CHEMICAL ENGINEERING TRANSACTIONS

VOL. 36, 2014

A publication of AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

Guest Editors: Valerio Cozzani, Eddy de Rademaeker
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ISBN 978-88-95608-27-3; **ISSN** 2283-9216

DOI: 10.3303/CET1436077

The application of System Dynamics to industrial plants in the perspective of Process Resilience Engineering

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Resilience can be defined as the ability of a system to recover from any failure or disturbance. In this light, Resilience Engineering should be then devoted to the comprehension of the evolution of any system when losing its dynamic stability, due to the erosion of safety level. Recently, several authors have discussed over the significance and possibility of applying these concepts to industrial safety. In their view, any methodology for resilience differs from classical risk assessment as it depends on either known or unknown initiating-accident events. Or, resilience can be assumed as the ability of the industrial system to sustain required operational safety under both expected and unexpected conditions. This definition can be defined if holistic risk assessment is adopted. To this aim, however, due to the intrinsic complexity of the analysis, specific tools as System Dynamics (and Causal Loop Diagrams) are suggested for the quantitative evaluation of resilience of industrial systems. In this paper, this opportunity has been preliminary evaluated and the application for a simple storage plant of LPG is presented.

1. Introduction

Resilience assumes different meaning in dependence of the technical or organizational domain. In the most classical significance, it is the physical property that characterises the capacity of any material to return to the original shape or position after deformation that has not exceeded its elastic limits (Garcia-Serna et al., 2007). Following this definition, with regards to the process engineering, Mitchel and Mannan (2006) have given to the term resilience a practical meaning: it is the energy limit of a disturbance that a system can absorb before becoming unstable. In analogy with these definitions, Steen and Aven (2011) have defined the concept of resilience as the probability of a system of succumbing to any negative event, and have formalized it as a function depending on different parameters such as safety barriers, consequences, uncertainty, incidental events. With specific reference to the industrial safety, Pasman and Knegtering (2008) and Pasman et al. (2013) have considered that a resilience approach should be addressed to minimise damages and to restore any system to normal operations immediately after an accident has occurred. Furthermore, they stated that the typical structured analyses for the design and for the management of safety systems are not suitable for the evaluation of industrial risks derived from the combination of different factors as e.g. lack of competence, technical factors, or organization. Hence, an holistic risk assessment is required. Finally, Hollnagel et al. (2006) have defined resilience as the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances so that it can sustain required operational safety under both expected and unexpected conditions (known and unknown events, see Paltrinieri et al., 2012; 2013). This latest significance has been assumed for the quantitative definition of resilience and for the definition of a resilience level for the process industry, as described in the following. Besides, the goals described by these authors are extremely complex to achieve with classical risk assessment tools. Hence, new tools such as the System Dynamics (SD), nowadays adopted in several technical and organizational fields, should be developed for the definition of safety of industrial operations and systems, which is the aim of this work. In this paper, this opportunity has

Please cite this article as: Salzano E., Di Nardo M., Gallo M., Oropallo E., Santillo L.C., 2014, The application of system dynamics to an industrial plant in the perspective of process resilience engineering, Chemical Engineering Transactions, 36, 457-46
DOI: 10.3303/CET1436077

been preliminary evaluated. A very simple storage plant of LPG has been considered as a first practical attempt of analysing the risks in terms of resilience function. A comparison of results with classical risk assessment is also reported. For the construction of SD we have used the code Studio 9 by Powersim Software AS ®.

2. System Dynamics for the definition of resilience of industrial installations

System Dynamics (SD) is a methodology and computer simulation modeling technique for framing, understanding, and discussing complex issues and problems either qualitatively or quantitatively. Several examples of application are given in the open literature (Sterman, 2000; Xiang and Bingquan, 2002; Hollnagel et al., 2006). Its implementation comprises two main steps. The first one is the definition of a Casual Loop Diagram (CLD), which is a graphical visualization (map) used to represent the causal structure of the analyzed system. More specifically, in the CLD development, the set of nodes representing the key variables of a system are linked together by arrows. Then, the relationships are labelled as positive (or negative) for the identification of reinforcing loops. The second step consists in translating the CLD, which provides only a qualitative representation of the model, into a simulation model that constitutes the essence of the quantitative model. To this aim, writing a mathematical relationship linking causes and effects is the essential step in the construction of the dynamical system to be simulated. Details on CLD and System Dynamics can be found elsewhere (Sterman, 2000).

Figure 1 shows the CLD for the description of resilience in industrial environment or system. The model descends from the theory of “added value chain”, which describes any structure as a set of a limited number of processes (Porter, 1985).

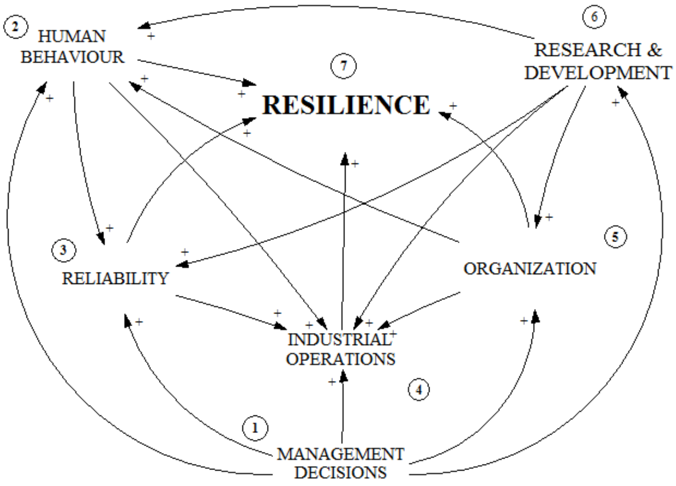

Figure 1. The Casual Loop Diagram for the resilience of an industrial context.

Quite clearly, the proposed CLD is very general. Indeed, each node of Figure 1 may be further detailed in associated sub-loops or sub-nodes such as that described in Figure 2, where the CLD sub-node related to the cognitive process, to be connected to node 1 for management decisions, is shown (Khawaji, 2012). Other sub-nodes are under development in a larger project for the SD-based resilience and will be not shown here for the sake of brevity.

Starting from the proposed CLD, a resilience indicator (RI) – or resilience function - must be defined. This indicator has to be holistic in nature, i.e. all possible and functional components of risks in a productive system should be taken into account. To this aim, according to the definition of Hollnagel et al. (2006), we have considered that relevant accidental scenarios such as fires (flash fire, pool fire, jet fire), explosions (Vapour Cloud Explosion, BLEVE), or toxic dispersion can be considered as catastrophic events which compromise the ability of any industrial system to operate and cope with failures, loss of control and loss of content. In other words, the resilience of any industrial process is measured as the ability of the system to prevent and mitigate accidental scenarios of such intensity that the integrity of the industrial system and, at the same time, the integrity of the overall safety systems (active and passive prevention and mitigating actions) are strongly affected. On the basis of this definition, we have defined the resilience indicator as the product of the total life of the industrial system, which is typically 50 years, with the overall annual probability of occurrence of fire, explosion, and dispersion as calculated by SD.

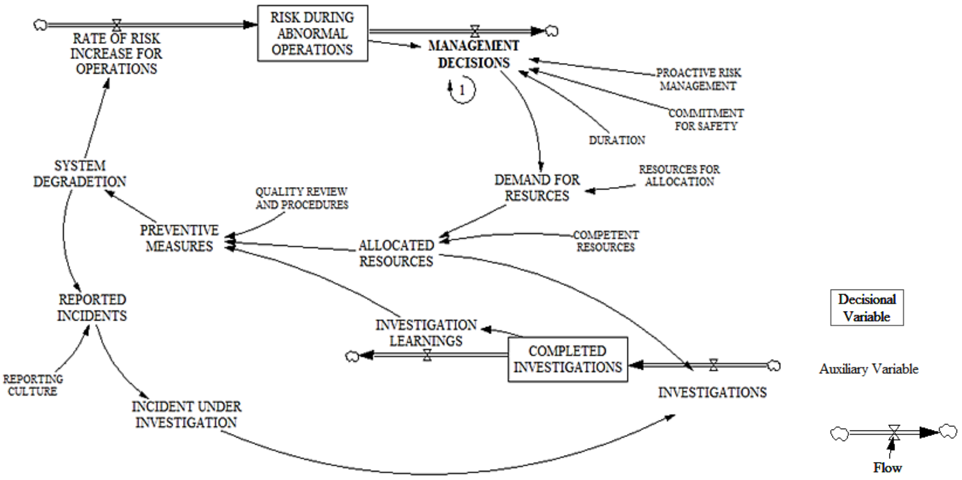

Figure 2. The Cognitive Casual Loop Diagram as proposed by Khawaji (2012). The CLD is connected to the node 1 for management decisions in the main CLD.

Once defined the indicator, RI, a proper SD has been developed. This operation is quite complex and should include the mathematical formulation of any node included in the main loop and all sub-nodes (as in Figure 3). For the purpose of this work, we have developed and shown here the node 2 only, which is properly related to the main engineering aspects of chemical process safety. In Figure 3, the circles represent probability functions. Further details on the entire procedure and extension to other nodes will be published in future works. External event includes natural event or sabotages (Salzano et al., 2009) whereas domino effects are related to the propagation of accidental scenario from explosion or long-duration fires (Salzano and Cozzani, 2006; Salzano et al., 2012). The developed SD is adopted for a case study, described in the following section.

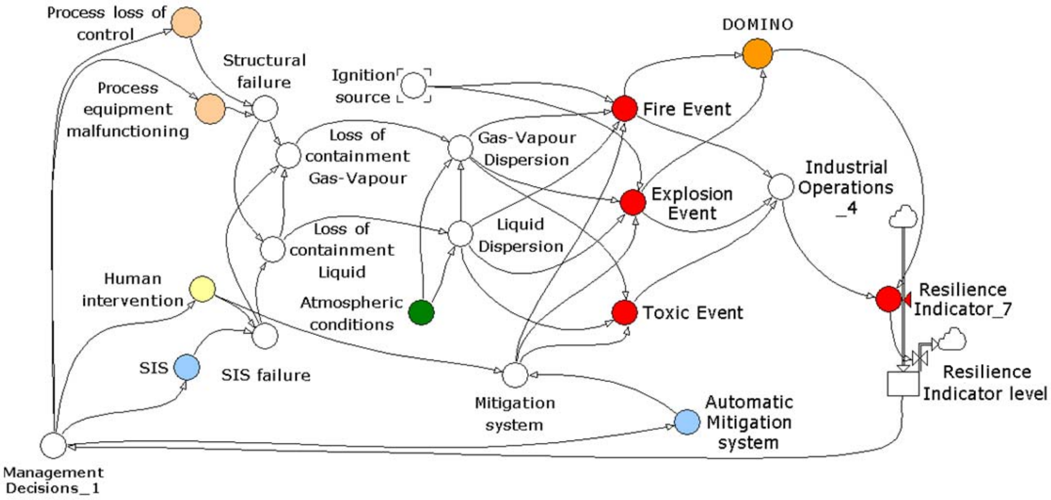

Figure 3: The sub-system SD for the node 1-2-4, for the resilience evaluation (node 7) as developed in this work. SIS: Safety Instrumented System. Circle: Function; Square: Level; Diamond: constant.

3. Case Study

The case study considered is a LPG storage composed by one underground tanks (180 m^3 each) with a loading unit via road tanker and a compression unit. When arriving to the LPG installation, the truck driver stops on the charging scale, then opens the compartment of connecting pipes. At this point, the on-site operators connect the pipes for the loading the tank. The sketch of the plant is given in Figure 4. The corresponding SD for the node 1 is shown in Figure 5.

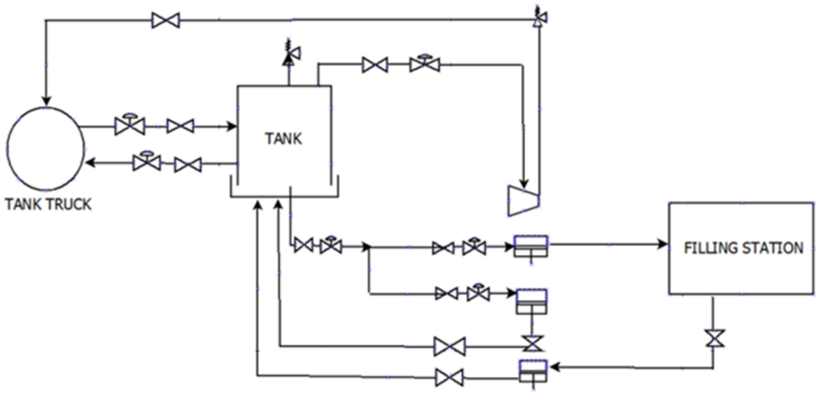

Figure 4: The section of the LPG plant considered in this work.

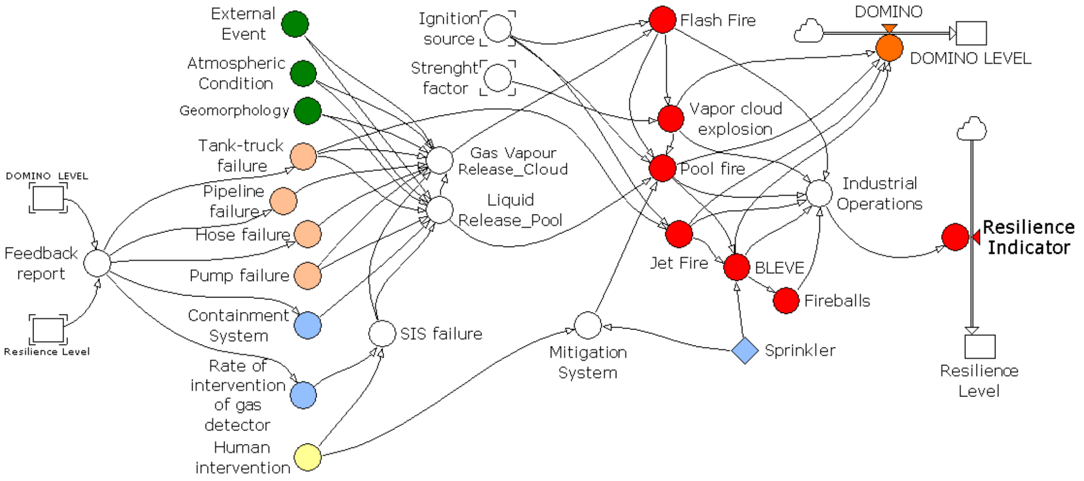

Figure 5: The SD model developed for the specific LPG plant installation of this work.

The analysis has been performed by using either static or dynamic modelling. The static analysis considers constant values for the failure rate λ(t) of equipment and operations (see Table 1). In this case, $\lambda(t) = \lambda_0$ and the results of SD are equivalent to classical risk assessment procedure. The values of λ_0 have been retrieved from the Rijnmond report as reported in Mannam and Lees (2005). For the dynamic modelling, we have considered the probability of structural failure of equipment by using either Exponential or Weibull probability distribution functions. The Exponential model uses the failure rate λ(t) in terms of Probability Distribution Function (PFD) and Cumulative Distribution Function (CFD):

$$PFD = Prob(t) = \lambda_o e^{-\lambda_o t} \tag{1}$$

$$CFD = Prob(t > T) = 1 - \lambda_o e^{-\lambda_o t} \tag{2}$$

The Weibull model is defined as:

$$PFD = P(t) = e^{-(^{t}/_{\alpha})^{\beta}} \tag{3}$$

$$CCFD = P(t > T) = 1 - e^{-(^{t}/_{\alpha})^{\beta}} \tag{4}$$

where 1/α is equivalent to λ_o and β has been set as a linear function between 0 and 5 for the time range between the equipment installation and the total life of the system (50 years).

In this preliminary analysis, some of the variables in Figure 5 (e.g. atmospheric conditions, external event, geomorphology, and domino effects) have been neglected. Other probabilities have been set on the basis of classical event tree data as reported in the Rijmond report (Mannam, 2005) and Vilchez et al. (2011).

Table 1: Failure Rate used for the SD reported in Figure 5. SIS = Safety Instrumented System

Variable	Function	Failure Rate [y^{-1}]
Compressor failure	Cooling system failure	$5 \cdot 10^{-4}$
Pump failure	Cooling system failure	$5 \cdot 10^{-4}$
Human Behaviour	Probability that the worker operates for the safety of plant after the release of content and/or after malfunctioning of equipment	0.91
Ground failure	Grounding fails due to bad design or bad maintenance (human error)	0.09
Lightning	Probability of lightning in the specific area	$1 \cdot 10^{-6}$
Faraday cage failure	Human error in design and maintenance	0.09
Hot Surface	Hot surface due to cooling system failure	Compressor U Pump failure
Ignition Source	Ignition may occur due to hot surface or static electricity, due to ground failure or lightning	Hot surface U Lightning ∩ Grounding failure
Tank truck failure	Structural failure of tank shell followed by release of content	$2 \cdot 10^{-5}$
Pipeline failure	Structural failure of the pipeline (hole or cut), followed by release of content	$5 \cdot 10^{-6}$
Hose failure	Detachment (failure, breaks), followed by release of content	$4 \cdot 10^{-4}$
Pump failure	Structural failure of pump, followed by release of content	$5 \cdot 10^{-4}$
Gas/Liquid Cloud	Formation of flammable gas/vapour cloud	Tank truck U Pipeline U Hose U Pump failure ∩ SIS
Liquid Pool	Formation of a liquid pool	Tank truck U Pump failure ∩ SIS
Jet Fire	Formation of a jet fire	Ignition ∩ Tank truck failure

Table 2 reports the results of SD analysis in terms of Resilience Indicator by using both Static and Dynamic functions. The larger is the RI, the greater is the resilience. Quite clearly, the static analysis gives a single value for the overall Resilience Indicator, which is larger than any other dynamic value, because the effects of the infrastructural and equipment ageing on equipment are not considered. On the other hand, the time affects the dynamic RI value with time due to the time-dependant reliability functions.

Table 2: Result of SD analysis in terms of Resilience Indicator RI for the LPG installation given in this work, for the 50 years-life of the plant, by using static and dynamic functions.

RI $\cdot 10^5$	10 y	20 y	30 y	40 y	50 y
Static			0.78		
Exponential	0.49	0.40	0.31	0.24	0.21
Weibull	0.76	0.46	0.46	0.44	0.42

In this preliminary analysis, we have tested the effects of adding a maintenance function, which refers to the node 3 of the model presented in Figure 1. The model is relatively simple: when the resilience function exceeds the value of $1 \cdot 10^{-6}$ (e.g. for the aging effects on the plant structure, equipment and instruments that increase the failure rate), a maintenance cycle starts and the components come back to the original state, as if they were new. Results are reported in Table 3, where the variation of the RI due to maintenance (RI_m) is given as the ratio between the data with the inclusion of maintenance and the data reported in Table 2. Quite clearly, a maintenance cycle cannot be included in the static model, whereas the implementation of the maintenance has affected strongly the dynamic models, in particular in the Weibull model. The variation of trend for the Weibull mode at longer equipment life (after 40 years) depends mainly on the constant value adopted for the tank truck failure.

Table 3: The variation of the Resilience Indicator with maintenance cycles .

RI_m/RI	10 y	20 y	30 y	40 y	50 y
Static			1.00		
Exponential	1.56	1.49	1.39	1.33	1.22
Weibull	1.00	25.00	20.00	100.00	50.00

4. Conclusions

System dynamics can be a useful tool in order to define and quantify the resilience of any industrial plant in a holistic point of view.

For the specific field of industrial safety, we have then defined a resilience indicator which depends on the annual probability of the occurrence of catastrophic accidental scenarios, and more specifically to fire, explosion, and toxic/noxious dispersion of substances in the atmosphere. Indeed, we have directly connected the occurrence of these events to the inability of the system to cope with the system failure, which in turn is related to either the loss of control of the process or to the structural failure of one or more equipment, followed by the release of energy or mass of hazardous substances.

Future work will be addressed to the development of other nodes of the main CLD (human behavior, maintenance, budget issues), and the inclusion of domino effect, natural events (Lanzano et al., 2014; Salzano et al., 2013), security issues in the consequence-based SD for the analysis or resilience.

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