AIDIC *Conference Series*, Vol. 9, 2009
Editor Sauro Pierucci
DOI: 10.3303/ACOS0909018

ISBN 978-88-95608-10-5 ISSN 2036-5969
Copyright © 2009, Aidic Servizi Srl

SYSTEMS DYNAMICS MODELLING TO IMPROVE RISK ANALYSIS IN THE CONTEXT OF SEVESO INDUSTRIES

Emmanuel Garbolino[a], Jean-Pierre Chery[b] and Franck Guarnieri[1]

[a] MINES ParisTech, CRC, rue C. Daunesse, BP 207, 06904 Sophia Antipolis, France
[b] ENGREF/AgroParisTech, Maison de la Télédétection en Languedoc-Roussillon, 500 rue Jean-François Breton, 34093 Montpellier Cedex 5, France

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 Systems Dynamics theory introduced by Forrester in the 60's, 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 DYNAMICS 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 modeling 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 simulating its behavior in a dynamic way because they represent only the processes in a linear mode. This article proposes to apply a dynamical modeling 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, 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

Please cite this article as: Garbolino E., Chery J.P. and Guarnieri F., (2009), Systems dynamics modelling to improve risk analysis in the context of seveso industries, AIDIC Conference Series, 09, 149-158 DOI: 10.3303/ACOS0909018

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 at every 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 identifying 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.

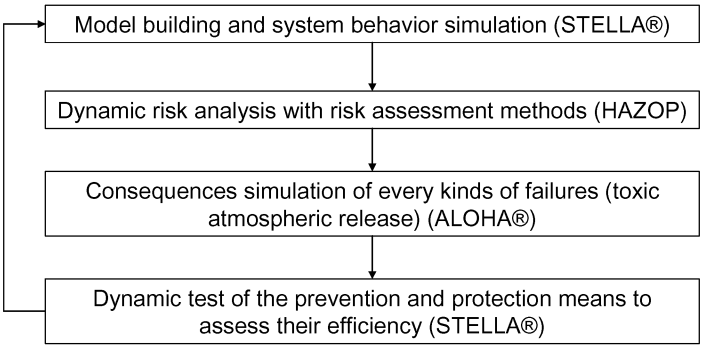

Figure 1. Description of the dynamic system modelling methodology applied to the industrial risk assessment and management.

1.1 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 edema can occur in few minutes and causes the death of the contaminated persons.

The chlorine transfer unit is composed by three subsystems (figure 2):

- 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.

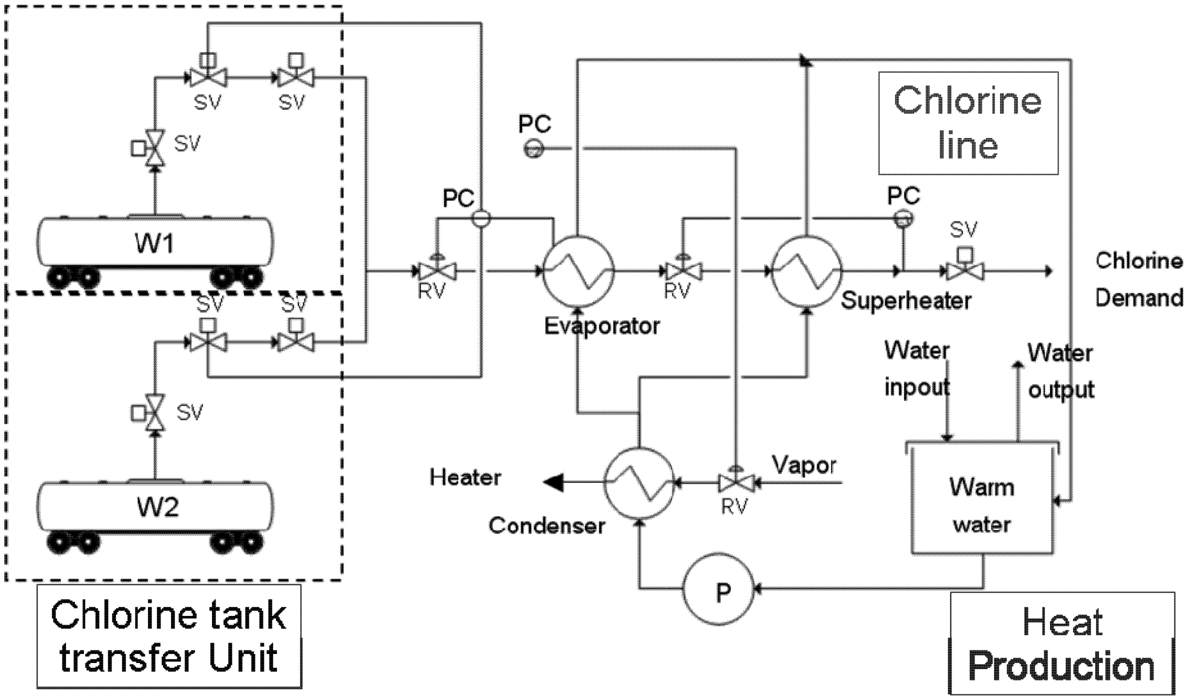

Figure 2. Description of the chlorine transfer unit (W= Wagon ; SV= Security valve ; RV= Regulation Valve ;PS= Pressure Sensor ; P= pump).

As soon as it arrives on the site, the chlorine transfer unit is directed into a tight blockhouse, built with non-temporary materials and provided with ventilation creating a light depression. The operations of connection, disconnection and draining of the chlorine transfer units are thus carried out in a closed space where detectors of chlorine leakage analyze the quality of the air uninterruptedly. In the event of a release equivalent to 5 ppm of concentration in the atmosphere, the chlorine which passes in the gas form to the atmospheric pressure is aspired and directed towards a column of demolition containing soda for the neutralization of gas (not represented on figure 2). The temperature of the air of the blockhouse is maintained to 35°C thanks to a system of heating made up of a steam circuit coming from a boiler located in another workshop of the factory. This temperature makes it possible to increase the internal pressure of the transfer unit up to a value ranging between 8 and 9 bars. To this pressure, liquid chlorine passes in the pipes and moves towards the chlorine routing line which delivers it to the synthesis workshop. This method allows tapping chlorine without introducing inert gas. The duration of the extraction of chlorine from a transfer unit is approximately of three to four days according to consumption. The chlorine transfer unit is replaced when the pressure drop of the line indicates that the connected transfer unit is almost empty. The process of transfer from an empty transfer unit to a full transfer unit lasts approximately an hour and a half. When the transfer unit gets into the shed it is first stabilized, then it is connected to a pipe of 25 mm via a quadrant to lead liquid chlorine towards the evaporator. Piping transporting chlorine in the liquid phase is setting in the blockhouses to ensure its containment and their length is reduced to the maximum. The evaporator is set in an adjacent building to the blockhouse which also shelters a superheater to ensure the routing of chlorine gas towards the production unit without the risk of condensation in the chlorine line. In the evaporator, the chlorine arriving from the transfer unit at 35ºC passes in the gas phase, the superheater then increases the temperature of chlorine up to 40ºC to compensate for the losses of heat in the production unit supply pipe, losses which could involve the condensation of part of the chlorine. The regulation valve preceding the evaporator allows also ensuring that only a constant quantity of liquid chlorine comes in. The evaporator, like the superheater, uses warm water which circulates through a closed circuit and which itself is heated by means of a vapour exchanger. The regulation of the warm water circuit is made by the water steam output. The temperature of water on the outlet side of the evaporator is controlled by the steam valve (36ºC under normal functioning). To guarantee a pressure of 2,5 bars on the level of the production workshop, a valve is set before the superheater. Other valves of safety (completely opened or closed “all or nothing” valves when they are activated) are set along the line and are controlled according to the chlorine pressure, during the setting off of alarms in case of leakage and according to the other safety sensors defined at the time of the conception of the risk analysis. There is a separation of the functions of control and safety of the system. The causality relations between these three sub-systems and theirs components are represented in the causal graph (figure 3).

1.2 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.

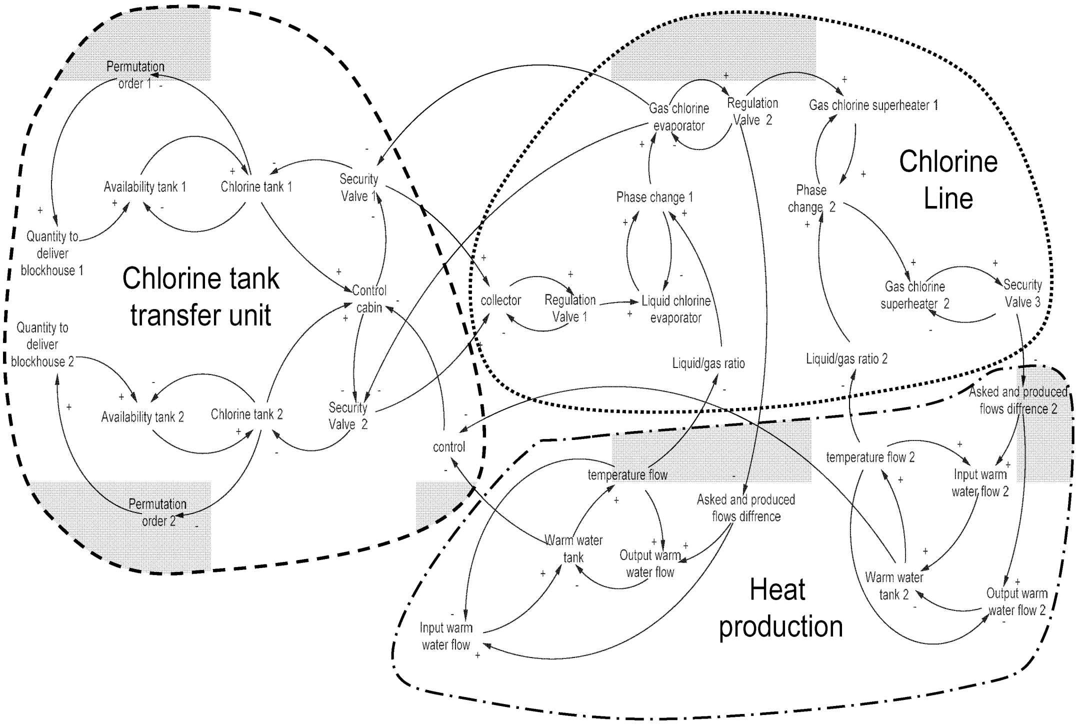

Figure 3. Detailed causal graph at the disaggregated level, of the system of discharge and transfer of chlorine from the industrial site.

This causal graph is a qualitative mean to assess the relationships between the modeled components and to identify the ones that are significant to the numerical expression.

1.3 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 4) 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.

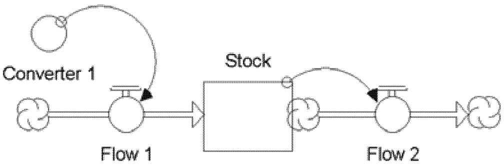

Figure 4. STELLA® stock, flow and converter variables.

The prevention (atmospheric chlorine sensors, alarms etc.) and protection (valves, etc. stripping interruption.) components are also modeled 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 modeled components and variables. Figure 5 presents the modeling of the system of chlorine discharge starting from the transfer units located in the blockhouses: this figure shows well the relations between the various variables of stock, flow and control.

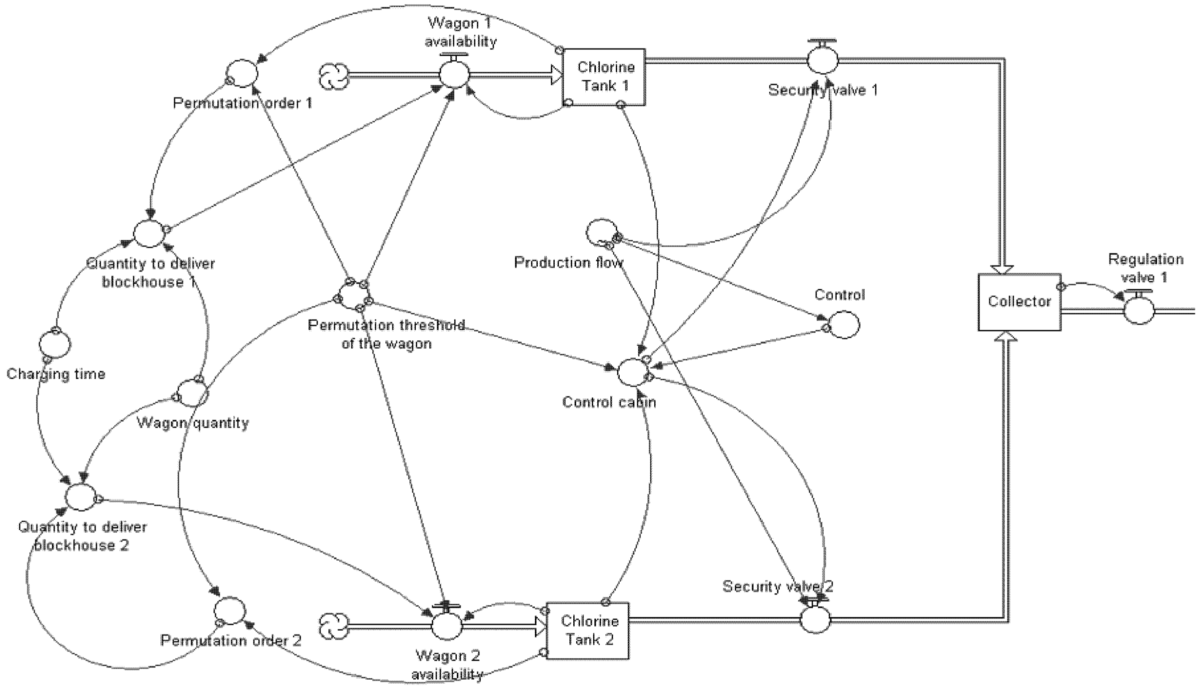

Figure 5. Modeling under STELLA® environment of the unit of transfer of chlorine starting from the tanks of the transfer units.

Table 1 Definition and the role of the whole set of variables used to model the unit of chlorine discharge.

Variables' names	Definition	Function
Wagon_1 availability	IF (Chlorine__Tank_1 < Permutation_threshold_of_the_wagon) THEN (Quantity_to_deliver_blockhouse_1) ELSE (0)	Chlorine available in transfer units which are in the blockhouses
chlorine_tank_1	55000 or 59000	quantity of chlorine contained at a certain point into the transfer unit
Security_valve_1	IF (Control_cabin=1) THEN (IF (Gas_chlorine_evaporator>2000) THEN(0) ELSE (Production_flow)) ELSE(0)	simulate the chlorine draught towards another storage called "manifold"
collector	stock	quantity of chlorine going through the piping on the outlet side of valves 1 and 2
Permutation_order_1	IF (Chlorine__Tank_1 < Permutation_ threshold_of_the_wagon) THEN 1 ELSE 0	depends on the remaining quantity of chlorine in each transfer unit
Permutation_threshold of the wagon	1000	chlorine threshold which activates the change of transfer unit
Quantity to be delivered blockhouse 1	DELAY ((Permutation_order_1 * Wagon_ quantity) , Charging_time)	quantity of chlorine to be delivered in blockhouse1
Charging time	NORMAL (48,5)	time needed to change a transfer unit (48 hours more or less 5 hours)
Wagon quantity	RANDOM (55000, 59000,1)	variable quantity of liquid chlorine brought by the rail network (between 55 and 59 tons)
Production_flow	graph	chlorine needs which vary between 570 kg and 645 kg per hour
control	IF (Production_flow>700) THEN 1 ELSE (IF (Warm__water_tank<700 or Warm_water__tank_2<700) THEN 1 ELSE (IF Alert_status=1 THEN 1 ELSE 0))	allows to control the quantity of chlorine going through the piping
control_cabin	IF(Control=1) THEN(0) ELSE (IF ((Chlorine__Tank_1 < Permutation_threshold_ of_the_wagon) AND (Chlorine__Tank_2 > Permutation_threshold_of_the_wagon)) THEN(2) ELSE (IF ((Chlorine__Tank_1 > Permutation_ threshold_of_the_wagon) AND (Chlorine__ Tank_2 < Permutation_threshold_of_the_wagon)) THEN(1) ELSE (IF ((Chlorine__Tank_1 < Permutation_threshold_of_the_wagon) AND (Chlorine__Tank_2 < Permutation_threshold_ of_the_wagon)) THEN(0) ELSE (IF (Chlorine__ Tank_1 < Chlorine__Tank_2) THEN(1) ELSE (2)))))	allows to select the transfer unit to be discharged by the successive activation of the safety valves

The following paragraph points out 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 simulation of the operation of this system using the software STELLA® is controlled through graphs representing the state of the various variables over the time. In this case, time is defined arbitrarily over a 400 hours duration, that is to say a little more than 16 days. Figure 6 represents the variations of the quantity of chlorine of the transport units at the time of the activities of discharge.

Two types of variations are observed: the first relates to the quantity of chlorine discharged which fluctuates between 55 and 59 tons, accounting for the difference in level between the two transport units on their arrival on the site (mitigating); the second variation relates to the duration of the discharge which fluctuates according to the quantity of chlorine delivered and that required by the production unit.

As shown in this figure, the discharge of the transport unit 1 is carried out first throughout a time period of 90 hours, and then the transport unit 2 is in turn discharged during approximately 100 hours.

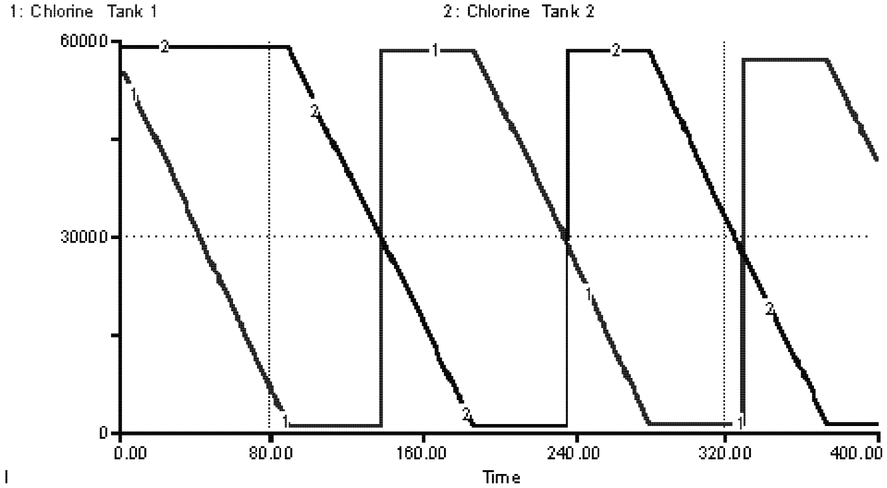

Figure 6. Simulation of the discharge of the chlorine transport units. 1 = chlorine transport unit n°1; 2 = chlorine transport unit n°2; in X-coordinate is represented time in hours, from 0 to 400 hours; in ordinates is represented the quantity of chlorine in both transport units, from 0 to 60.000 kg.

Figure 7 presents the chlorine flow going through the regulation valve n°1 which is at the exit of the system of discharge of the chlorine transport unit set in the casemate n°1. This chlorine flow varies according to the request of the production unit of the plastics.

The chlorine flow going through the manifold varies in the same proportions since it collects liquid chlorine at the exit of the blockhouse to convey it to the evaporator.

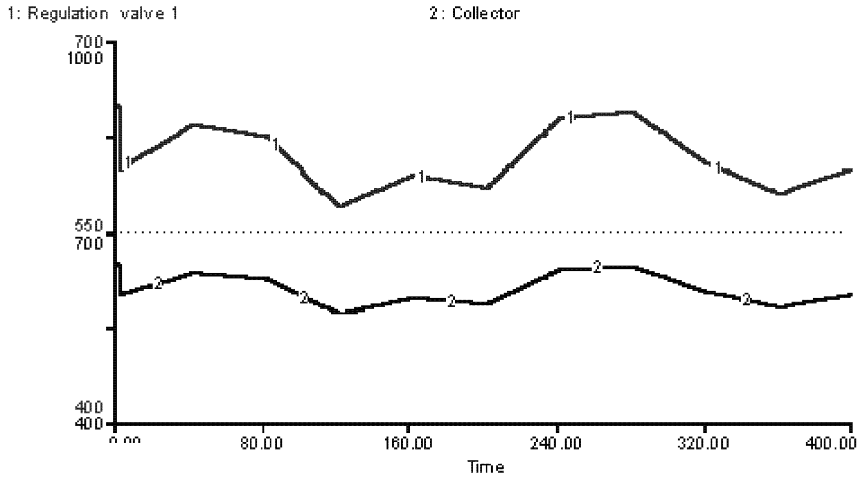

Figure 7. Simulation of the liquid chlorine transfer from the blockhouse n°1 towards the chlorine line for its transformation into the gas phase. (in X-coordinate is represented time in hours, from 0 to 400 hours; 1 = Regulation valve n° with in ordinates the liquid chlorine flow going from 400 to 700 kg/h; 2 = Manifold with in ordinates the liquid chlorine flow going from 400 to 1000 kg/h).

The proposed scenario of failure is a broken pipe, due to a collision with an aerial lift, at the end of the chlorine line, just before the unit of plastics synthesis. The modeling of leakage and the means of alert using STELLA® is represented in figure 8.

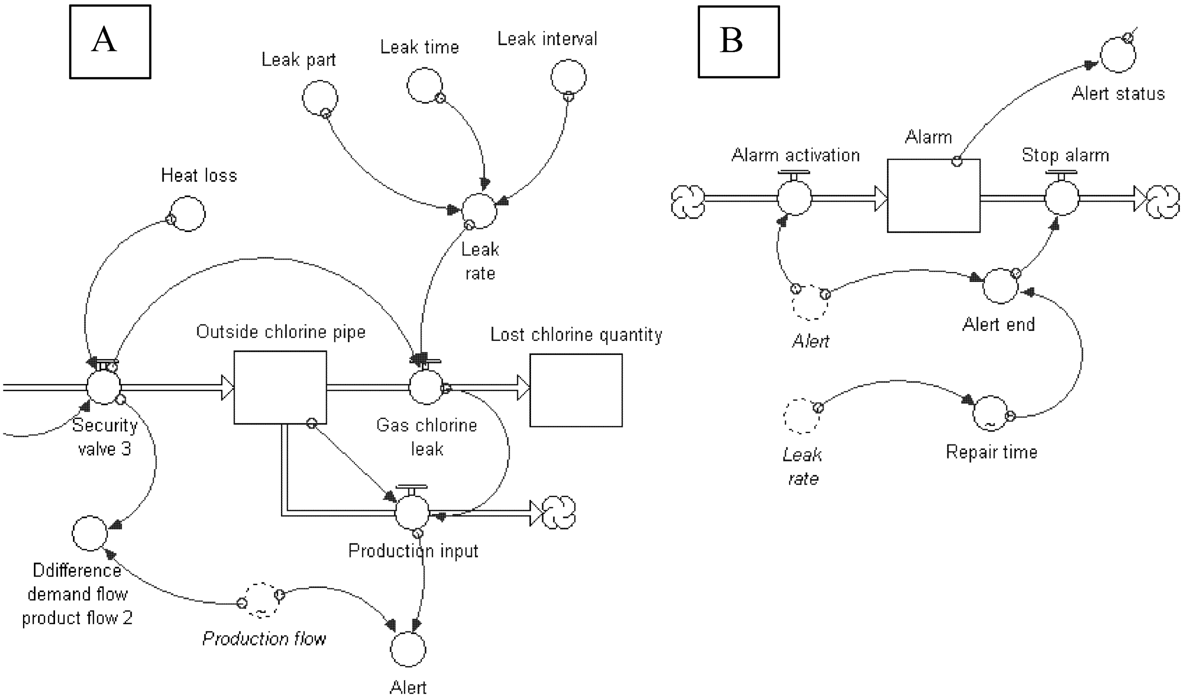

Figure 8. Modeling of chlorine leakage at the end of the line (A) and of the means of alert (B) under environment of STELLA®.

Table 2 presents the definition of the variables which were used to model the chlorine leakage at the end of the line and the means of alert.

Table 2: Modeling the barriers of prevention and protection

Variables’ names	Definition	Function
Leak_part	RANDOM(0.1,0.3)	proportion of chlorine which is released in the atmosphere
Leak_time	(RANDOM (1,400)) ×0 + 200	determines the moment when the leakage will occur. Here, the leak time is equal to 200 hours
Leak_interval	fixed at 72 hours	period which separates two leakages on the same element
Leak_rate	PULSE (Leak_part, Leak_time, Leak_interval)	quantity of chlorine which is released at a certain point and being able to reappear after an interval between two leaks
Gas_chlorine_leak	Security_valve_3 × leak_rate	flow of chlorine release
Alert	IF (Production_input < (Production_flow * 0.90) OR Production_input > (Production_flow * 1.10)) THEN 1 ELSE 0	This variable is activated when the chlorine flow at the entry of the production is either lower than 90% or higher by 10% of the required flow of production
Repair_time	graph	proportional variable, in a nonlinear way, to the proportion of gas which is released
Alert_end	DELAY (Alert,Repair_time)	represent the time necessary to raise the alert
Stop_alarme	binary values: 0 or 1	variable activated by the variable ending the alert
Alert_status	IF Alarm > 0 THEN 1 ELSE 0	taking into account of the restart

Figure 9 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 tons. 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 a phenomenon perceptible by the system: a lack of chlorine input flow in the plastics production that activate the alert system. 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.

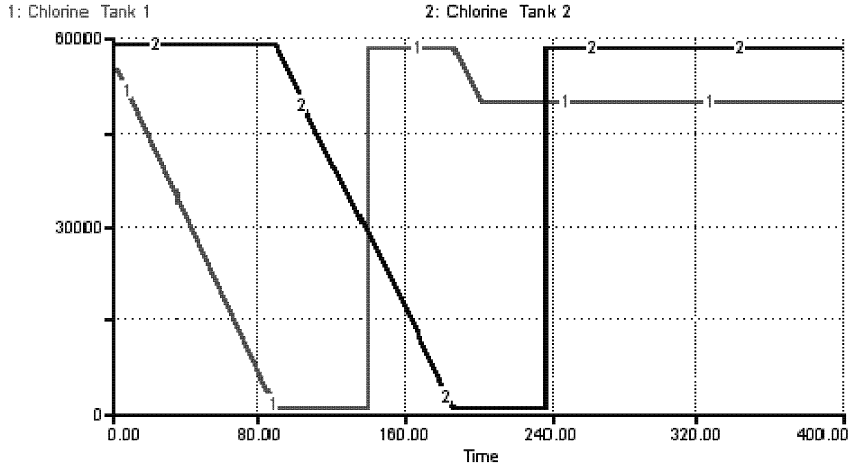

Figure 9. Shut down of the chlorine tank discharge after the alert activation due to the breaking of a chlorine pipeline at the end of the chlorine line and at t = 200 hours.

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 10).

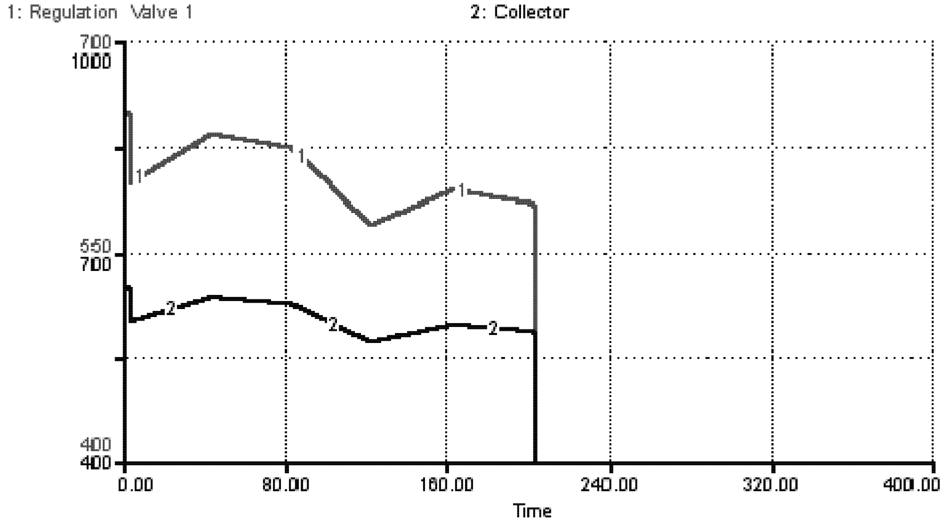

Figure 10. Chlorine flow in the collector and the regulation valve 1 in normal mode and after a shut down due to the activation of the safety means at t = 200 hours.

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 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.

5. REFERENCES

Andrews J. D. and Moss T. R. (2002). Reliability and Risk Assessment, John Wiley And Sons Ltd.
CDC NIOSH (2008). Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, http://www.cdc.gov/niosh.
Forrester J.W., 1961, Industrial dynamics, M.I.T. Press.
NOAA and EPA, (2007).- ALOHA : user's manual, NOAA EPA.
Richmond B. (2005). An introduction to Systems Thinking, Isee systems.
Santos-Reyes J. and Beard A.N. (2008). A systemic approach to managing safety, *Journal of Loss Prevention in the process industries*, n°21, 15-28.