes can add several extra minutes, which may lead agents to rush the execution of the procedure within the scheduled time. A lack of resources can be modelled by a transfer station that is out of service (e.g., for maintenance or repair), or the absence of an attendant. This can lead to both a lack of information (e.g., not all drivers can be identified) and a lack of time (e.g., drivers feel that they must operate more quickly when there is only one station available).

5. Conclusion

This paper proposed an approach to testing and evaluating the safety report for a French LPG facility. The STAMP model was used to simulate control measures and the implementation of safety directives proposed in the report. Directives and constraints are listed at each level of the system. Here, we presented one control structure in order to understand interactions between the controller and the physical plant. The system was simulated using AnyLogic software to understand the behavior, over time, of a frontline operator who follows written procedures that comply with the safety report's requirements. The case study implemented the STAMP approach to simulate a dynamic control structure and communication channels between controllers who are required to enforce directives. This approach allowed us to evaluate the sequences of control tasks executed by the operator, in a scenario where each command complies with safety directives. The simulation made it possible to assess whether control tasks are performed correctly in terms of preparation and execution time, and priorities in a system that changes over time. Combining the STAMP model with a simulation tool made it possible to simulate multi-sequencing and the scheduling of control actions depending on the status of the system. This has the benefit that it is possible to modify the control algorithm and simulate the way safety directives can change in classical operational phases.

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