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Dynamic Systems Modelling to improve risk analysis in the context of Seveso industries

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Industries that fall under the legal requirements of the EU Seveso Directives must produce a safety report principally demonstrating that major-accident hazards have been identified and that the necessary measures have been taken to prevent their consequences. This legal specification involves the choice of a risk analysis approach, usually deterministic or probabilistic. These approaches have been formalized since the early of the 60's for the most of them, and they are based upon the consultation of expert judgments and reliability databases (for technical and human aspects). Due to the complexity of the industrial systems and their own dynamic in time and space, these risk assessment methods need to be supported by a systemic vision of their processes.
Based on the systemic theory introduced by Forrester, this paper aims to propose a methodology to modeling and simulate the functioning of a chlorine storage and distribution unit, in order to promote a better risk prevention. This methodology include four complementary steps: i) the modeling of the system using the systemic theory principles and terms; ii) the implementation of this model into a Dynamic System platform for its simulation; iii) the simulation of the system using normal and abnormal scenarios in order to identify and to estimate the consequences of these deviations; iv) the assessment of the proposed barriers efficiency. After the application of this systemic methodology, these results are introduced into a HAZOP analyze to support the experts' risk assessment. As a conclusion, the authors discuss the benefits and limits of the implementation of a systemic approach in the safety reports, and propose some ways to generalize the proposed methodology.

1. Systems dynamic and industrial risk prevention

In Europe, the industrial risk management is based on the safety report that contains the analysis of every kind of failures provoked by the use, the transport and the storage of hazardous material. Due to the complexity of the industrial systems, it is useful to model the involved units in order to apply the risk assessment methods such as the Preliminary Risk Analysis (PRA) or the bow-tie analysis (Andrews and Moss, 2002). The modelling methods usually represent the functions and the relations between the components of an industrial system by the use of some adequate diagrams (Santos-Reyes and Beard, 2008), but they do not allow to simulate its behaviour in a dynamic way because they represent only the processes in a linear mode. This article proposes to apply a dynamical modelling methodology of a Chlorine (Cl_2) transfer unit for the plastics synthesis in order to assess the efficiency of the prevention and protection means that are implemented in the industrial site. This approach is based on the notions and the approach of the systems dynamic that envisages to study, to model and to simulate the processes that make a change or a conservation of status, information,

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matter or energy in a system for a certain period. The following paragraphs present the developed methodology, the results of its application from a case study. The conclusion discusses the benefits and the limits of this risk management methodology.

2. Methodology and case study

The "systems dynamic" has been defined by J.W. Forrester (Forrester, 1961) as « *a way of studying the behavior of industrial systems to show how policies, decisions, structure, and delays are interrelated to influence growth and stability* ». Our approach is based on the following four steps that ensure a continuous improvement of risk management of a plant (figure 1):

- **Model building and system behaviour simulation:** this step is mainly based on the choice of the variables that describe the state of the system components in interaction in each moment, the definition of the assumptions that establish the interactions in order to formalize the proposed system, the development of a causal model of the relations between the variables, the writing of the relations with the differential equations and their implementation in the STELLA® software (Richmond, 2005).
- **Dynamic risk analysis with risk assessment methods:** it is based on a very well defined method such as the HAZOP one (Andrews and Moss, 2002). It allows to identify all possible failures and, with the dynamic model, to study the eventual variations of the system behaviour.
- **Consequences simulation of every kind of failures:** this step is related to the use of the ALOHA software (NOAA and EPA, 2007) in order to simulate dangerous phenomena (toxic atmospheric releases, overpressures, heat flux etc.) and to estimate the effects on the structures and the population (workers, residents etc.).
- **Dynamic test of the prevention and protection means to assess their efficiency:** this step consists to measure the efficiency of the prevention and protection means implemented in the plant. It allows defining new safety means if it is necessary. In this case it is envisaged to return to the model design step in order to implement the new prevention and protection means and to simulate their integration.

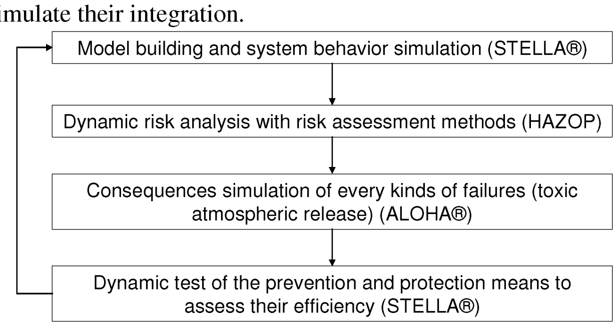

Figure 1. Description of the dynamic system modelling methodology applied to the industrial risk assessment and management.

2.1 Industrial site and chlorine unit

The industrial site is located in a suburban sector surrounded by a relative dense population (more than 6.000 residents in a 1.000 m radius), near a highway (at 150 m), a railway (at 20 m) and different kinds of economical and leisure activities like supermarkets, companies and cinema located in a two kilometers radius. The installation that contains the hazardous activities is represented by the chlorine transfer unit that dispatches this substance to the plastics production unit.

The chlorine gas is heavier than air (3.2 g / l at 0 º C) which tends to form a cloud near the ground. Its odor is suffocating and pungent at a concentration of less than 1 ppm (CDC NIOSH, 2008). The Cl_2 effects on the human health are linked to its irritant potential. At a low atmospheric concentration less than 15 ppm, the chlorine irritates the eyes quickly, the skin and the respiratory system cells (nose, throat, respiratory tract). In the case of a longer exposure and with a higher concentration (around 1.000 ppm for 1 minute of exposure), a pulmonary oedema can occur in few minutes and causes the death of the contaminated persons.

The chlorine transfer unit is composed by three subsystems:

- The tank transfer unit that provides the CL_2 to the chlorine line with a continuous flow insured by two tank carried by the railway;
- The chlorine line that supplies an information to the tank transfer unit in terms of chlorine demand for the plastics production unit;
- The device that controls the physical conditions of this system is the heat production unit composed by two boilers that regulate the temperature to maintain the chlorine in a gas phase. The connection of the two boilers is established at the level of the evaporator and the superheater. The heat production receives the information of the chlorine phase form the sensors of the chlorine line.

The causality relations between these three sub-systems and theirs components are represented in the causal graph (figure 2).

2.2 Causal Graph

The feedback loops, formed by the chains of causality, identify the processes producing an against-intuitive phenomenon through the simulations developed by a computer language. The graphical feedback loops between the system components is named "causal graph". In this figure, some constants or other parameters are not presented but they are modeled with the stock-flow diagrams (Figure 3): these components are not involved in a feedback loop as a causal factor, but they are involved in the resolution of the numerical equations for the simulations. This causal graph is a qualitative mean to assess the relationships between the modelled components and to identify the ones that are significant to the numerical expression.

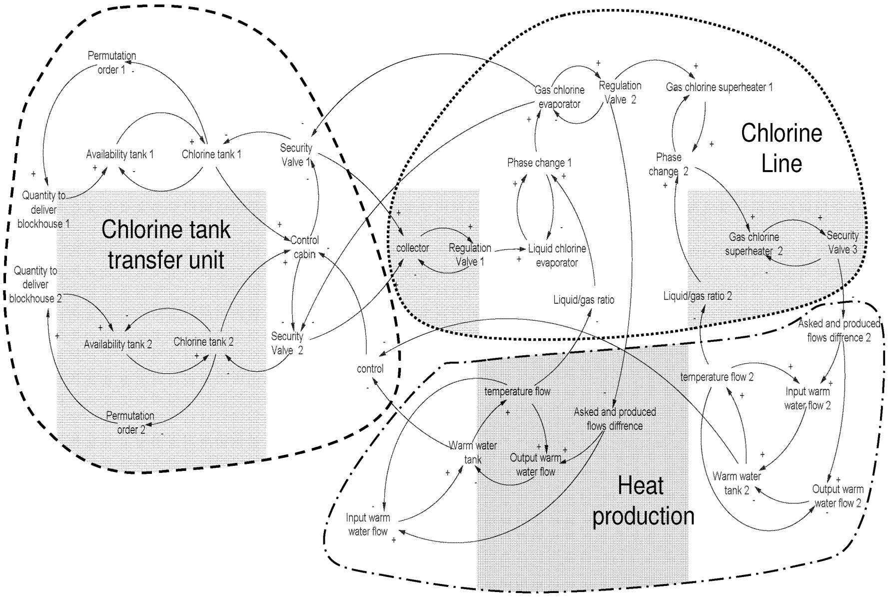

Figure 2. Graphe causal détaillé au niveau désagrégé, du système de dépotage et transfert de chlore du site industriel.

2.3 Model implementation with STELLA® software

From this representation, most of the softwares used to program a model to provide simulations offer a graphical construction with a stock-flow diagram (Figure 3) in order to define the components according to their causal interactions. STELLA® software has been used to implement and simulate the operations of the model in normal mode and in the case of failures such as a leak caused by the rupture of a pipeline. The user of this software can work in an environment that proposes three windows (interface, diagrams and equations) to design a model with different degrees of accuracy.

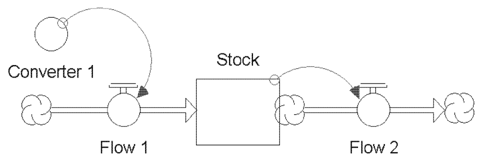

Figure 3. STELLA® stock, flow and converter variables.

The prevention (atmospheric chlorine sensors, alarms etc.) and protection (valves, etc. stripping interruption.) components are also modelled with the same logic in order to test their relevance. Because of the complexity of the studied system, it is not envisaged to show all the modelled components and variables. The following paragraph points out only the graphical results relating to the operations of the chlorine tank transfer unit in a normal mode and when the prevention and protection systems are activated in the case of a leakage. These results underline the efficiency of the accidents prevention means that are implemented.

3. Results: a dynamic risk assessment

The proposed scenario of failure is a broken pipe at the end of the chlorine line, just before the unit of plastics synthesis. Figure 4 shows two chlorine tanks that perform, one after another one, their chlorine discharge in order to ensure a continuous flow to the plant and with an amount flow of about 600 kg / h. The amount of chlorine carried by these tanks varies between 55 and 59 tonnes. It takes between 72 and 96 hours to empty a tank as requested by the demand of the production unit. In this scenario, the pipeline rupture occurs at t = 200 hours. It causes two phenomena perceptible by the system: a lack of chlorine input flow in the plastics production unit and the activation of an atmospheric chlorine sensor located beside the pipeline. The activation of the alert triggers, in a second time, the sending of an emergency message that causes an alert sent to the control cabin. This activation shut down immediately the safety valves 1 and 2 in the chlorine tank transfer unit.

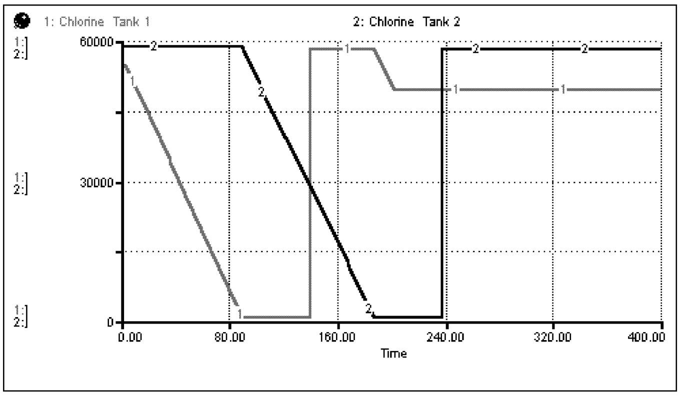

Figure 4. Shut down of the chlorine tank discharge after the alert activation due to the breaking of a chlorine pipeline at the end of the chlorine line and at t = 200 hours.

This interruption continues throughout the simulation because it requires a major repair of more than 200 hours. The consequence of this decision is the cessation of the chlorine flow throughout in the collector and the regulation valve 1 (Figure 5).

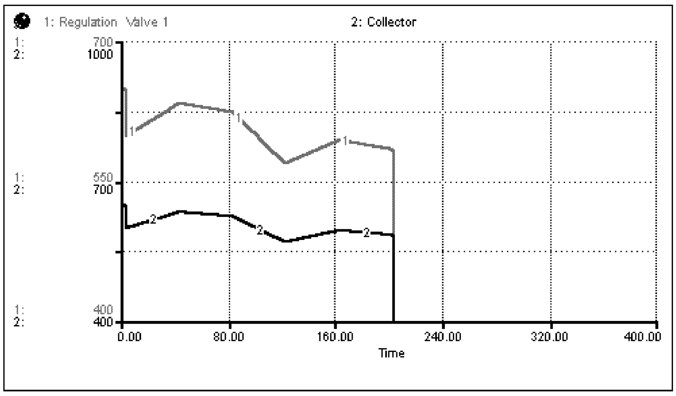

Figure 5. Chlorine flow in the collector and the regulation valve 1 in normal mode and after a shut down due to the activation of the safety means at t = 200 hours.

The simulation of the system behaviour during a pipeline break underlines the role of the prevention and protection barriers. Indeed, their activation allows securing quickly the system by the action on the safety valves, which stop the emission of the chlorine flow in the atmosphere. The ALOHA software simulation of atmospheric releases (NOAA and EPA, 2007) shows the formation of a toxic cloud over a distance less than 20 m at a concentration of 910 ppm (concentration inducing the death of 1% of the exposed people for one minute of exposition) due to a quick activation of the safety valves (less than one minute).

4. Conclusion

The modelling of an industrial system helps the analysts to represent and thus to appropriate this one, insisting on its properties highlighted during its functioning and with a determined complexity level. The use of a modelling environment incorporating the capability to simulate the activity of the system is an asset to understand the industrial unit behaviour in both normal and abnormal modes. The formalization of such model represents a communication mean, even a training tool, for policy makers and operators. This kind of model can also be modified throughout the life cycle of the industrial activity, both in design and working operations phases. The inspection services may also be interested in such tool in their monitoring and control activities, especially for the evaluation of the efficiency of means to prevent major accidents. At this stage, the dynamic modeling is already a first validation tool of the security means that can be installed in connection with other models that allow assessing the consequences of the scenarios outlined in the safety report. The application of this approach in the context of risk management provides a dynamic analysis of risks. The limits of this dynamic modeling approach is essentially linked to the complexity degree that the expert seeks to handle because of the time devoted to the development of the model, the definition of the variables, the simulation and the interpretation of the results.

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