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Wu, Jing; Lind, Morten

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

J. Wu*, M. Lind*

* Department of Electrical Engineering, Technical University of Denmark, Kongens Lyngby, 2800, Denmark (e-mail: jinwu@elektro.dtu.dk and e-mail: mli@elektro.dtu.dk).

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 supporting brainstorm section in HAZOP studies. The oil and gas industry can implement the method for HAZOP study on real plants to test its usefulness.

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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 Vaidhyananathan (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
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.

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.

### 2.1 HAZOP Method

In贯彻1960s,一个改进的什么-如果分析形式出现了,它最初被称为可操作性和危险研究。后来,为了强调过程安全的重要性,“HAZOP”这个词被使用。HAZOP研究是一个被广泛接受的方法来识别过程设计的危险和计划的修改，这最初是在分析化学过程危险时提出的(Kletz, 2001)。HAZOP的培训也在教育和工业中持续进行。它大大加快了,在1984年,对墨西哥城,德克萨斯州,一家炼油厂的大规模氢氟酸泄漏促使石油和天然气工业开始接受HAZOP研究。

这个方法是结构化的头脑风暴,使用引导词,由一个多学科团队在一系列会议进行,来推导出原因和后果记录。一个有效的HAZOP确保所有潜在的偏离设计意图的危险被识别和过程危险被揭示。基于头脑风暴会议,缓解措施可以被计划来防止不可接受的过程后果或行动为了改进系统安全完整性水平。重要的是,记录头脑风暴会议和规划行动的文档可以被管理方和当局用于审核。

HAZOP面临5个挑战: (1) 系统复杂性知识管理; (2) 不确定性; (3) 模糊性; (4) 完整性级别; (5) 效率。挑战金字塔如图1所示。下面的章节将详细探讨第一个挑战。

### 2.2 Challenges Facing HAZOP

HAZOP 主要面临 5 个挑战：(1) 专业知识管理系统复杂性；(2) 不确定性；(3) 模糊性；(4) 完整性级别；(5) 效率。图 1 中的金字塔展示了第 1 个挑战。下面的章节将详细探讨这个挑战。

#### 3. KNOWLEDGE MANAGEMENT OF SYSTEM COMPLEXITY IN HAZOP

HAZOP 是一个可以识别潜在的危险和可操作性问题的工具。它被用于提供管理方与掌握的潜在危险有关的知识,并要求提供关于缓解建议的信息,为设计变更提供在设计前的缓解建议,并提供针对特定细节的行政控制,有关危险的信息推荐。理解系统的复杂性是其核心。HAZOP 是一个结构化的方法来应对复杂性。此外,HAZOP 自身是一个结构化的方法来应对复杂性。在 HAZOP 的步骤中,将过程分为“节点”是一种方法来表达设计意图。如果忽略这些“节点”,这些是过程的步骤,它们分享设计意图。然而,如何将“节点”明确地解释在传统的 HAZOP 方法流程中。Dunjö et al. (2011) 提出了一个标准来选择和定大小。但是,即便是这些意图在论文中没有被提到。设计的复杂性是根植于不同层次的系统目标。设计的复杂性可以被表示为一个目标树 (GT)。GT 是关心的目标和目标,它们必须由系统来实现。根据定义严苛的目标要求。所有目标都是描述为子目标。
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 (Seurle, 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 regulatory 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 fulfillment 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-relationships 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 that 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 EGoIF developed by ELDOR Technology, Norway.

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 EGoIF 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.

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.
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_tr low, CV07_pres_tr 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. There are four possible consequences: CV07_pres_tr low, Sep01_PCtrl_obj false, AFM02_M_Mfs_tr decrease, CV03_CVX04_pres_tr high and AirTo Mt02_pres_sin high. Following such procedure, all possible consequences for each possible cause can be identified.

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 modelling 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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