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Management of System Complexity in HAZOP for the Oil &Gas Industry

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Abstract: The paper gives an insight in how to deal with system complexity from a HAZOP study perspective. The research enlightens the importance of understanding system complexity in oil and gas industry and thereby gradually to change old-fashioned HAZOP industrial practice and improve safety performance in oil and gas industry. Methods and computer aided tools mentioned in the paper can improve HAZOP quality and efficiency with low manpower cost and support brainstorm section in HAZOP studies. The oil and gas industry can implement the method for HAZOP study on real plants to test its usefulness.

Keywords: Knowledge engineering; Systems engineering; Models; Safety analysis.

1. INTRODUCTION

Development of systematic methods and techniques for ensuring safety across the life cycle of complex systems is an important challenge for the systems engineering community. HAZOP (HAZard and OPerability) is among these systematic methods and techniques, which is used by oil and gas industry to identify hazards and operability problems. After several decades of its application from 1974, very little focus has been on the dimensions of system complexity dealt with in HAZOP studies in the different stages of life cycle of a plant project. Recent accidents in advanced industrial processes and technological infrastructures also have demonstrated that system complexity is a major challenge in the management of process safety. Understanding the nature of system complexity and how to deal with it and manage the associated risks are the focus aspects of system designers as well as operators, and also the focus of science-based safety engineering research.

Plant design documents, operating procedures, online data are in different forms used to represent the system complexity. As always, these are necessary sources to carry out HAZOP. Proper integration of these sources of information requires a fundamental knowledge of system complexity and knowledge of how to cope with it by means of system models.

As indicated by the literature review presented by Dunjó et al. (2010), approximately 40 % of HAZOP-related research is focused on HAZOP automation. Some computer-aiding applied to HAZOP reviewed by Lees (1996). In principle, it is commonly agreed that it is impossible to completely eliminate the presence of a human expert team in the HAZOP execution process, but there are several attempts to create a robust support tool that is able to automate some of the procedures necessary to perform a HAZOP study. Zhao et al. (2009) argued that the difficulties of fully automating HAZOP by computer lie in the fact that the highly flexible reasoning mechanism and knowledge structure of human experts cannot be effectively simulated by computer systems. In addition, it is problematic to assume we ever be possible to obtain complete knowledge.

Besides the available documentation tools which provided workflow support for HAZOP analysis, such as PHAWorks, and PHAPro, there are two basic approaches in HAZOP automation experts system with reasoning capabilities: shallow knowledge based and model based. Shallow knowledge-based approach uses large knowledge databases containing information about the failure mode, causes and consequences of various process units and/or pieces of equipment. Typical knowledge-based experts systems are e.g. projects of OptHAZOP, TOPHAZOP and EXPERTOP by Khan and Abbasi (2000), ExpHAZOP by Rahman et al. (2009). Typical model-based experts systems are e.g. HAZOPExpert, a HAZOP automation tool developed by Venkatasubramanian and Vaidhyanathan (1996), PHAsuite and PetroHAZOP by Zhao et al. (2005), HAZID by McCoy et al (1999).

This study gives an insight of how to deal with system complexity from a HAZOP study perspective. A functional based HAZOP method and computer aided tool are introduced for improving HAZOP quality and efficiency with low manpower cost and supporting brainstorm section in HAZOP studies.

Section 2 gives necessary background about HAZOP technique and relevant topic of the paper. Section 3 analyses the knowledge management of system complexity in HAZOP. Section 4 presents the methodology used in this paper, namely functional model-based HAZOP method. Section 5 presents a simple case study to illustrate the proposed method. Some discussion and perspectives are in section6. Section 7 concludes the work and gives an outlook for future work.

2. HAZOP TECHNIQUE

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2.1 HAZOP Method

In the 1960s, an improved form of what-if analysis emerged within Imperial Chemical Industries (ICI), and its application first became known as operability and hazard studies. Later, to emphasize the importance of process safety, the name HAZOP was coined. HAZOP study is a well-accepted method for hazard identification of process designs and for planned modifications, which initially was developed for analysing chemical process hazards (Kletz, 2001). The training of HAZOP is also continuously done in education and industry and lessons were learnt. It greatly accelerated after the methyl isocyanate (MIC) release in Bhopal, India, in 1984. A large release of hydrogen fluoride from a Texas City, Texas, refinery in 1987 prompted the oil and gas industry to embrace HAZOP studies.

The approach is a structured brainstorming using guidewords and is performed by a multidisciplinary team during a set of meetings to derive the records of causes and consequences of deviations. An effective HAZOP ensures that all potential deviations from design intentions are identified and process hazards are revealed. Based on the brainstorming sessions, mitigating actions can be planned against unacceptable process consequences or actions for improvement of the system safety integrity level. It is important that records of the brainstorming sessions and documentation of planned actions are available for review by management and authorities.

2.2 Challenges Facing HAZOP

HAZOP mainly faces 5 challenges: (1) Knowledge management of system complexity; (2) Uncertainty; (3) Vagueness; (4) levels of completeness; (5) Efficiency. The challenges pyramid is shown in Fig. 1. The following sections address the first challenge in detail.

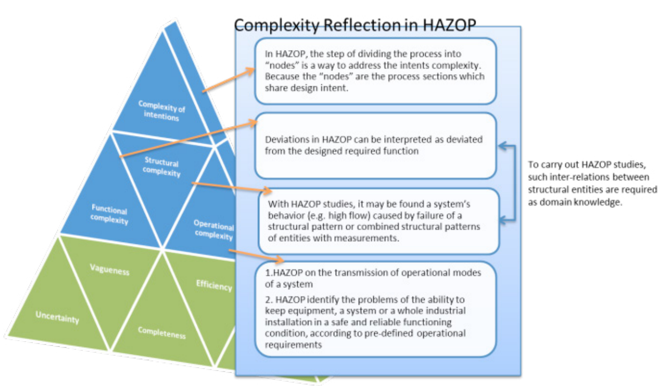

Fig. 1. Pyramid of HAZOP challenges

3. KNOWLEDGE MANAGEMENT OF SYSTEM COMPLEXITY IN HAZOP

HAZOP is a tool or process to identify potential hazard and operability problems. It is used to provide management with knowledge of where potential hazards may exist and to provide information on mitigation recommendations for plant design modifications prior to construction, on mitigation recommendations for providing specific details for administrative controls, on hazard information communication. Understanding of the system complexity is the means to carry HAZOP. In addition, HAZOP itself is a structured method to cope with complexity.

Complexity in system engineering can be expressed by the multiple levels of subsystems, their connections and the number of system elements and their interrelations (Lind, 2014). In terms of functions, the function of entire complex systems is the aggregation and convergence of the functions of the sub-parts.

Before we look into the complexity of an engineered system, the distinction between three types (structure, function and behaviour) of description of a physical system is explained.

The essence of a functional description is teleology or intention, the relation of the structure and behaviour of a mechanism to its larger context. For example, pumps have two generic functions: one function of a pump is to transport fluids under specific conditions and another function of a pump contains all fluids under all pertinent design conditions. Semantic analysis reveals that the verb transport represents a relation between an element of structure (the pump) and a possible behaviour (fluids are not vaporized). However, simulation of the working equipment does not include vaporization among its possible behaviours. The possibility of vaporization is command in the design process for the equipment, prior to the addition of the pump. The operating pressure of the pump ensures the fluids are able to be in liquid phase under design conditions.

Different dimensions of complexity of a system are elaborated below.

3.1 Complexity of Intentions

At the highest level of a design process, the designer bears the design intent in mind. Through the design process, the designer transforms the design intentions into realizable design details. HAZOP plays a role in verifying if the design solution is safe and safe enough considering foreseeable and unforeseeable events. .

In HAZOP, the step of dividing the process into "nodes" is a way to address the complexity of design intentions. Because the "nodes" are the process sections which share design intentions. However, how to divide the "nodes" is not explicitly explained in the traditional HAZOP method procedure. Dunjó et al. (2011) proposed a criterion for selecting and sizing nodes. But the complexity of intentions was not addressed in his paper. The complexity of design intentions is rooted in the hierarchical levels of design objectives. The complexity of intentions can be expressed by a goal tree (GT). The GT is concerned with the goals and objectives which must be achieved by the system. Both safety and process objectives are represented in the GT. The customary usage is to start the GT with a single top objective which is achieved if all safety and process objectives are met. All objectives are then described in terms of sub-objectives which may also be further refined, continuing to any level of detail required. In general, at the upper levels which comprise the GT, this decomposition is found to form a conjunctive hierarchy, in that, at these levels of abstract description, objectives decompose into sub-objectives all of which must be achieved.

3.2 Functional Complexity

In engineering, a function is interpreted as a specific process, action or task that a system is designed to perform (Khazaei, 1993). System functions are facts such as that all knowledge shared by engineers is agreed upon in the community (Searle, 1995). These for two interwoven principles, namely as machine-like functions and 'regulation' functions, then machine-like functions are ideally defined by precise operational principles, while the correctness of a regulative achievement can be expressed only in gestalt-like terms. In process engineering domain, these two principles refer to the process functions and control functions. Therefore, the functional complexity is inter-subjective (Wu et al., 2014).

Suh's measure of complexity (Suh, 2012) in the functional domain is built on the concept and framework of axiomatic approach of design. In his complexity theory, complexity is defined as a measure of uncertainty in satisfying the functional requirements (FRs) within the specified accuracy. In designing engineered systems, by means of design parameters (DPs) or physical parameters to satisfy the FRs. When a given DP is chosen to satisfy the FR, the uncertainty is characterized by the system's ability to satisfy the FR within its design range. The FR is satisfied only when the system range is within the design range. HAZOP is used to identify the scenarios when system range is overlapped or completely out of design range. However, the traditional HAZOP method is not able to verify the functional requirements in a satisfactory way. Because it does not start from the intended system functions analysis.

3.3 Structural Complexity

Structural complexity deals with multiple connections between component and subsystem of a technical system. Structural Complexity Management is often seen as having evolved out of the first complex engineering projects that were accompanied by the paradigm of Systems Engineering, having it evolved out of Systems Theory. There is a substantial body of metrics available that is able to assess the structural complexity of a system with a view to different patterns. However, the transfer to the specifics of engineering design processes, i.e., what behavioural aspects relate to what structural characteristic evaluated in a metric, remains unsolved. The relation between structural complexity and behaviour is a challenge for traditional HAZOP studies because it can be difficult to associate parameter deviations with structure patterns.

3.4 Means-end Relation Links Functions and Structures

In the context of system objectives, the structural complexity can be expressed by five types of inter-relations between structural entities (e.g. components, energy and material medium) and system functions in means-ends relations, see in Fig.2: (1)Side effect: Although the structural means are dedicated to achieving a particular function, some of them may exert secondary effects on other functions.(2) conditional constraints: in many cases, the use of a structural entity in order to ensure a function may be conditioned on the fulfilment of another structural entity.(3) Technical dependencies: They are generally due to the sharing of technical resources between several structural entities. (4) Sharing dependencies: To achieve a specific function (capacity), it is required to share structural entities or interactions of structural entities. (5) Arbitration: In some cases, alternative structural entities are required to achieve a specific function. To carry out HAZOP studies, such inter-relations between structural entities are required as domain knowledge.

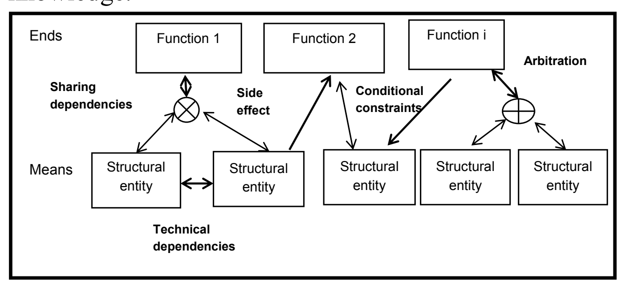

Fig. 2.A generic presentation of structural complexity in the context of system objectives

3.5 Operational Complexity

Operability is the ability to keep equipment, a system or a whole industrial installation in a safe and reliable functioning condition, according to pre-defined operational requirements. Accordingly, operability problems are associated with any operation which under the requirements would cause a shutdown or possibly lead to a violation of HSE (Health, Safety, and Environment) regulations or negatively impact profitability.

Operational complexity includes the consideration of the operational modes of a system, for example, start-up mode is required to get the system into the nominal operation situation, emergency modes guarantee secure operation when shutting down, or different configurations to comply with varying demands (Kirchhübel, 2016). Process HAZOP needs to pay more attention to the transmission between operational modes of a system.

3.6 Summary

HAZOP is required to relate a system representation to the underlying chain of causality of triggering hazards. Therefore, there is a need to provide a modelling method which can reveal above system complexity aspects relevant for system design and operation. Also such modeling language should be with clear syntax and semantics to decompose and aggregate the above mentioned different aspects of complexity in a meaningful way, such as for example by using means-ends and whole-part decomposition. Furthermore, it should have a feature for supporting cause-consequence reasoning.

4. METHODOLOGY

4.1 *Functional model-based HAZOP method*

Deviation scenarios can be categorized into typical and atypical scenarios. Typical scenarios are those happen frequently and known deviation from normal expectations of undesired events based on prior knowledge. Normally, they can be identified and analyzed by HAZOP. Atypical scenarios (Paltrinieri et al. 2012) are those unknown scenarios due to lack of knowledge, which are usually missed or outside the scope of HAZOP. Those atypical scenarios can be learnt through the accident lessons.

Functional model-based HAZOP method presented in the paper can support process knowledge representation as well as the brainstorm section of HAZOP dealing with both types of scenarios. The reason is that the causality of events comes from functional means-end analysis. It will be explained in detail in following sections.

4.2 Multilevel Flow Modeling (MFM) technique

MFM is a network structured hypergraph, where the connection between function nodes (flow functions and control functions) is constrained by syntax rules. Connections represent casual relation (influencer and participate) as shown in Fig. 3. The set of function primitives are defined on the basis of a theory of action types applied for process systems. States of the function nodes are defined by possible failure modes of the specific function. MFM provides facilities for semantic distinctions between different functional abstractions of a system and gives guidelines of how to decompose and aggregate system functions, and how to relate them to objectives using means-end relations (Lind, 2017). Terminologies of MFM can be found in tutorial (Zhang & Lind 2017a). The MFM models presented in the following are built using a web-based model builder called EGolF developed by ELDOR Technology, Norway.

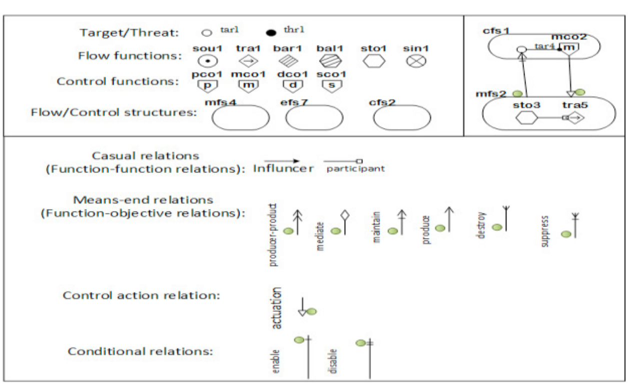

Fig. 3. MFM symbols

4.3 MFM reasoning

Reasoning with MFM models is based on the cause effect relations associated with the function–function and function–objective relations (Zhang et al. 2015). These casual-effect relations are general, i.e. independent from the concrete systems to be modelled. MFM model reasoning is based on a fixed set of cause-effect inference rules defined by MFM model patterns. Those cause-effect inference rules are still under exploration for expanding to accommodate for more specific engineering domains and cases. The recent developed rules for reasoning about control and barrier functions are implemented and applied in the case study described below. For readers who are interested in the reasoning rules pattern of control functions and barrier functions in detail, please refer to the relevant work published in (Zhang & Lind 2017b; Wu et al. 2017).

The MFM reasoning engine developed at Technical University of Denmark (DTU) implements the inference rules in a rule-based reasoning shell. The reasoning system propagates state information of each function and can derive possible cause and consequence paths of a given deviation in a functional state. The functionality of EGolF is under development for implementing the inference rules. Currently, it can be used for reading the reasoning case file from the reasoning engine developed in DTU and display the evidence and cause-consequence paths. For HAZOP studies, the reasoning rules can be used. What is more, the same reasoning rules can be used for offline/real-time diagnosis analysis in the light of observations or other evidence is used by the reasoning system to select cause-consequence paths consistent with the given evidence.

5. CASE STUDY

The scope of the HAZOP was the Water Treatment Pilot Plant at AAU Esbjerg. A specific operational case was defined including the following main process equipment: waste water tank (MT02), waste water pump (WP01), compressed air addition, vertical pipeline rise, 1-stage separator and one hydro cyclone (HY05). The stream diagram of the system is shown in Fig. 4.

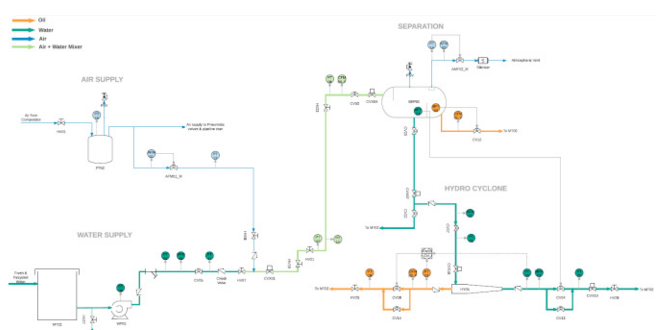

Fig. 4. The stream diagram of the Water Treatment Pilot Plant at AAU Esbjerg

A traditional HAZOP study was completed by 13 HAZOP team members in a 2 days' workshop. All in all, 60 deviations from design intent were identified and 27 recommended actions were put forward.

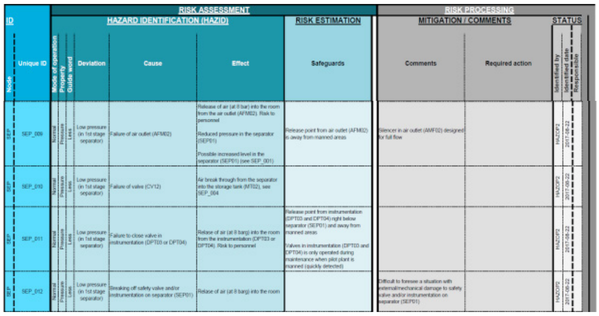

Fig. 5. Traditional HAZOP results of separator pressure low

In order to compare the results from traditional HAZOP and functional-based HAZOP, the deviation of the separator pressure low is taken as an example. The result from the traditional HAZOP study is shown in Fig. 5. By contrast, an MFM model was built for the same scope of the system following a modelling strategy (Lind, 2017). The MFM model is shown in Fig. 6. Separator pressure low means the state of the storage function PT14_pres_sto is low. The cause reasoning results for the separator pressure low are five causal paths: PSV_pres_bar breach-ds, CV03_CVX04_pres_tra low, CV07_pres_tra high, Level_Sep_sto low and CV12_pres_bar breach-ds. If we take CV12_pres_bar breach-ds as possible causes, then the other possible causes are isolated by setting those functions' states as normal, then the consequences are shown in Fig.8. Tnere are four possible consequences: CV07_pres_tra low, Sep01_PCtrl_obj false, AFM02_M_Mfs_tra decrease, CV03_CVX04_pres_tra high and AirTo Mt02_pres_sin high. Following such procedure, all possible consequences for each possible cause can be identified.

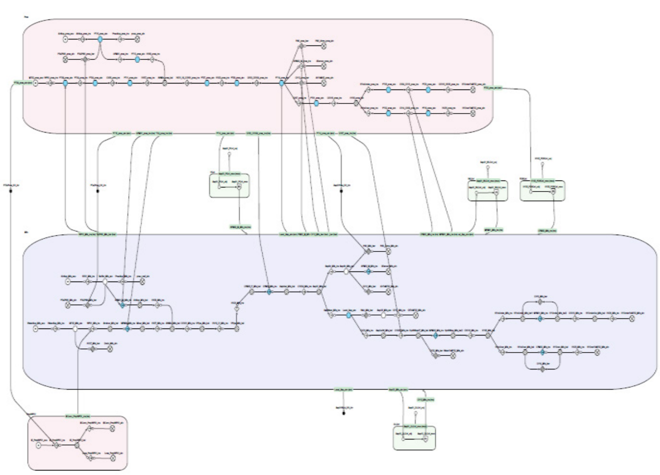

Fig. 6. An MFM model of the Water Treatment Pilot Plant at AAU Esbjerg

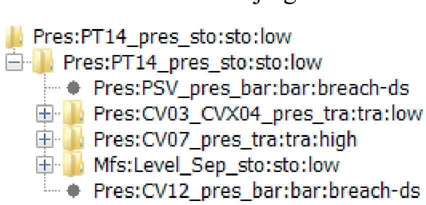

Fig. 7. Causual paths for the separator pressure low

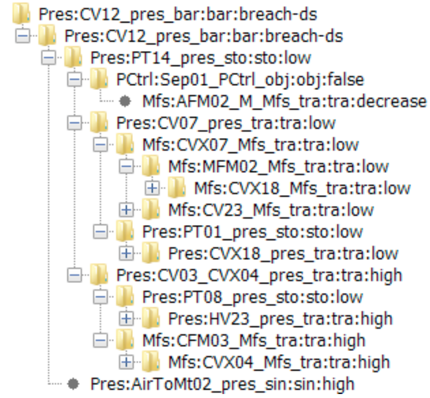

Fig. 8. Consequence paths for the CV12 breach downstream

The result clearly indicates that one more possible cause is the upstream inlet pressure is low and consequences along the timestamp change can be identified by the functional-based HAZOP method.

6. DISCUSSION and PERSPECTIVE

From the case study results, some significant features of the proposed method are discussed below:

First, functional modelling may reduce the modelling complexity and thereby reduces the complexity of HAZOP studies. Modeling of a plant from functional perspectives may be abstract; however, it is coherent with the functional requirement of process system design. The functional requirements for a process system are less than the possible physical objects combinations such as plant structure model of ISO 15926. In this way, the modeling complexity decreases. Multilevel Flow Modeling is a best suitable technique for functional modeling. Traditionally, HAZOP only considers one node at a time, and the node boundary selected maybe based on the structural decomposition, which could result in poor boundary selection. The different isolated nodes may contribute to the same function requirements. By contrast, if the process is modelled by functional stream, the isolated nodes can be aggregated into one node await for the following HAZOP analysis since the functional nodes decomposition attempt to capture the functional requirements. Consequently, it reduces the complexity of HAZOP studies.

Second, qualitative functional models facilitate better understanding the process system in a high level abstraction and require capability of representing knowledge associated with non-routine HAZOPs to improve completeness. Functional models represent safety functions together with plant process functions. Control function in MFM models can represent mode transmission by additional studies on means-ends decomposition of the control system so that it can assist in HAZOPs for non-routine modes of operation, namely, non-routine HAZOPs.

Third, casual reasoning in functional-based HAZOP is based on tacit knowledge. The communication among HAZOP team members is based on the sharing prototypical definitions of physical objects because they have similar experience, so called tacit knowledge. The causal reasoning is an analog formalizing process. The qualitative casual reasoning is useful to perform backward reasoning (cause) and forward reasoning (consequence) assisting the brainstorming session tailored to a specific domain.

7. CONCLUSIONS

It concludes that HAZOP technique is a key in Process Safety Review methodology for risk management. It pointed out the HAZOP challenges and the computer aided methods for HAZOP involve with application of functional models to deal with those challenges in the aspect of knowledge management of system complexity. Multilevel Flow modeling (MFM) should be selected to do modelling of process systems and reasoning to generate hazard scenarios. The completeness of such HAZOP results can be verified by industrial HAZOP studies. Although best HAZOP practice is always the target to achieve in oil and gas industry, the performance satisfactory varies from companies. Therefore, companies should be encouraged to have an open mind to embrace such advanced safety technologies by all means.

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