HAZOP STUDIES USING A FUNCTIONAL MODELING FRAMEWORK

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Abstract

In this paper we present a HAZOP Assistant based on D-higraphs, a functional modeling technique that gathers functional and structural information of the process under study. The Assistant and the methodology are presented and applied to an industrial case: H_2S absorption and DEA regeneration. Its results are compared with other existing techniques showing that the Assistant fills the gaps and solves the drawbacks present in other approaches.

Keywords

Functional modeling; HAZOP; risk assessment; D-higraphs.

Introduction

In the last decades, in the process industry, there have been tighter environmental regulations, an increasing public concern on industrial accidents and, of course, the ever existing economic pressure on having more benefits, issues that have made that accident prevention be a fundamental task for this industry.

Process Hazard Analysis (PHA) are carried out to identify potential safety problems and to propose possible solutions such as process changes, new control strategies, etc. Different methods exist such as failure modes and effects analysis (FMEA), fault-tree analysis (FTA) and hazard and operability analysis (HAZOP) among others. HAZOP is the most used to conduct PHA analysis in the process industry (Knowlton, 1989).

This methodology works on the fundamental principle that hazards arise due to deviations from normal behavior. It is important to note that hazards may occur in any element of a controlled process plant including the equipment, control system and the operating personnel. Thus a HAZOP analysis preferably addresses both the process equipment, operating procedures and control systems. Beyond identifying the hazards and their possible causes, HAZOP analysis also identifies the issues that are recommended for risk management, that can lead to elimination or mitigation of a hazard.

HAZOP studies are easy, systematic and reusable but they take a lot of time and effort, which can be translated to money. In the last years, different approaches have been presented to (semi)automate HAZOP analysis, like HAZOPExpert (Venkatasubramanian et al., 2000), PHASuite (Zhao, 2005a,b) or recently MFM HAZOP (Rossing, 2010).

In this work a new HAZOP assistant is developed, based on the developed D-higraphs methodology, it considers functional and structural information of the system under analysis. Besides, this methodology and the tool developed takes into account in a natural way not only the process itself but the control system (or any other element in the system).

This paper is structured in 6 main sections. This first one has made a brief introduction on the necessity of PHA studies and specifically of automating HAZOP analyses. The following one briefly presents the D-higraphs methodology: elements, properties, representation and

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reasoning. The third one presents the D-higraphs HAZOP assistant and the environment to develop the models and the studies. The fourth one applies the methodology proposed to an industrial case. The following one compares this methodology with other approaches and in the last section the conclusions are drawn and future work is proposed.

D-higraphs

This section briefly introduces D-higraphs, their elements, properties, representation and application. For further information and deeper understanding of the methodology, the reader is encouraged to have a look at De la Mata & Rodríguez 2010b.

Dualization of Higraphs

Higraphs are a general kind of diagramming objects well suited to the behavioral specification of complex concurrent systems. They were first presented by Harel (1987, 1988) and they can be considered as an extension and combination of conventional graphs and Venn diagrams. Higraphs consist of two elements, blobs (states) and edges (transitions) connecting the blobs. However, higraphs are not suitable for process systems specifications.

Rodríguez & Sanz (2009) first presented D-higraphs as a functional modeling technique that merges functional and structural information of the system modeled.

They came from the dualization of Higraphs: blobs represent transitions and edges represent states. Disjoint blobs imply and AND relation, i.e., both transitions between states take place. Orthogonal blobs represent and OR relation, i.e., only one of the transitions takes place.

It has to be noticed that a D-higraph is NOT a dual higraph (like dual graphs), obtained from changing blobs by edges and edges by blobs. The duality lies in the interpretation of blobs, edges and their properties.

Blobs and Edges

Blobs represent functions (transitions) and they are depicted with their elements as shown in the top of Fig. 1. The function is performed by the ACTOR producing state 2 if the state 1 is enabled and if the condition is true.

Firing the function causes new states, represented by edges coming out of the blob. Edges represent flows of mass, energy or information, which are responsible of all of the interactions in a process system (Lind, 1994).

Mass, energy and information edges are depicted differently, as shown in the bottom of Fig. 1. However, the type of flow does not affect the behavior of the model, it is a visual aid to represent more information.

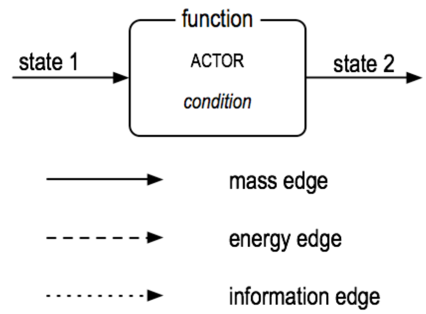

Figure 1. Basic blobs and types of edges.

Properties

- *Blob connection*. An edge always links two blobs: its tail and its head. Under certain conditions, the blob in the tail or in the head can not be represented (elliptic blob) but it exists.
- *Blob inclusion*. Blobs can be included inside of other blobs (Venn diagrams inclusion property). This means that the inner blob performs a function that is necessary for the function of the outer blob. This is how hierarchical functions are represented and how structural and functional information is integrated.
- *Partitioning blobs*. A blob can be partitioned into orthogonal components, establishing an OR condition between the partitions.

Causal Reasoning

The main objective of D-higraphs is not only the representation of knowledge about process systems. De la Mata & Rodríguez (2010a,b) provide a series of causation rules relating two events (cause and effect) that allow us to track the evolution and propagation of failures across the system. This rules combined with sensor data of the process enables the possibility of performing FDI analysis using D-higraphs models.

Qualitative Simulation

Certain analyses require not only reasoning with failures but with deviations, for example, HAZOP studies. In a certain way, we need to simulate qualitatively the system to propagate these deviations.

The description of a system is made in three different layers (Kuipers, 1984):

1. *Structural* description: variables that characterize the system. If we consider a process plant, the most common variables are: flow (F), temperature (T), composition (x), pressure (P), energy (E), information (I), level (L), valve opening (O), etc. These symbols will be used across D-higraphs.

2. *Behavioral* description: potential behavior of the system as a network. The connection between variables will be established using the M^+ and M^- constraints of Qualitative Physics (Kuipers, 1986). We will use the following compacted notation:

$$Z^{X_1,X_2\ldots X_n}_{Y_1,Y_2\ldots Y_m} \Leftrightarrow M^+(X_i,Z)\wedge M^-(Y_j,Z) \quad \forall i,j \qquad (1)$$

Meaning that variable Z is related with the n variables X_i by a M^+ constraint and with the m variables Y_j by a M^-.

3. *Functional* description: Purpose of a structural component of connections. The functional description of the process is provided by the D-higraph layout. The three layers of this representation are shown in Fig. 2.

In this example there is a physical device, the decanter, whose main (intended) purpose is to store liquid, it has to characteristics variables: level and temperature (Ld and Td). Level (Ld) is affected by the inflow (F3) and the outflow (F4), Ld^{F3}_{F4} means that increasing F3, the decanter level increases and that increasing F4, the decanter level decreases. In the same way, the flow (F4) is affected by the level of the decanter, in such a way that an increase in the level produces an increase in the flow.

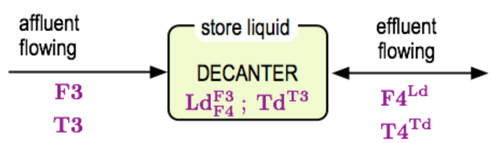

Figure 2. Three layer D-higraph.

D-higraphs HAZOP Assistant

Fig. 3 shows the environment where D-higraphs are developed together with its reasoning system. The models are implemented using a tool developed with Microsoft Visual Basic (Álvarez, 2010). This tool has as inputs the P&I of the process (it also has a D-higraph template built in). The tool produces the D-higraph of the process under study and it also generates the file needed for the reasoning engine. This engine runs on CLIPS (C Language Integrated Production System) which is a software tool to construct rule or object based expert systems (CLIPS, 2011).

Once the model has been implemented and loaded on the expert system using the above-mentioned environment, the HAZOP study is carried out following a conventional approach (setting process variable deviations) but using the reasoning engine to draw the conclusions. The results of the analysis (causal tree) are output to the user and they can be fed back to the modeling tool in order to make changes into the process and/or D-higraph.

Case Study

Amine gas treating is a process that uses an aqueous solution of an amine to remove H_2S and CO_2 from gases. In this case we consider the treatment of an off-gas from a secondary absorber of a FCC in an oil refinery using an aqueous solution of diethanolamine (DEA).

The process is shown in Figure 4 and it is a simplification of an already existing DEA process in a Spanish oil refinery; De la Mata & Rodríguez (2010b) provides further information.

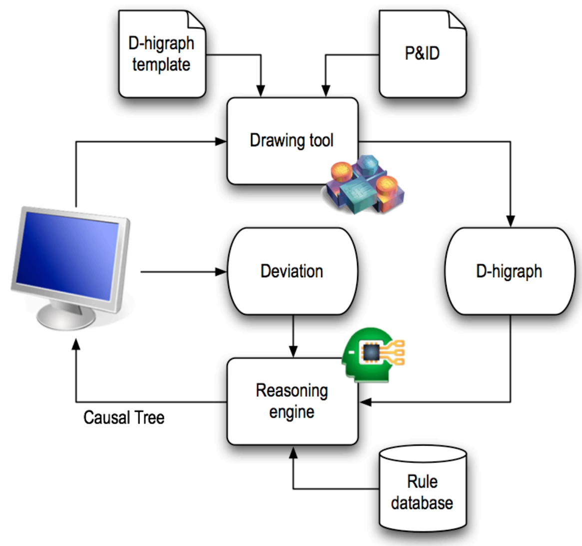

Figure 3. D-higraphs environment.

Process Description

In the absorber the DEA solution absorbs H_2S and CO_2 from the incoming off-gas producing a sweetened gas stream and a DEA solution rich in the absorbed acid gases. The sweet gas is sent to the high-pressure gas system of the refinery while the rich amine is routed to the regenerator.

The regenerator is a stripper with a reboiler where the rich amine desorbs H_2S and CO_2 producing a lean amine stream that is recycled to the absorber for reuse. The reboiler is fed with steam to vaporize the DEA solution. The temperature at the stripper must be carefully controlled because at temperatures greater than 120ºC the DEA degrades.

The stripped overhead gas is condensed to produce two streams. One is the acid gas (H_2S and CO_2 concentrated) and the other one is mainly condensed water and DEA, which is reintroduced in the stripper as reflux. The acid gas is sent to a Claus process while the lean DEA is recycled to the absorber.

As DEA is regenerated in the stripper, it degrades over time, even operating below 120ºC. In addition, the output stream can carry small amounts of DEA, so a make-up DEA stream is needed to keep the amine inventory.

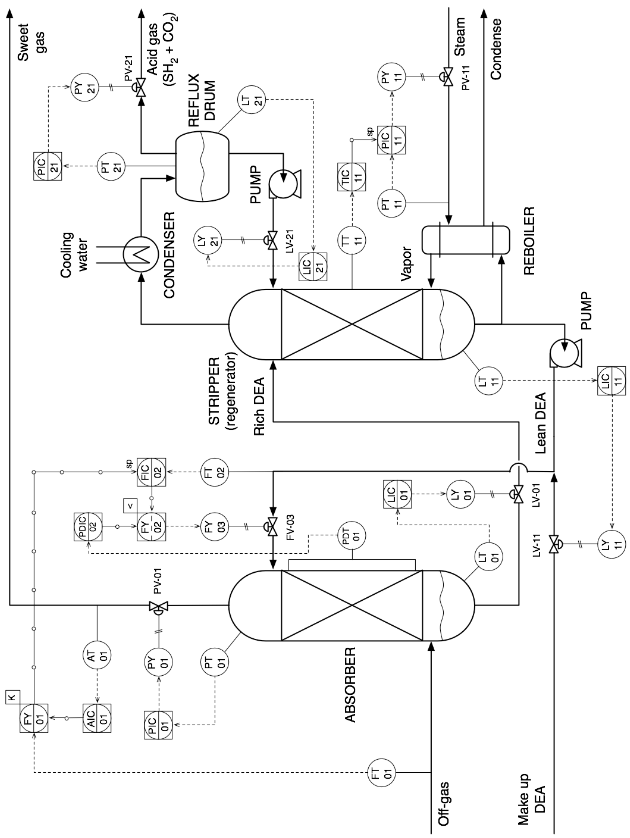

Figure 4. H_2S absorption and DEA regeneration.

Note that Fig. 4 also shows the basic control of the absorption unit.

Functional Decomposition and D-higraph

The main objective of the overall system is to "sweeten the off-gas within operation conditions", to that end the system can be divided in the following subsystems (with their own subgoals):

- *Absorption*. Absorb H_2S and CO_2.
  - *Absorber*. Contact DEA and off-gas.
  - *Absorber level control loop (CL)*. Keep level.
  - *Absorber pressure CL*. Keep pressure.
  - *Sweet gas quality CL*. Keep sweet gas quality.
  - *Pressure drop CL*. Avoid flooding.

- *Regeneration*. Regenerate DEA.
  - *Stripper*. Desorb H_2S and CO_2.
  - *Reflux section*. Provide reflux.
  - *Stripper temperature CL*. Keep temperature.

In this paper, due to space constraints, only a small part of the overall D-higraph is shown: the reflux section of the stripper (see Fig. 5).

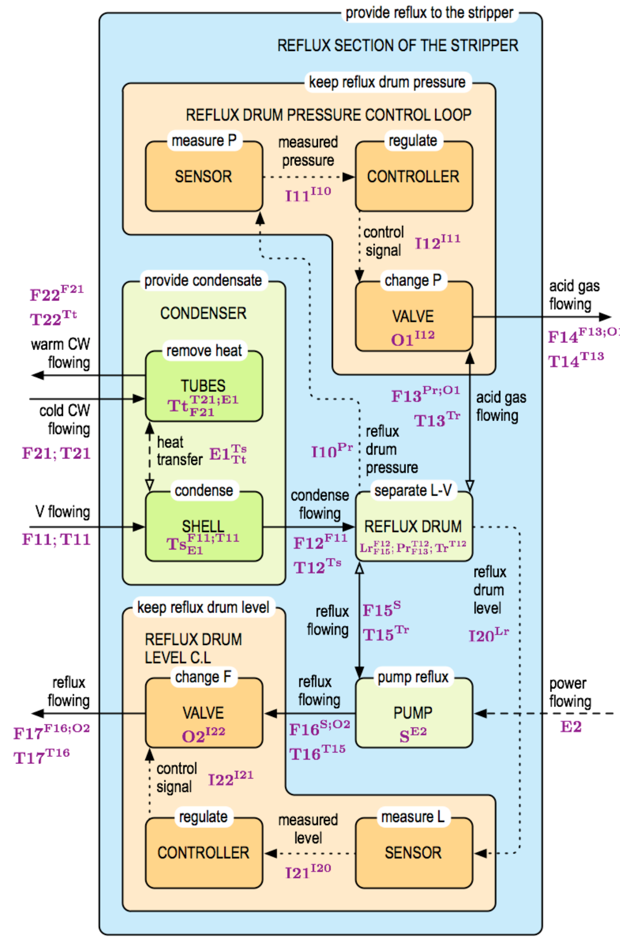

Figure 5. D-higraph of the reflux section of the stripping part of the amine process.

Deviation 1: High Temperature in the Reflux Drum

This deviation consists in the variable "Reflux drum temperature" and the HAZOP guide word "MORE OF". According to the methodology presented and the D-higraph in Fig. 5, the causal tree obtained is shown in the left part of Fig. 6. This tree can be directly translated to the variables of the process: The fact that the temperature in the reflux drum is higher than its expected value (*Tr: inc*) can be motivated by a higher temperature in the flow from the condenser to the reflux drum (*T12: inc*) and this deviation can be a consequences of a higher flow to the condenser (*F11: inc*), a higher temperature in the flow to the condenser (*T11: inc*) or to a low heat transfer in the condenser (*E1: dec*), and so on.

Note that as flow to the condenser (*V flowing*) is an input to the D-higraph it would be a primary cause. However, if we consider the overall D-higraph of the process, this chain of causation can be expanded.

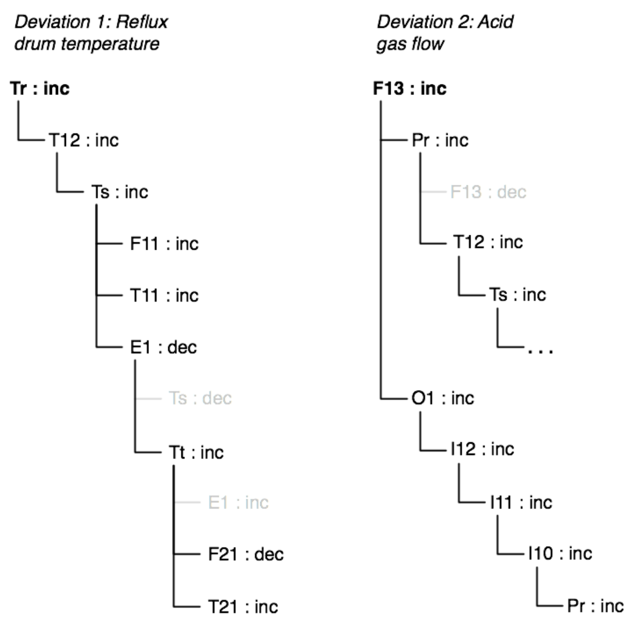

Figure 6. Causal trees for the deviations considered.

Deviation 2: High Flow of Acid Gas

This deviation consists of the variable "acid gas flow" and the HAZOP guide word "MORE OF". The causal tree obtained for this deviation is presented at the right hand side of Fig. 6.

The possible causes of this deviation are a high pressure in the reflux drum (*Pr: inc*) or a valve opened more than it should be (*O1: inc*). These causes can be developed and translated as before, as it appears in the tree. Note that in this case the control loop is also included in the analysis. The control signal (*I12: inc*) and the measured value of the pressure (*I11: inc*) appear in the causal tree, so the control system is also included in the HAZOP analysis.

Comparison with Other Methodologies

Conventional HAZOP Studies

Conventional HAZOP studies are a systematic and logical approach to PHA but 70% of the time involved is devoted to routine deviations (Venkatasubramanian et al., 2000).

The automation of the procedure saves times and hence, money. Another advantage of automating the analysis is that each node is fully explored and no nodes are left unexplored. All of this means that the quality of the analysis is enhanced: the HAZOP team can devote its time to analyze the deviations, the causal trees and their possible solution while they do not have to produce them.

HAZOPExpert

HAZOPExpert (HE) is a model-based, object-oriented, intelligent system consisting of two knowledge bases: process specific and process general knowledge. The main problem with this approach is that the specific knowledge base has to be updated for each process. D-higraphs HAZOP Assistant only needs a D-higraph of the process as its rule database remains the same. The accuracy of HE lies in the specific expertize of the team developing the knowledge base. However, it has ben tested in a number of actual process plants and it can be also applied to batch processes.

MFM HAZOP Assistant

The methodology presented in this paper is quite similar to the functional HAZOP assistant based on the Multilevel Flow Modeling (MFM) (Lind, 1994, 2005) technique. The main difference lies in the modeling paradigm. The main disadvantage of the MFM HAZOP Assistant is that the conclusion of their studies "*can not be mapped to the P&ID*" (Rossing et al., 2010). As D-higraphs integrate functional and structural information, the conclusions of the study can be directly related to the devices and equipments of the process.

The MFM HAZOP Assistant needs a MFM model for each node considered in the study while the D-higraph HAZOP study uses a single model for the whole study. To perform the analysis only depth (in terms of causation) has to be specified.

Conclusions

In this paper we have proposed a systematic methodology to perform guided HAZOP studies based on the D-higraphs functional modeling technique. To show how it works, we have applied the methodology to an industrial process and it has been compared with other existing approaches.

The resulting HAZOP analyses are more complete than other methodologies with an additional advantage; the functional model, the D-higraph, used to guide the studies integrates functional and structural information about the process under consideration.

Further work will involve the application of this formalism to on-line fault diagnosis identification and the isolation of these faults integrating quantitative models to verify and disambiguate non-unique possibilities. Future work will also be devoted to the implementation of a "translator" which will transform the P&IDs to D-higraphs models in a semi-automatic way.

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