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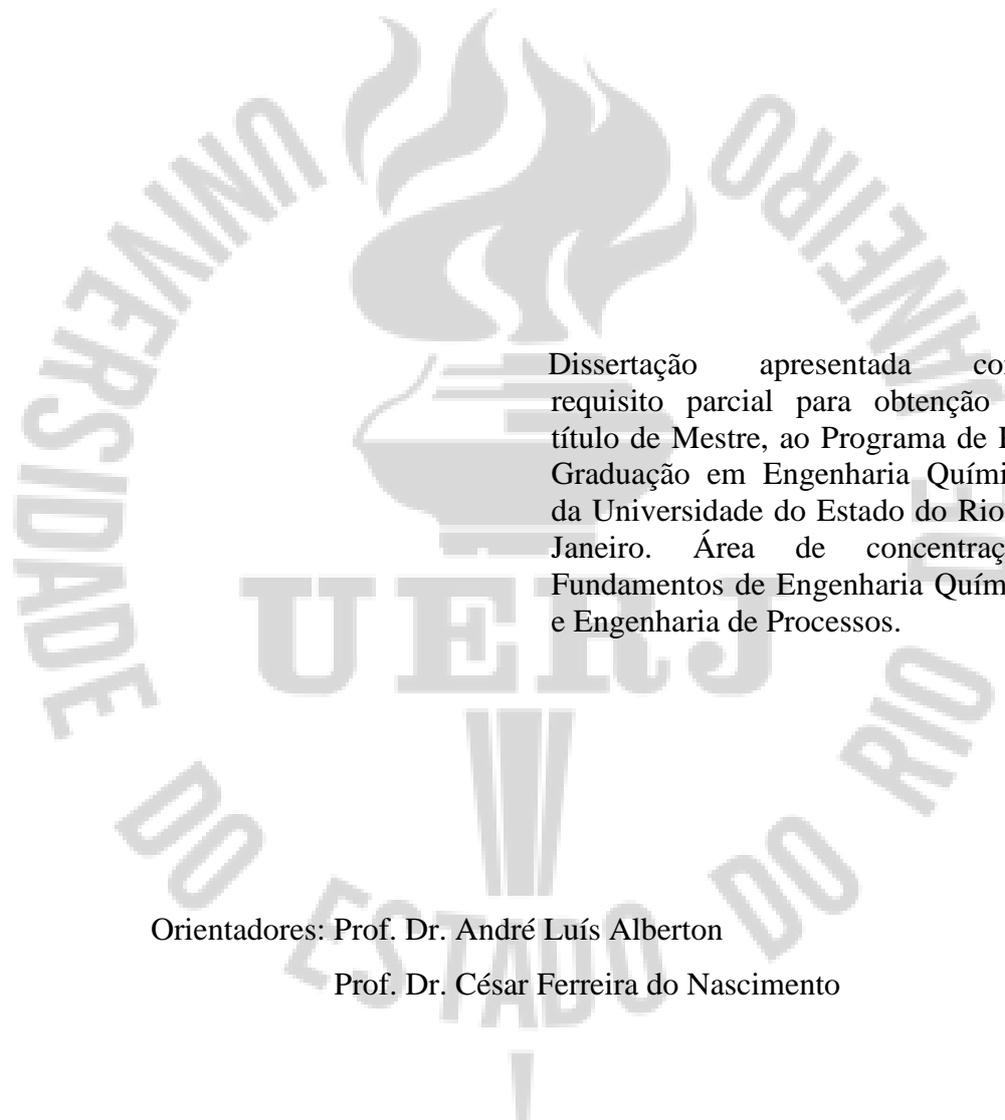
**Utilização de ferramentas computacionais para avaliação de estudos de
HazOp**

Rio de Janeiro

2018

Gabriel Drummond Guilherme

Utilização de ferramentas computacionais para avaliação de estudos de HazOp



Dissertação apresentada como requisito parcial para obtenção do título de Mestre, ao Programa de Pós Graduação em Engenharia Química, da Universidade do Estado do Rio de Janeiro. Área de concentração: Fundamentos de Engenharia Química e Engenharia de Processos.

Orientadores: Prof. Dr. André Luís Alberton

Prof. Dr. César Ferreira do Nascimento

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Gabriel Drummond Guilherme

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RESUMO

GUILHERME, G. D. *Utilização de ferramentas computacionais para avaliação de estudos de HazOp*. 2018. 140 f. Dissertação (Mestrado em Engenharia Química) – Instituto de Química, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, 2018.

A presente dissertação propõe o uso de ferramentas computacionais para auxílio a estudos de análise de perigos, sendo a técnica de HazOp o foco deste trabalho. Duas abordagens foram adotadas. A primeira diz respeito à realização de simulações estacionárias de processo, usando softwares industriais tradicionais. Os resultados das simulações foram avaliados em forma de uma análise de sensibilidade, de maneira a estabelecer uma relação entre as variáveis dentro de um mesmo processo, auxiliando assim em estudos de HazOp. A segunda abordagem diz respeito à criação de uma representação objetiva de estudos de HazOp, através da elaboração de matrizes de causa-efeito para equipamentos usuais da indústria química. Estas matrizes individuais foram então combinadas, a partir de rotinas computacionais e, de acordo com os estudos de caso, aplicadas com o objetivo de obter as consequências para dadas perturbações em um processo químico. Neste caso, mediante análises de grafos, foi possível caracterizar as inter-relações das variáveis lógicas e caracterizar o número de sequências com possíveis inconsistências obtidas a partir da técnica de HazOP tradicional. Pôde-se observar que as metodologias propostas demonstram potencial, com capacidade de adicionar informações a estudos de HazOp tradicionais, o que permite auxiliara eliminação de incoerências e na verificação de causas primárias das perturbações. Além disso, a nível acadêmico, mostram potencial para o ensino de estudos de segurança de processos industriais a alunos de graduação.

Palavras-chave: *HazOp*. Árvore de falhas. Árvore de eventos. Segurança de processo.

ABSTRACT

GUILHERME, G. D. *Use of computational tools to evaluate HazOp studies*. 2018. 140 f. Dissertação (Mestrado em Engenharia Química) – Instituto de Química, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, 2018.

The present work proposes the use of computational tools to aid in hazard analysis studies, being the HazOp technique the focus of this work. Two approaches were adopted. The first is related to the development of steady state process simulations using traditional industrial software. The results of the simulations were evaluated in the form of a sensitivity analysis, in order to establish a relationship between the variables within a given process, therefore aiding in HazOp studies. The second approach is related to the creation of an objective representation of HazOp studies, through the elaboration of cause and effect matrices for usual equipment of the chemical industry. These individual matrices were then combined, through a computational routine and according to the applied case studies, in order to obtain the consequences for given perturbations in a chemical process. In this case, through graph analysis, it was possible to characterize the interrelationships of the logic variables and to characterize the number of sequences with possible inconsistencies obtained from traditional HazOp technique. It could be observed that the proposed methodologies demonstrate potential, with the capacity to add information to traditional HazOp studies, which helps to eliminate inconsistencies and to verify the primary causes of disturbances. In addition, at the academic level, they show potential for teaching process safety studies to undergraduate students.

Keywords: HazOp. Fault tree. Event tree. Process safety

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LISTA DE ABREVIATURAS E SIGLAS

EI	Evento Indesejável
ETA	<i>EventTreeAnalysis</i> (Análise de Árvore de Eventos)
FMEA	<i>FailureModeandEffectAnalysis</i> (Análise dos Modos de Falha e seus Efeitos)
FMECA	<i>FailureModes,EffectsandCriticalityAnalysis</i> (Análise dos Modos de Falha, Efeitos e Criticalidade)
FTA	<i>FaultTreeAnalysis</i> (Análise de Árvore de Falhas)
GP	<i>Graph of a Process</i>
HazOp	<i>Hazard and Operability Study</i> (Estudo de Perigos e Operabilidade)
IAPS	<i>Intelligent Accident Prevention System</i>
ICI	<i>Imperial Chemical Industries</i>
IHAS	<i>Integrated Hazard Analysis System</i>)
INPP	<i>Ignalina Nuclear Power Plant</i> (Usina Nuclear de Ignalina)
IPL	<i>IndependentProtectionLayer</i> (Camada de Proteção Independente)
LDM	<i>LayeredDigraphModel</i>
LOPA	<i>LayerofProtectionAnalysis</i> (Análise das Camadas de Proteção)
LT	Limite de Tolerâncias
NR	Norma Regulamentadora
OSHA	<i>OccupationalSafetyand HealthAdministration</i> (Segurança Ocupacional e Administração Saudável)
P&ID	<i>Pipingand Instrumentation Diagram</i> (Diagrama de Tubulação e Instrumentação)
PDAH	<i>PressureDifferentialAlarmHigh</i> (Alarme de Alto Diferencial de Pressão)
PDI	<i>PressureDifferentialIndicator</i> (Indicador de Diferencial de Pressão)
PDSH	<i>PressureDifferential Shutdown High</i> (Desligamento de Alto Diferencial de Pressão)
PDF	<i>ProbabilityofFailureonDemand</i> (Probabilidade de Falha na Demanda)
PFR	<i>PlugFlowReactor</i> (Reator de Fluxo Pistonado)
PHA	<i>ProcessHazardAnalysis</i> (Análise de Perigos de Processo)
PSV	<i>PressureSafetyValve</i> (Válvula de Segurança de Pressão)
SDG	<i>SignedDirectGraph</i>
SIL	<i>SafetyIntegrityLevel</i> (Nível de Integridade de Segurança)

SIS *SafetyInstrumented System* (Sistema Instrumentado de Segurança)
SRU *Sulfur Recovery Unit* (Unidade de Recuperação de Enxofre)

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INTRODUÇÃO

Processos químicos cada vez mais complexos refletem a evolução tecnológica advinda de extensas pesquisas científicas, motivadas por demandas da sociedade atual. E com processos mais complexos, novos perigos, diferentes daqueles aos quais equipes de projeto possuem experiência, podem surgir. Neste contexto, a segurança de processo tem se destacado como um dos pilares da indústria e uma das áreas que mais tem crescido nos últimos 20 anos, possibilitando que engenheiros e desenvolvedores investiguem e prevejam as mais diversas causas de falhas, consequências e suas severidades, que podem impactar diretamente tanto a produção quanto a imagem das empresas perante a sociedade. Para suportar tais estudos, existem diversas técnicas de análises de perigos usadas atualmente, tais como o *Hazard and Operability Study* (HazOp), *Layer of Protection Analysis* (LOPA), *Failure Mode and Effect Analysis* (FMEA), *Fault Tree Analysis* (FTA) e *Event Tree Analysis* (ETA). Diversas destas análises procuram estabelecer uma relação causa-efeito entre variáveis de processo, que levem a potenciais acidentes. Apesar de bem estabelecidas, processos de melhoria estão sempre em pauta para tais técnicas. Sendo assim, a presente dissertação propõe o uso de ferramentas computacionais como auxílio à análises de perigos obtidas a partir da técnica de HazOp, a mais difundida mundialmente.

Neste contexto, os objetivos da presente dissertação consistem no desenvolvimento de ferramentas que auxiliem e permitam efetuar avaliações de análises HazOp e árvore de eventos e falhas. As linhas de atuação desta dissertação incluem:

- i. Descrição e levantamento bibliométrico das técnicas de análise de perigo na indústria química, identificando a HazOp como a técnica predominante;
- ii. Análise por grafos, quantificando incoerências possíveis de análises HazOp;
- iii. Obtenção de sensibilidades a perturbações e consequentes eventos, obtidos por simulação estacionária empregando softwares comerciais.

Para tanto, a presente dissertação está estruturada da seguinte forma:

- No Capítulo 1 são discutidas as principais técnicas de análises de perigo utilizadas na indústria, mostrando seus principais conceitos, vantagens e desvantagens. Além disso, discute-se um levantamento bibliométrico sobre segurança de processo e estas principais técnicas associadas.

- No Capítulo 2 são apresentadas as metodologias propostas e resultados obtidos associados a eventos gerados por análise heurística oriunda de HazOps.
- No Capítulo 3 são apresentadas as metodologias propostas e resultados obtidos associados a eventos gerados por análise de sensibilidade segundo rotinas desenvolvidas que geram simulações a partir de softwares comerciais
- Em seguida são discutidas as conclusões da presente dissertação e apresentadas as referências bibliográficas.

1 SEGURANÇA DE PROCESSO: CONCEITOS E PRINCIPAIS TÉCNICAS

Neste capítulo são discutidos os principais conceitos envolvendo segurança de processo, assim como as principais técnicas de análises de perigos existentes e praticadas na indústria: HazOp, LOPA, FMEA/FMECA e FTA.

1.1 Principais Conceitos

Segurança de Processo é um ramo da engenharia de segurança voltado para a prevenção de acidentes e incidentes industriais, notadamente representados, ao longo da história, pela perda de contenção de substâncias químicas perigosas, que levaram a consequências catastróficas. No contexto desta dissertação, entende-se por “processo” qualquer operação envolvendo manuseio, transporte, produção e armazenamento de produtos químicos.

De modo geral, substâncias químicas perigosas são aquelas que possuem, pelo menos, uma das seguintes propriedades: inflamabilidade, toxicidade, corrosividade, reatividade e radioatividade.

Com base nestas propriedades, é possível afirmar que o desafio diário do engenheiro de segurança de processo é estudar e prever mecanismos que possibilitem a operação segura de uma planta de processos, mesmo com a presença de substâncias com as características acima. Neste contexto, as principais ferramentas utilizadas são as técnicas de análises de perigos de processo. De forma geral, o uso das mesmas possibilita que equipes de engenharia estudem detalhadamente as plantas industriais as quais projetam, em busca de possíveis fontes de falha que necessitam de proteção. A seguir são apresentadas as principais técnicas e suas características.

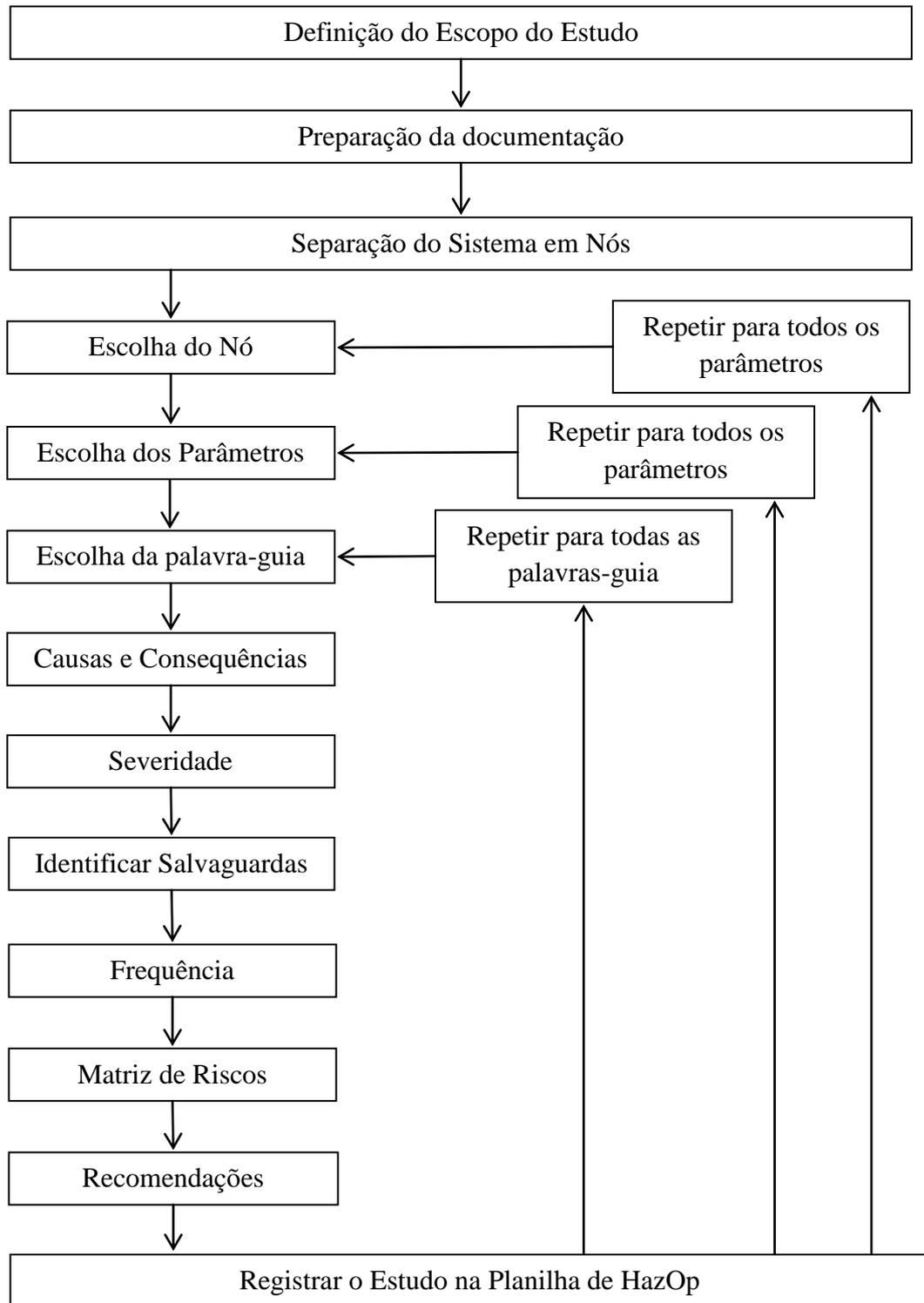
1.2 HazOp

O HazOp foi desenvolvido na década de 1960 na ICI, *Imperial Chemical Industries*, no Reino Unido, segundo Venkatasubramanian, Zhao e Viswanathan (2000). O HazOp é uma técnica que compreende a análise sistemática de um processo, na qual investigam-se os efeitos de possíveis desvios das condições de operação consideradas no projeto, que podem levar a cenários potencialmente perigosos. Para esta análise de desvios, palavras-guia são utilizadas e conectadas a um determinado parâmetro de processo. Os principais exemplos de palavras-guia são: baixo(a), alto(a), sem, menor, reverso e parte de. No que diz respeito à indústria de processos, os principais parâmetros atendem por fluxo, pressão, temperatura e nível. Dessa forma, desvios tais como “sem fluxo”, “alta pressão”, “baixo nível” podem ser formados e estudados. Para cada desvio, listam-se as causas, consequências e salvaguardas. Salvaguardas são proteções existentes no sistema, que agem no sentido de evitar que uma determinada consequência, advinda de uma causa, se concretize. Cada análise feita, englobando estes itens mencionados anteriormente, chama-se “cenário”. Atualmente, para cada cenário é estipulada uma severidade e uma frequência. A severidade diz respeito à extensão dos danos à pessoas, instalações e meio-ambiente que uma determinada consequência pode gerar. A frequência diz respeito à probabilidade de um dado cenário se concretizar, levando em conta as salvaguardas existentes no sistema. A severidade e a frequência são relacionadas por uma matriz de risco, que informa se o risco é aceitável, indesejado, inaceitável, etc. Não existe normatização para esta matriz e, normalmente, empresas possuem padrões internos que regem a classificação da severidade, frequência e risco em um HazOp. Esta abordagem não foi considerada na época do surgimento da técnica, aparecendo apenas na década de 1980, de acordo com Pérez-Marín e Rodríguez-Toral (2013). Pautada por estas classificações de cenários, recomendações podem ser geradas de forma a minimizar a frequência de ocorrência, ou eliminar uma causa de um perigo, gerando um risco aceitável para o processo.

Com o crescimento e modernização da indústria química, que gera processos cada vez mais robustos e complexos, a aplicação de tal técnica considerando todo o processo de uma só vez geraria um estudo confuso, complexo, e perigos poderiam não ser identificados. Com isso, os sistemas são subdivididos em seções chamadas de “nós”, de forma a facilitar a análise. Tais “nós” comumente dizem respeito a um conjunto de equipamentos que possuem

um objetivo claro no processo. Por exemplo, tanques para armazenamento de líquido criogênico, equipamentos em dada área de reação, colunas de destilação, etc. Cenários são identificados para o “nó”, em busca de uma análise completa e detalhada. Pode-se estabelecer um fluxograma para a sistemática do HazOp, conforme a Figura 1.1, a seguir.

Figura 1.1– Fluxograma para sistemática do estudo de HazOp



Fonte: Herrera et al., 2015

Para condução do estudo, deve-se dispor de uma equipe multidisciplinar, que engloba um líder, responsável por coordenar o estudo e extrair o máximo de cada participante, além de compilar as informações e controlar planos de ação gerados, engenheiro de processos,

engenheiro de equipamentos mecânicos, engenheiro de equipamentos elétricos, engenheiro de controle, engenheiro de automação, engenheiro de tubulação, entre outros, conforme aplicável de acordo com o escopo do estudo. A técnica baseia-se integralmente em um *brainstorming* e na experiência dos participantes, para busca dos cenários perigos. O HazOp é a técnica mais aplicada globalmente, em parte devido à sua flexibilidade e adaptação para diferentes situações. Como exemplo de flexibilidade, Pitt (1994) cita o uso de HazOp em análises financeiras, a partir de desvios tais como “Sem pagamento”, “Maior pagamento”; Rimkevičius et al. (2016) mostram o uso do HazOp para atividades de desmontagem e descontaminação da Usina Nuclear de Ignalina (INPP – *Ignalina Nuclear Power Plant*), dividindo as principais etapas dessas atividades, chamando-as de nós, e com a sistemática do HazOp, identificando os perigos das etapas e as recomendações geradas; e Li et al. (2015), que realizam o estudo para um sistema de controle de uma cadeia de trens chinesa, através da elaboração de modelos que descrevem a interação entre as estruturas do sistema e possibilitam a análise.

Ao mesmo tempo em que se encontram aplicações inusitadas, aplicações usuais são demonstradas em Alaeiet al. (2014) e Herrera et al. (2015), que realizam uma aplicação direta do estudo de HazOp em uma Unidade de Recuperação de Enxofre (SRU – *Sulfur Recovery Unit*) e em um sistema para produção de proteínas recombinantes, na indústria biofarmacêutica.

Apesar de bem estabelecida, a técnica sofre críticas principalmente no que diz respeito ao esforço a ser dispendido, dependência do conhecimento do time participante e longo tempo para sua conclusão, o que gera um alto custo. Baybutt (2015) mostra uma extensa análise destes pontos e de vários outros que podem comprometer ou diminuir a eficiência de um estudo de HazOp.

Com base nestes pontos negativos, esforços têm sido feitos para automatizar o estudo de HazOp, tornando-o mais prático e permitindo ao time focar nas salvaguardas e possíveis recomendações para os cenários encontrados. Dunjóet al. (2010) informam que 40% das citações de “HazOp” na literatura dizem respeito ao desenvolvimento de sistemas automatizados para aplicação da técnica. Na literatura encontram-se vários trabalhos que corroboram tal informação, como por exemplo, Rodríguez e De La Mata (2012) que se utilizam de grafos para elaboração de um modelo funcional-estrutural para sistemas de processo; e Rossing et al. (2010), que desenvolve um assistente baseado em *MultilevelFlowModeling* (MFM). Tais modelos permitem prever a propagação de um determinado evento a partir de um evento inicial, estabelecendo relações de causas e

consequências. Além disso, existem trabalhos que buscam a utilização de uma ferramenta de simulação dinâmica para a análise do HazOp. Tal ferramenta auxilia em uma identificação mais precisa das consequências, indicando também qual o percentual de desvio de um determinado parâmetro que pode levar a uma dada consequência. Tal fato pode ser visto em Labovský, Jelemenský e Markoš (2006) que realiza um estudo de HazOp dinâmico de um reator tubular tipo PFR, usado na produção de óxido de etileno.

1.3 LOPA

O estudo de LOPA é uma ferramenta semiquantitativa para estimativa de riscos de processo. É normalmente conduzido após a realização de uma análise de perigos puramente qualitativa, tal como o HazOp. A partir do estudo qualitativo já feito, o LOPA analisa separadamente cada par causa-consequência com foco na frequência do evento iniciador (causa) e na identificação de salvaguardas chamadas de Camadas de Proteção Independentes, ou IPL, *Independent Protection Layers*. De acordo com Dowell III (2011), uma dada salvaguarda deve seguir sete premissas básicas para ser considerada como um IPL:

- a) **Independência:** este critério indica que o desempenho da camada de proteção não pode ser afetado pelo evento inicial nem por qualquer outra camada de proteção existente;
- b) **Funcionalidade:** indica que a camada de proteção deve ser capaz de detectar o início de um cenário perigoso e agir de forma a interrompê-lo e garantir que a consequência indesejada não ocorra;
- c) **Integridade:** relacionada à redução de risco esperada pela ação da dada camada de proteção;
- d) **Confiabilidade:** garantia de que a camada de proteção irá operar por todo o tempo determinado para o qual foi projetada;
- e) **Auditabilidade:** diz respeito à capacidade de inspecionar documentos, registros, procedimentos que confirmem que a camada de proteção sofre inspeções, manutenção e testes regulares de maneira a garantir seu funcionamento perfeito de acordo com o projeto;

- f) **Segurança de Acesso:** existem meios administrativos de controle que evitam alteração sem autorização ou acidental da camada de proteção;
- g) **Gerenciamento de Modificações:** existe um procedimento formal de gerenciamento de modificações que revisa, aprova e documenta quaisquer modificações na camada de proteção, ou no processo ao qual a mesma está relacionada.

Para cada IPL é atribuído um valor de probabilidade de falha na demanda, usualmente conhecido como PFD, *Probability of Failure on Demand*. Este valor nada mais é que uma representação estatística da taxa de falha da camada de proteção e indica a redução do risco fornecido pela existência desta camada. O valor de PFD de cada IPL é utilizado para o cálculo do risco final da seguinte forma:

$$FREQ = (EI) \times \prod_{i=1}^n P_i \quad (1)$$

Onde:

FREQ= risco, entendido como a frequência de ocorrência da consequência indesejada;

EI=frequência de ocorrência do evento iniciador;

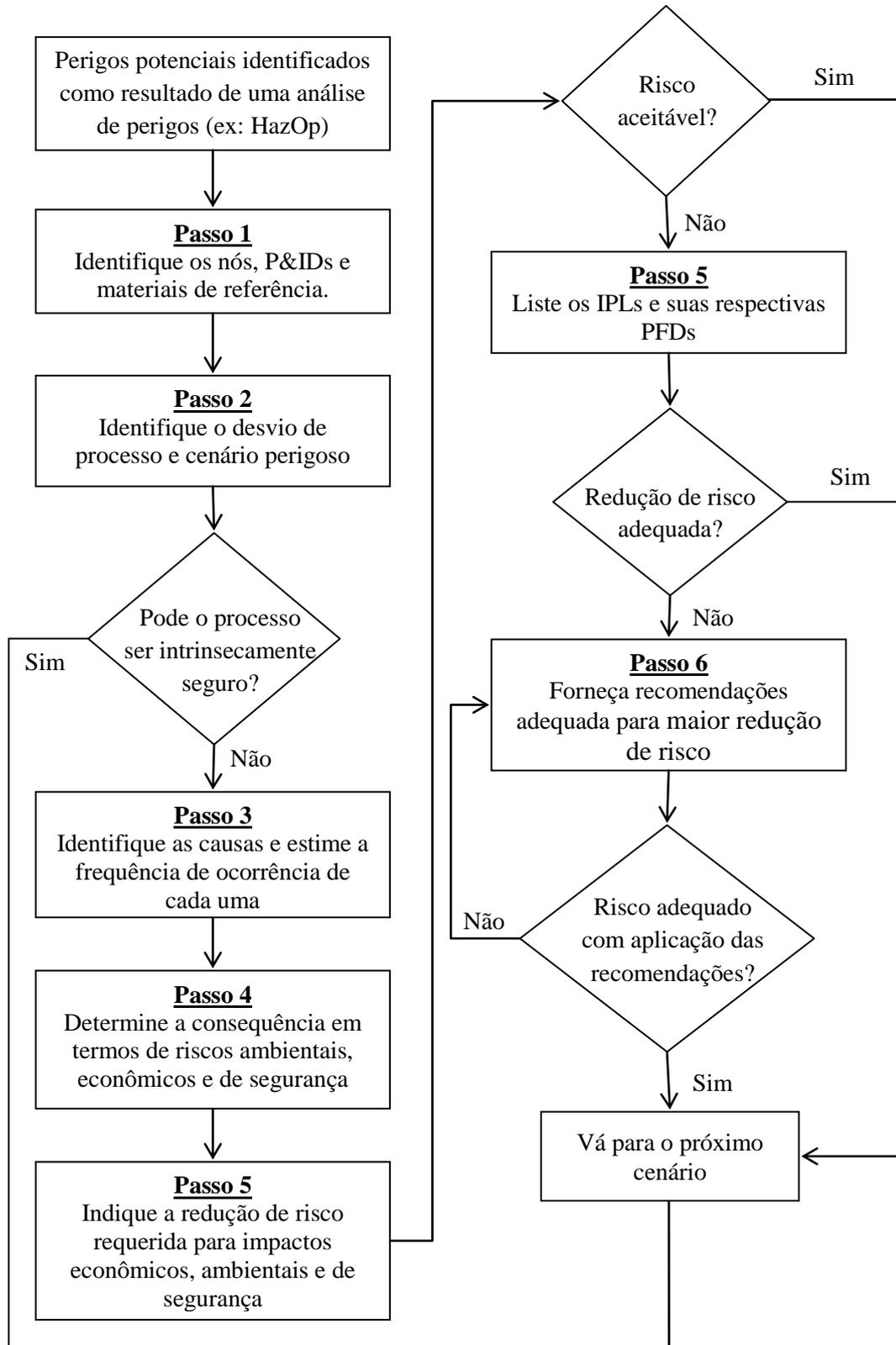
P_i = PFD de uma determinada camada de proteção i ;

A equação acima é conhecida como equação básica do estudo de LOPA.

Após estimativa da frequência do evento iniciador, identificação dos IPLs, atribuição dos PFDs, e cálculo conforme equação acima, um valor de risco final do cenário é obtido e comparado com critérios corporativos ou de regulamentações locais, para verificação da aceitabilidade do risco.

Após avaliação, caso o risco seja inaceitável, recomendações são feitas, envolvendo mudança no projeto do processo ou adição de IPLs. Tal procedimento pode ser sintetizado no seguinte fluxograma da Figura 1.2a seguir:

Figura 1.2 – Fluxograma da sistemática do estudo de LOPA



Fonte: Summers, 2003

Com base nos itens abordados, é possível perceber facilmente que o estudo de LOPA é mais detalhado que uma análise puramente qualitativa, estando mais sujeito a falhas durante execução. Study e Champion (2009) abordam quais os erros mais comuns em um estudo de LOPA, passando por não consideração da cultura operacional, dos modos de falha comuns, do impacto de um IPL em um sistema como um todo, uso incorreto de bases de dados industriais, tempos sob risco usados inadequadamente, falta de análise das consequências de *trips* espúrios e falha no entendimento de eventos iniciadores de alta demanda. Para cada erro, demonstram um exemplo prático de aplicação.

Com toda essa quantidade de itens a considerar, o estudo de LOPA agrega incertezas em cada variável inserida no cálculo do risco. Ouazraouiet al. (2013) relatam que as principais fontes de incertezas estão relacionadas às informações de PFDs dos Sistemas Instrumentados de Segurança (SIS), já que os SIS normalmente possuem baixa demanda (< 1/ano) e que com isso não operam por tempo suficiente para gerar dados confiáveis sobre a quantidade de falhas raras.

Apesar de apresentar maior complexidade, o estudo de LOPA é amplamente utilizado no campo de segurança de processo. Morrison, Fecke e Ramirez (2012) demonstram aplicação a sistemas de *steam boilers*; Evenson et al. (2009) aplicam análise à cenários perigosos de processos na indústria farmacêutica; e Dowell III (1998) aborda sobre o uso de LOPA para determinação do Nível de Integridade de Segurança (SIL), que é um nível relativo de redução de risco proporcionado por um SIS.

1.4 FMEA

A FMEA é uma técnica qualitativa e subjetiva. De acordo com Cicek e Celik (2013), foi desenvolvida e utilizada pela primeira vez no ano de 1949, pelo Departamento de Defesa dos Estados Unidos. Hoje em dia, é amplamente utilizada em diversos segmentos industriais, tais como aeroespacial, automobilístico, semicondutores e nuclear (Colli, 2015).

O objetivo principal desta técnica é identificar minuciosamente os modos de falha de cada componente de um sistema, analisando seus efeitos posteriores, tanto para o próprio componente, como para o sistema no qual está inserido. Para categorizar tal análise e indicar

quais modos de falha necessitam de correção imediata, pode ser feito o ranqueamento de três fatores principais:

- a) **Severidade (S):** A severidade diz respeito à magnitude do efeito final decorrente de um modo de falha. Pode ser categorizada considerando perdas econômicas, danos ao meio-ambiente e lesões aos trabalhadores, incluindo fatalidades;
- b) **Ocorrência (O):** descreve, de forma qualitativa, qual a probabilidade de ocorrência da causa que gerou um determinado modo de falha. Esta é uma distinção importante e que deve ser destacada. Segundo Arabian-Hoseynabadi, Oraee e Tavner (2010) destacam, o modo de falha não é a causa da falha si, mas o caminho no qual uma dada falha ocorreu;
- c) **Deteção (D):** este fator descreve, também de forma qualitativa, qual a probabilidade de deteção de uma falha.

Com a aplicação destes fatores acima, a técnica passa a ser chamada de *Failure Modes, Effects and Criticality Analysis* (FMECA). Cada um destes fatores é usualmente ranqueado de 1 a 10, com o maior valor indicando a situação mais crítica possível, como por exemplo, uma alta frequência de ocorrência de uma falha não detectada e com um efeito associado extremamente perigoso. Apesar desta atribuição de valores de 1 a 10 ser a mais usual, não existe uma diretriz obrigatória sobre o tema e tal ranqueamento pode variar de acordo com cada empresa.

Após atribuição de valores a cada uma destas variáveis, de acordo com o modo de falha observado, as mesmas são multiplicadas e o valor final é chamado de Número de Prioridade de Risco, ou em inglês, *Risk Priority Number* (RPN), conforme mostrado abaixo:

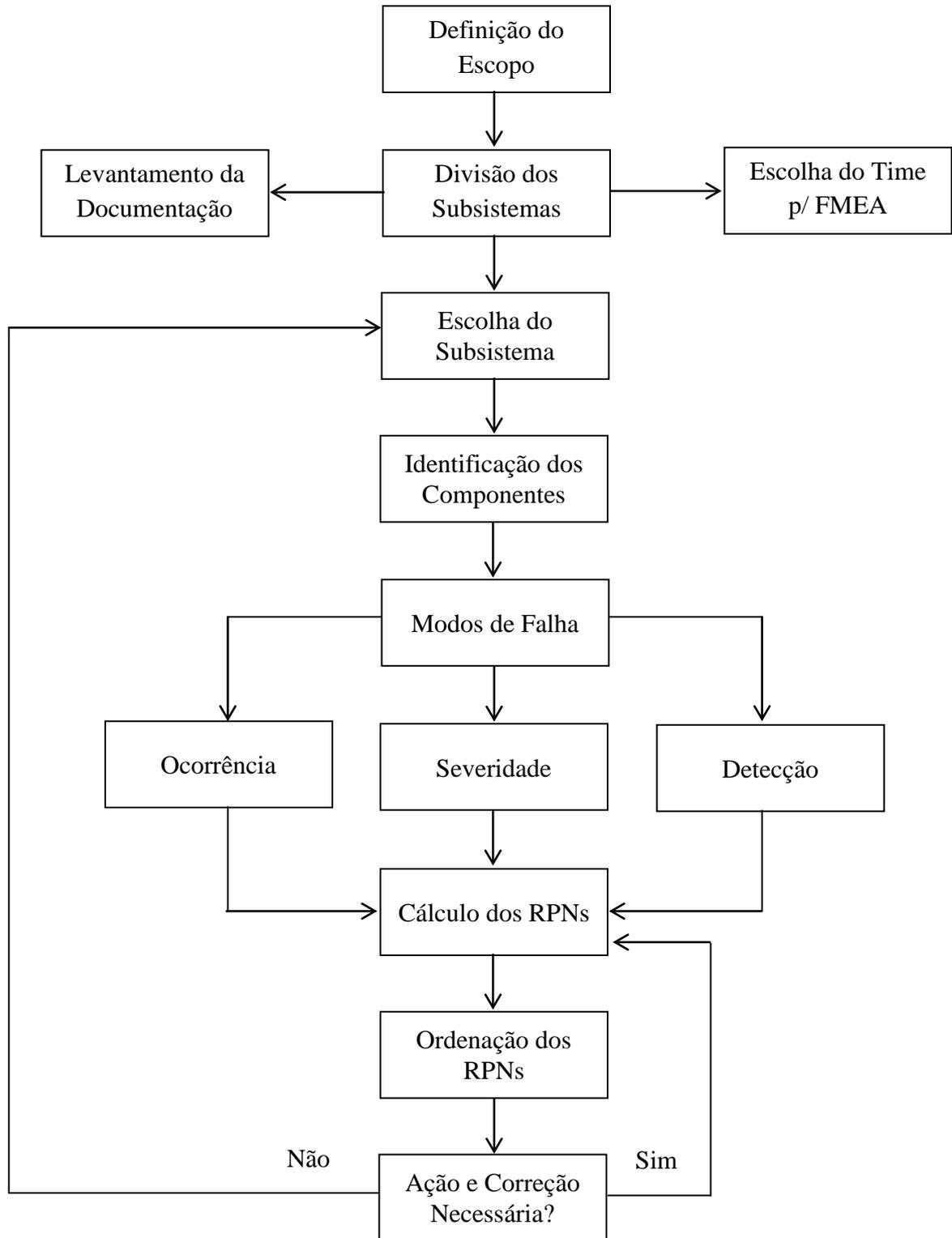
$$RPN = S \times O \times D \quad (2)$$

Este valor auxilia na priorização de quais modos de falha são mais críticos e demandam correção. Quanto maior o RPN, mais crítica é a interação dos três conceitos caracterizados para calculá-lo. Após recomendação e aplicação da ação a ser tomada para diminuir o RPN, o modo de falha deverá ser reavaliado e um novo RPN calculado. Dessa forma, a ordem de prioridades baseadas nos RPNs será sempre atualizada até que todos os modos possuam RPNs admissíveis de acordo com os critérios da empresa. A partir disso, introduz-se um conceito chamado de Índice de Melhoria (IM), que é calculado da seguinte forma:

$$IM = (\text{RPN Antes da Melhoria}) / (\text{RPN Depois da Melhoria}) \quad (3)$$

Este valor será sempre maior ou igual a 1, considerando que após uma melhoria o RPN nunca será igual ao RPN anterior. Para condução dos estudos de FMEA/FMECA, similarmente ao feito para demais técnicas de análises de perigos, é necessária a participação de representantes das mais variadas disciplinas envolvidas em um projeto ou empreendimento, tal como engenheiro de processo, engenheiro eletricista, engenheiro de controle e automação, engenheiro de instrumentação, engenheiro mecânico, etc. Estes profissionais estão mais relacionados a atividades industriais, mas devido à grande aplicabilidade e extensão da FMEA/FMECA, outros profissionais podem ser requeridos de acordo com o que está sendo estudado. Como é um estudo basicamente qualitativo, a experiência de time e o conhecimento sobre aspectos detalhados do que está sendo analisado é de vital importância para que a técnica traga os resultados esperados. No que tange à Engenharia Química, a FMEA/FMECA pode ser realizada desde a fase de um projeto conceitual até em uma planta em operação. No entanto, os melhores resultados, no que diz respeito à segurança e custo, são encontrados quando a técnica é aplicada ainda na fase de elaboração do projeto. Qualquer mudança em plantas em operação gera custos adicionais que afetam diretamente o caixa de uma empresa. Para condução na análise é de vital importância a divisão de sistemas em subsistemas menores, com seus respectivos elementos que deverão ser considerados. Isto facilita a análise e a torna mais intuitiva. Em uma reunião de FMEA/FMECA deve ser utilizado o maior número de documentos possíveis que forneçam informações sobre os sistemas, tais como diagramas de blocos, P&ID, folhas de dados de equipamentos, etc. Com base no explicitado até então, é possível demonstrar o processo de trabalho básico de uma FMEA/FMECA no seguinte fluxograma da Figura 1.3:

Figura 1.3 – Fluxograma da sistemática do estudo de FMEA/FMECA



Fonte: Autor, 2018

A principal característica da FMEA/FMECA é o principal alvo de crítica e de investigação de oportunidades de melhoria: o caráter extremamente qualitativo do cálculo do RPN. Liu, Liu e Liu (2013) mostram as principais críticas a FMEA/FMECA, tais como:

- a) A importância relativa entre ocorrência, severidade e detecção não é levada em consideração;
- b) Diferentes combinações de ocorrência, severidade e detecção podem produzir exatamente o mesmo valor de RPN, mas suas contribuições para o risco podem ser totalmente diferentes;
- c) Dificuldade de avaliar com precisões estes três fatores;
- d) Interdependência entre diferentes modos de falhas e efeitos não é levada em consideração.

Com base no descrito acima, e de forma mais detalhada, Liu, Liu e Liu (2013) fazem um longo estudo, mostrando diversas propostas para melhoria do estudo de FMEA/FMECA. Diversas aplicações do estudo de FMEA/FMECA podem ser encontradas na literatura, tais como em Wang et al. (2012), Arabian-Hoseynabadi, Oraee e Tavner (2010), Colli (2015) e Cicek e Celik (2013).

1.5 FTA

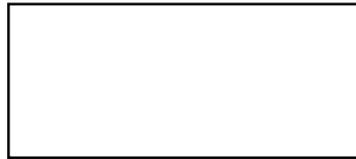
A FTA, segundo Sharma e Singh (2015), foi concebida e desenvolvida na *Bell Telephone Laboratories*, por H.A. Watson, em 1962, devido à necessidade em avaliar a confiabilidade de um sistema associado ao controle de lançamento de mísseis guiados e de alcance intercontinental. Desde então, foi utilizada em vários outros estudos e hoje em dia é possível ver sua aplicação nas mais diversas áreas, tais como nuclear, indústria química, petroquímica, fabricação, aviação, manutenção, etc. como apresentado em Bando, Marques e Patias (2015), na gestão de segurança de barragens e em Halme e Aikala (2012), paradecisão sobre estratégias de manutenção.

A FTA é uma técnica dedutiva, que parte de um evento indesejado principal, que pode ser uma falha ou um acidente/incidente e estabelece relações diretas de causa para aquele dado evento principal. Para estas causas imediatas, buscam-se outras causas geradoras, e assim sucessivamente, até que sejam identificados os eventos básicos, que são aqueles que desencadeiam toda uma sequência de ocorrências e são o limite de resolução da análise. Para representação de toda uma cadeia de eventos, a FTA se utiliza da construção de um diagrama lógico, onde o evento indesejado está localizado no topo e as demais relações de causas e

efeitos estão localizadas imediatamente abaixo, dando ao diagrama uma aparência de ramos de uma árvore, explicitando o porquê da técnica se chamar “Análise de Árvore de Falhas”.

Para indicar as relações lógicas dentro de uma árvore de falhas, são utilizados diversos símbolos. Os símbolos mais utilizados são mostrados a seguir, nas Figuras 1.4a 1.10, conforme Quadri, Zende e Dolas (2014).

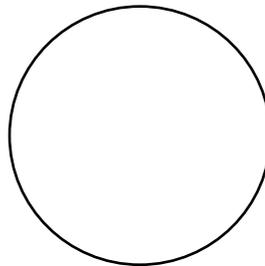
Figura 1.4 – Retângulo



Fonte: Autor, 2018

O retângulo é o principal constituinte de uma árvore de falhas e é como o evento indesejado é representado no topo. Representa também eventos intermediários que serão destrinchados em demais sequências ao longo da árvore. Esta é a única simbologia que admite os conectores lógicos “E” ou “OU” imediatamente abaixo.

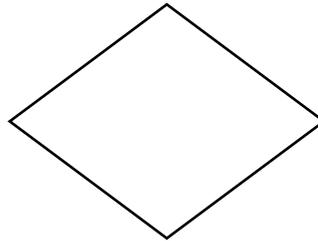
Figura 1.5 – Círculo



Fonte: Autor, 2018

O círculo denota um evento básico em uma árvore de falhas. É encontrado na base da árvore e não requer desenvolvimento adicional. Não existe qualquer evento abaixo do evento básico. Dessa forma, não existirá qualquer simbologia abaixo do círculo em uma árvore de falhas.

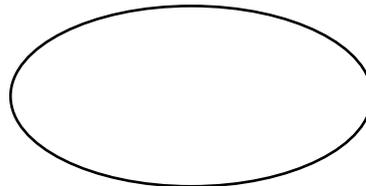
Figura 1.6 – Losango



Fonte: Autor, 2018

O losango indica um evento não desenvolvido de maneira mais aprofundada devido à falta de informação, ou por não ter significância para o estudo em questão. É possível em um estudo de FTA que um dos ramos da árvore termine com um evento em um losango.

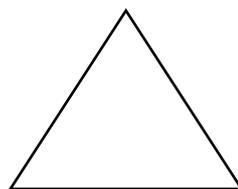
Figura 1.7 – Elipse



Fonte: Autor, 2018

A elipse representa uma situação especial que pode ocorrer apenas se certas circunstâncias se fizerem presentes.

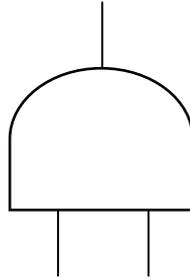
Figura 1.8 – Triângulo



Fonte: Autor, 2018

O triângulo representa a transferência de um ramo da árvore para um outro local dentro da própria árvore. Quando a simbologia do triângulo está presente, entende-se que todos os ramos abaixo dela foram transferidos para o local indicado por outro triângulo análogo se conectando à árvore.

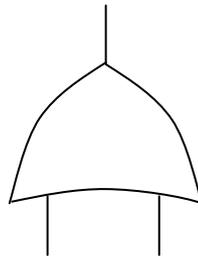
Figura 1.9 – Porta lógica “E”



Fonte: Autor, 2018

Este símbolo indica que todos os eventos imediatamente abaixo dele (*inputs*) devem ocorrer para que o evento imediatamente acima (*output*) seja observado. Em outras palavras, o *output* só irá ocorrer se todos os *inputs* ocorrerem simultaneamente.

Figura 1.10 – Porta lógica “OU”

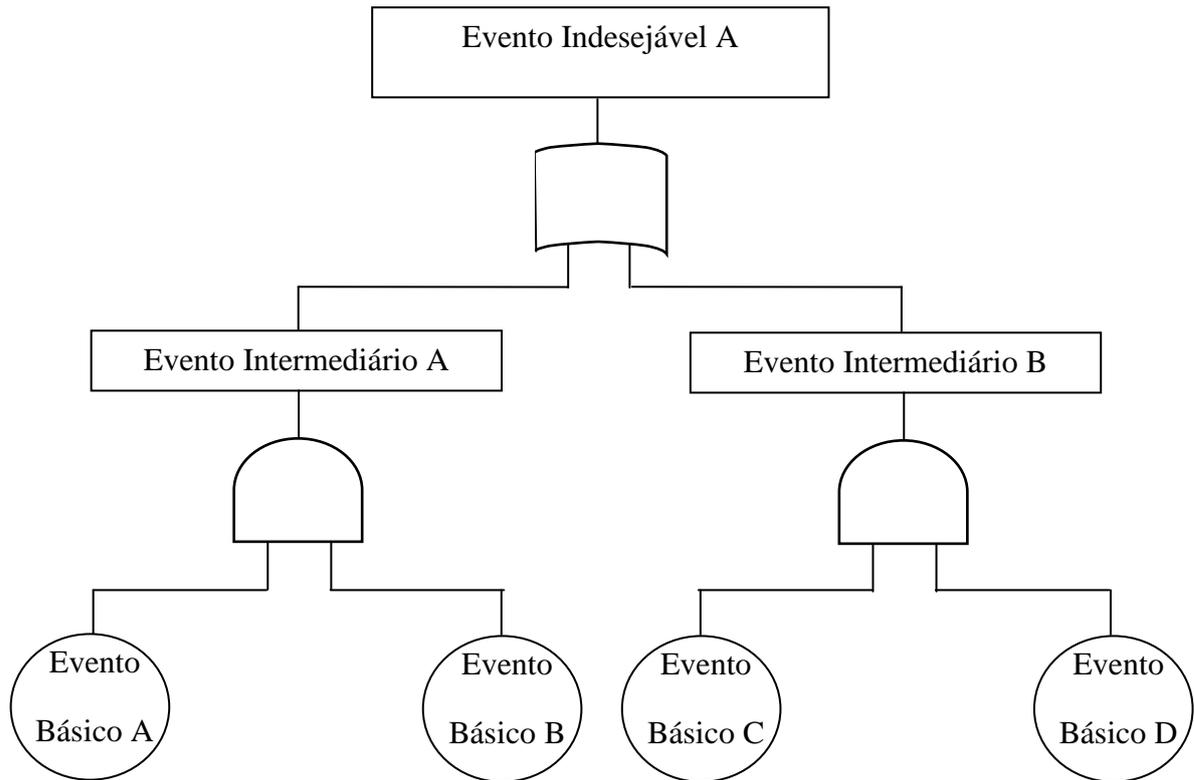


Fonte: Autor, 2018

Ao contrário da porta lógica “E”, este símbolo indica que pelo menos um de todos os eventos imediatamente abaixo dele (*inputs*) deve ocorrer para que o evento imediatamente acima (*output*) seja observado. Em outras palavras, o *output* irá ocorrer no caso de pelo menos um *input* estar presente.

Com base nos símbolos e explicações anteriores, pode-se exemplificar uma simples árvore de falhas da seguinte maneira, como representado na Figura 1.11:

Figura 1.11 – Exemplo da estrutura de uma FTA



Fonte: Autor, 2018

Pode-se entender o exemplo acima da seguinte maneira: o evento indesejável A irá ocorrer se o evento intermediário A OU o evento intermediário B ocorrerem. Por sua vez, o evento intermediário A apenas se fará presente se o evento básico A E o evento básico B se concretizarem. De forma análoga, o evento intermediário B só irá ocorrer se o evento básico C e o evento básico D forem observados ao mesmo tempo. Na estrutura apresentada, os eventos básicos estão no interior de círculos, simbolizando que não é necessária análise adicional a partir dos mesmos, conforme explicado anteriormente, e que estes são considerados os eventos geradores de toda uma cadeia de acontecimentos.

No entanto, a FTA é composta também por uma análise quantitativa. De posse da probabilidade de cada evento em uma árvore de falhas, o analista pode inferir a probabilidade de ocorrência do evento indesejável de acordo com a estrutura de cada ramal. Para tal, é importante levar em consideração os conectores lógicos “OU” e “E”, pois estes impactam a forma do cálculo da probabilidade. Para conectores do tipo “OU”, ou seja, união de eventos tem-se:

$$P(E1 \cup E2) = P(E1) + P(E2) - P(E1 \cap E2) \quad (5)$$

No entanto, se os eventos E1 e E2 forem mutuamente exclusivos, $P(E1 \cap E2)$ será igual a zero, e a equação se tornará:

$$P(E1 \cup E2) = P(E1) + P(E2) \quad (6)$$

Para conectores do tipo E, ou seja, interseção de eventos tem-se:

$$P(E1 \cap E2) = P(E1) \times P(E2/E1) \quad (7)$$

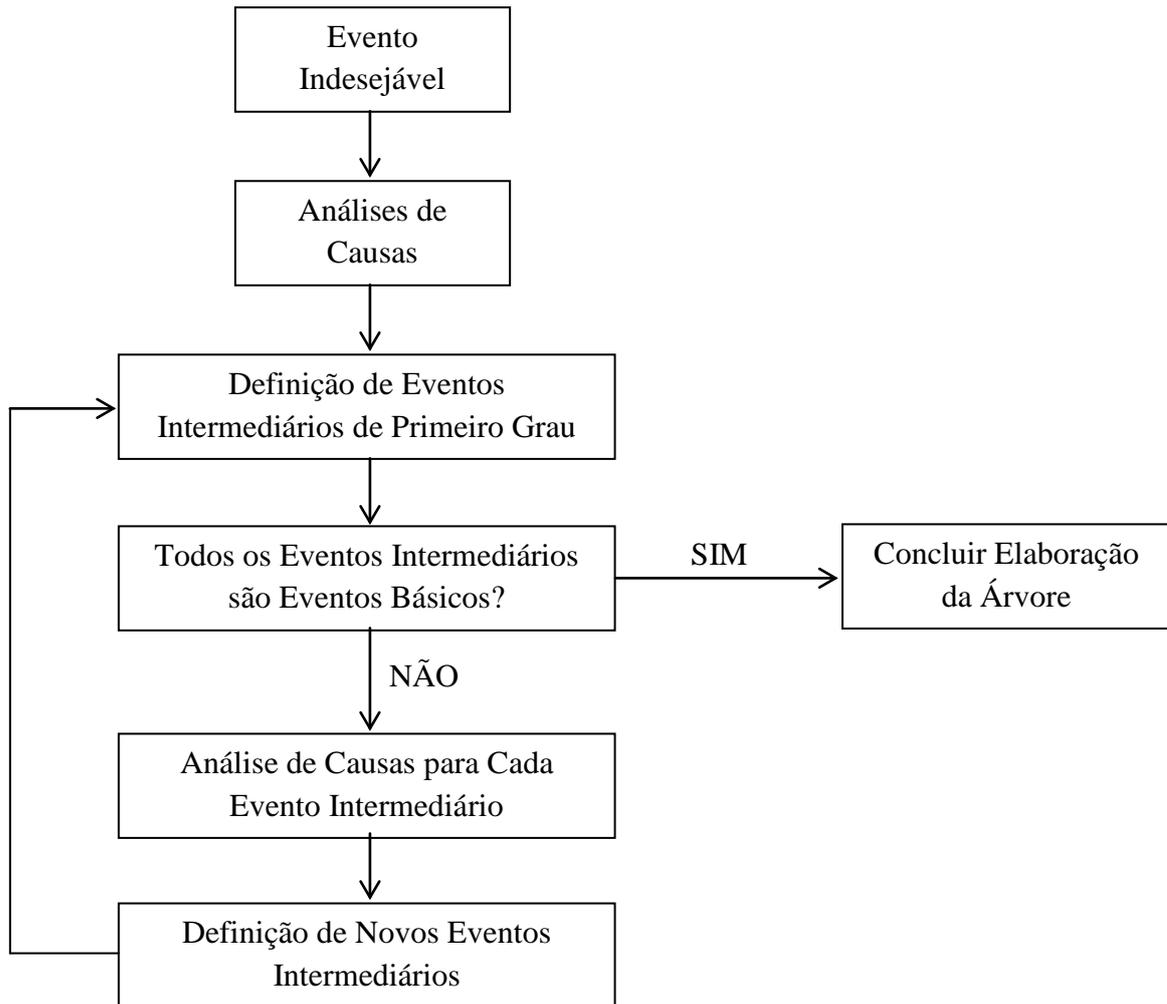
No entanto, se os eventos E1 e E2 são independentes, logo $P(E2/E1) = P(E2)$ e:

$$P(E1 \cap E2) = P(E1) \times P(E2) \quad (8)$$

Com base nas probabilidades decorrentes de cada ramal, o time responsável pelo estudo analisa e verifica quais medidas corretivas são necessárias de forma a diminuir a probabilidade gerada pelo dado ramal em estudo, de forma a atender critérios estabelecidos de admissibilidade.

Moraru(2012)propõe o fluxograma da Figura 1.12para orientar a construção de uma árvore de falhas:

Figura 1.12 – Fluxograma da sistemática de um estudo de FTA



Fonte: Moraru, 2012

Apesar de bem estabelecida, a técnica de FTA, tal como qualquer outra, possui lacunas que são constantemente alvos de críticas. Baig, Ruzli e Buang (2013) abordam estas lacunas, indicando o elevado tempo tomado para concluir uma análise, a complexidade que uma árvore atinge quando existe um grande número de equipamentos e variáveis de processo, e o fato de falhas humanas não serem estimadas de forma eficiente como as principais falhas. Já Chenget al. (2009) abordam o uso de valores exatos de probabilidade de falha como a principal falha, já que requer extenso conhecimento humano do processo em estudo e histórico confiável de falhas do sistema em questão. Além disso, para sistemas novos, os dados de falha podem não ser confiáveis com base em histórico de funcionamento. Com isso, Chenget al. (2009) propõem o uso de lógica *fuzzy* para levar em consideração intervalos de probabilidade de falha e aplicá-las a um sistema de emergência de um terminal de enchimento de gás natural liquefeito.

Da mesma maneira que as outras técnicas já comentadas, o desenvolvimento de uma FTA necessita de um líder com conhecimento sobre a técnica, participação de um grupo multidisciplinar para verificação correta das causas e relações dentro de uma árvore e documentação atualizada com os dados do processo em estudo.

1.6 Levantamento Bibliométrico

É possível evidenciar, a partir de pesquisa na base de dados Scopus, como a Segurança de Processo e estas técnicas relacionadas tem crescido em importância nos últimos anos. Para esta rotina, utilizou-se a seguinte estratégia: foram definidos cinco grupos de palavras relacionadas à segurança de processo de forma geral, e relacionadas entre si, dentro de um mesmo grupo. Os grupos são listados a seguir:

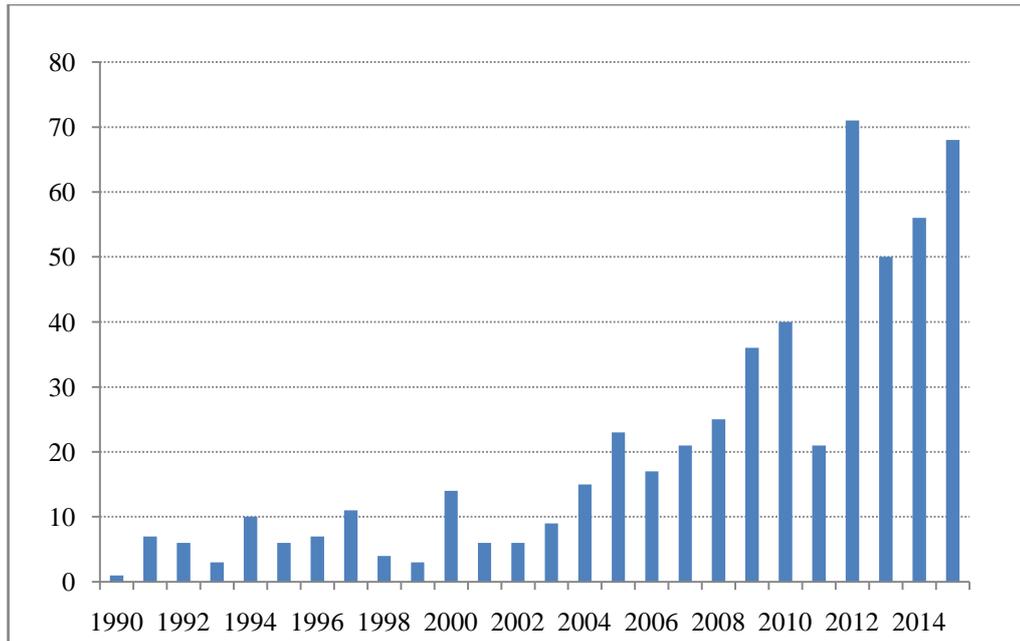
- a) **Grupo 1:***HazOp, Hazard and Operability, Operability Issues, Operational Hazards;*
- b) **Grupo 2:***LOPA, Layer of Protection, Independent Protection Layer;*
- c) **Grupo 3:***Process Safety, Industrial Safety, PHA, Process Hazard Analysis;*
- d) **Grupo 4:***FMEA, Failure Mode and Effect Analysis;*
- e) **Grupo 5:***FTA, Fault Tree Analysis;*

Optou-se por utilizar os termos em língua inglesa, devido à grande quantidade de artigos e publicações encontradas neste idioma. Após a definição dos grupos, escolheu-se uma rotina de pesquisa que retornasse a quantidade de artigos encontrados, levando em consideração a citação de pelo menos uma das palavras do grupo dentro do título ou como palavra chave do artigo. Para exemplificar, segue o código executado para o Grupo 1:

```
“(TITLE("HAZOP" OR "Hazard and Operability " OR "Operability Issues " OR "Operational Hazards") OR AUTHKEY ("HAZOP " OR "Hazard and Operability " OR "Operability Issues " OR "Operational Hazards"))”
```

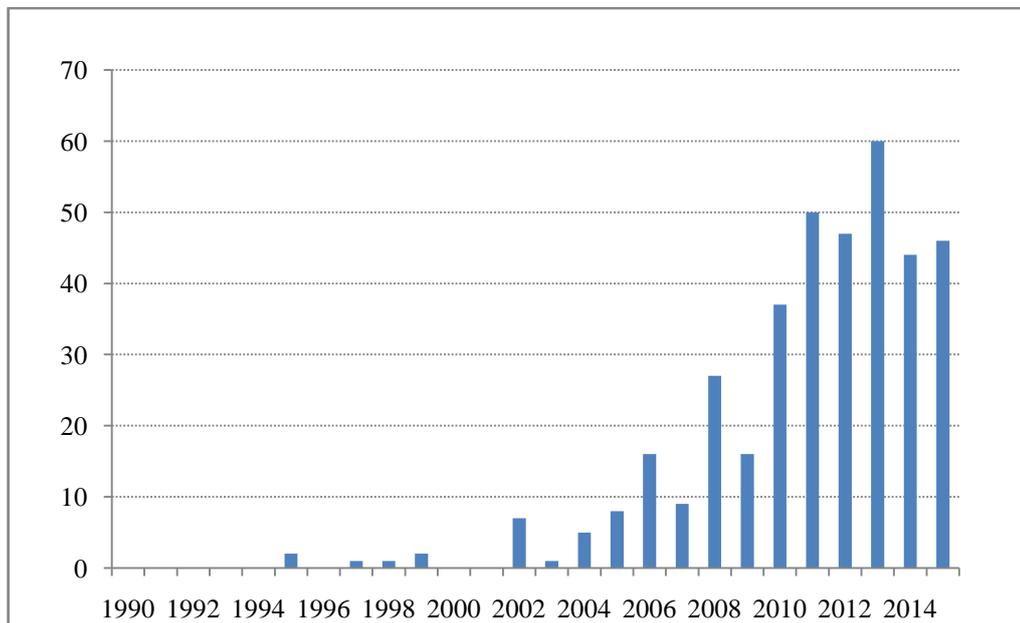
Os resultados a seguir são mostrados individualmente, por grupo, nos Gráficos 1 a 5, a seguir:

Gráfico 1–Evolução das citações do grupo 1 ao longo dos anos



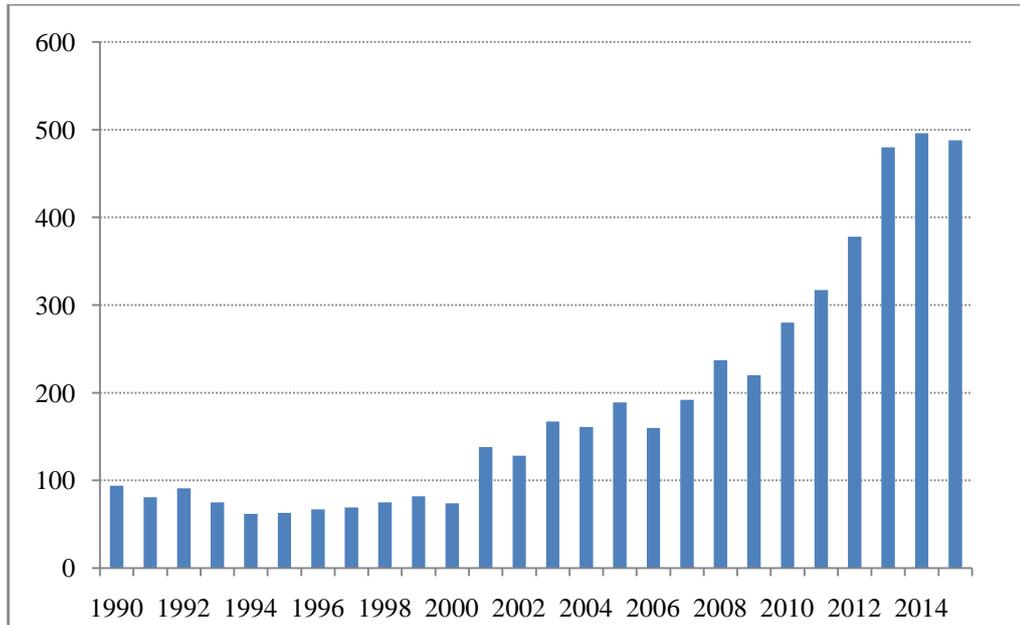
Fonte: Elsevier'sScopus. Disponível em: <<http://www.scopus.com>>. Acesso em 12 jun. 2016.

Gráfico 2– Evolução das citações do grupo 2 ao longo dos anos



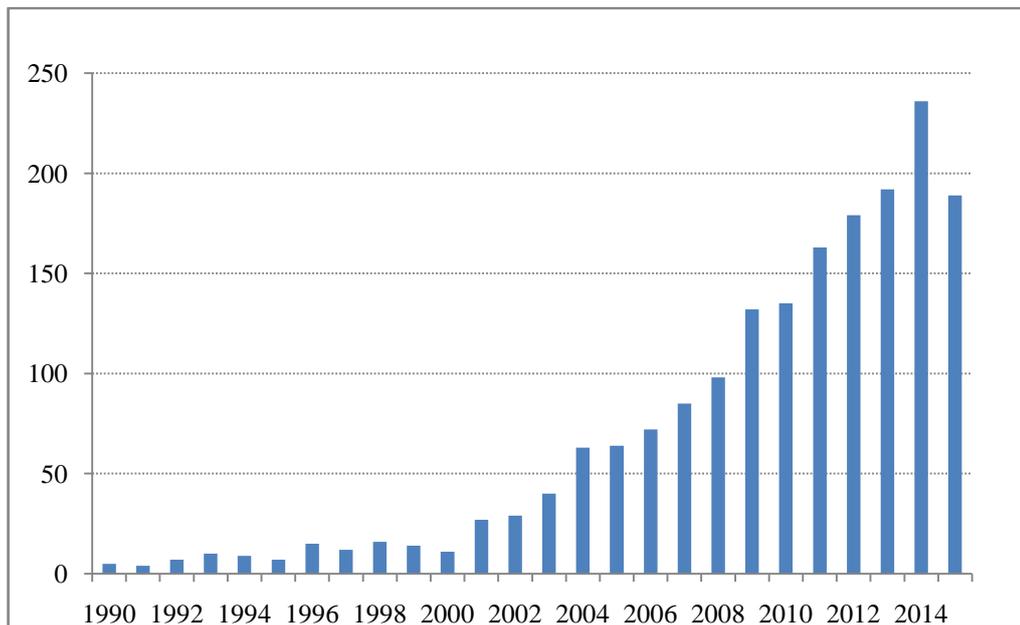
Fonte: Elsevier'sScopus. Disponível em: <<http://www.scopus.com>>. Acesso em 12 jun. 2016.

Gráfico 3– Evolução das citações do grupo 3 ao longo dos anos



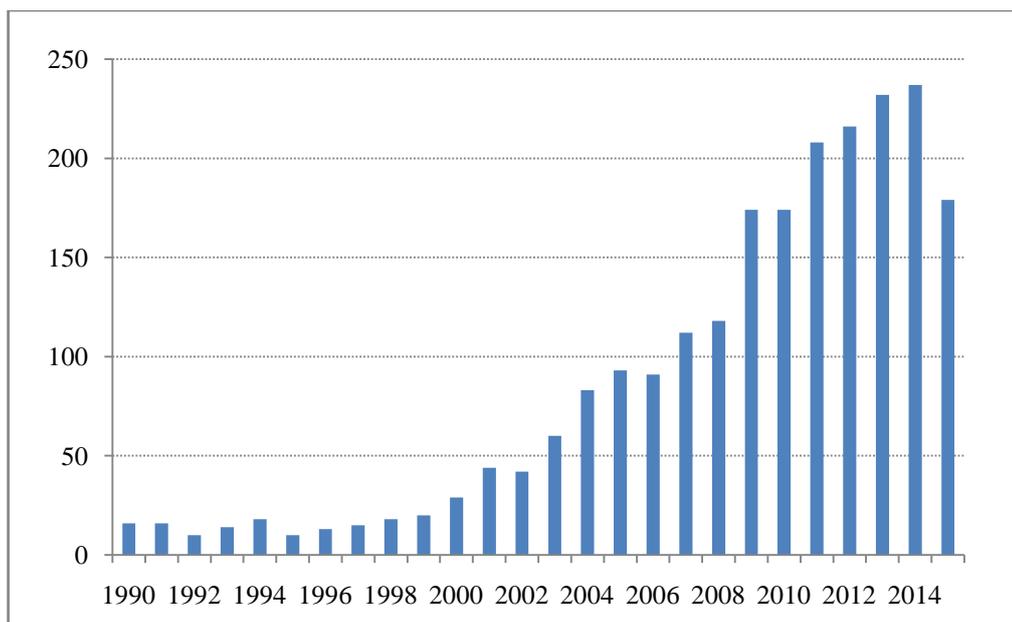
Fonte: Elsevier'sScopus. Disponível em: <<http://www.scopus.com>>. Acesso em 12 jun. 2016.

Gráfico 4– Evolução das citações do grupo 4 ao longo dos anos



Fonte: Elsevier'sScopus. Disponível em: <<http://www.scopus.com>>. Acesso em 12 jun. 2016.

Gráfico 5– Evolução das citações do grupo 5 ao longo dos anos



Fonte: Elsevier'sScopus. Disponível em: <<http://www.scopus.com>>. Acesso em: 12 jun. 2016.

Através da análise destes gráficos, é possível observar que de fato houve um grande aumento na quantidade de publicações envolvendo temas de segurança de processo nos últimos 25 anos. De 1990 a 2015, todos os grupos estudados tiveram um incremento de no mínimo 300% no número de publicações. Pode-se presumir, a partir deste estudo, que tanto empresas do setor industrial, quanto instituições acadêmicas estão investindo seus recursos no desenvolvimento da área de segurança. Além de promover vantagens tecnológicas óbvias, através da aplicação de processos e produtos cada vez mais seguros e confiáveis, um sistema de segurança de processo contribui para questões relativas à imagem de uma empresa. Um local de trabalho que não preze pela saúde dos seus funcionários e qualidade do meio ambiente, além de sanções legais, pode sofrer danos de imagem devido à ocorrência de eventos indesejados. É sabido, a partir de diversos exemplos, que eventual reputação negativa através da população e do mercado pode afetar consideravelmente os resultados de um negócio. Percebe-se assim, a complexidade e importância da segurança de processo na sociedade atual e a garantia de que, em um cenário tão competitivo, a mesma ainda será tema de discussões por muitos anos.

Com base no levantamento bibliográfico realizado, pode-se perceber que a análise de perigos é um dos pilares da segurança de processos industriais, sendo o HazOp a principal ferramenta utilizada globalmente. No entanto, por ser uma técnica baseada principalmente em um *brainstorming*, torna-se extremamente dependente do conhecimento e experiência dos

participantes, o que é visto como uma lacuna a ser corrigida e fruto de estudos na literatura. Tomando esta lacuna em consideração, e a relevância do tema, o presente trabalho propõe o uso de simulações estacionárias de sistemas de processo como ferramenta de auxílio à análises de perigos. Além disso, propõe uma metodologia para gerar o desencadeamento de consequências, a partir dos resultados das simulações estacionárias. O objetivo é facilitar a identificação de cenários, diminuindo a dependência em relação ao time participante e eliminar possíveis inconsistências em estudos de HazOp. Em adição, em uma segunda abordagem, propõe a adaptação de estudos de HazOp a uma representação matricial e de grafos, com o objetivo de auxiliar a análise e também buscar possíveis inconsistências na abordagem clássica. Os resultados obtidos através de simulações estacionárias, representações matriciais e de grafos, e HazOps clássicos serão comparados a fim de identificar vantagens e desvantagens de cada abordagem e podem ser vistos através dos artigos apresentados a seguir nos Capítulos 2 e 3. É importante destacar que os artigos foram elaborados em língua inglesa, visto que o objetivo é usá-los como ponto de partida para publicações em periódicos internacionais.

2 HAZOP AND EVENT TREE AIDED BY GRAPH ANALYSIS: CASE STUDIES

Abstract

HAZOP is one of the most important techniques for evaluating potential risks of the plants. It is made from a holistic team, where individual knowledges play a very important role. Although a systematic technic is applied, the results, may be however, subjected to lack of objectivity. In this context, some questions arise, such as how to convert HAZOP analysis in an objective form; and how to quantify and evaluate the coherence of a HAZOP analysis. The aim of this paper is to present discussions about these topics, based on three examples. Algorithms were developed and adapted to verify features and inconsistencies of HAZOP analysis (also an algorithm for developing an event tree was implemented). The first example is a Flash Pot System, the second is a Pumping System and the third is a CO₂ separation system. The algorithms allowed to obtain the sequences of HAZOP influences. The results show how some conclusions of HAZOP can be incoherent, counting for each system of possible suspicious or inconsistent sequences allowed according to HAZOP analysis. Event trees from HAZOP analysis were generated and evaluated for the examples. The paper endorses, with quantitative characterization of possible inconsistencies for the case studies, the prevailing trend in literature of performing HAZOP aided by computational systems.

Keywords:HAZOP, Process Safety, Event Tree;

2.1 Introduction

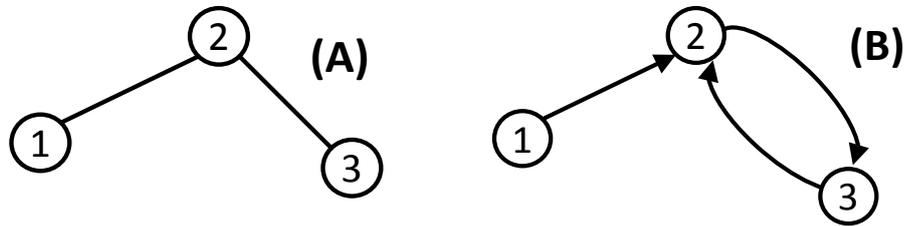
The previous chapter presented several tools for evaluating and reducing risks in chemical plants, such as: HAZOP, LOPA, fault tree analysis (FTA), failure mode and effect analysis (FMEA). The focus of this paper is an intersection between HAZOP, FTA, ETA, which important points are described below.

2.1.1. Traditional and graph aided HAZOP analysis

HAZOP consists in one of the most widely used tool for reducing risks, being a workaday task in several industries. Despite its popularity, studies draw attention to weaknesses of such technique (BAYBUTT, 2016; GUJAR, 1996), since even with its systematic approach, there are dependences on subjective aspects. To overcome or minimize some limitations, HAZOP has been integrated with others tools, such as: stationary and dynamic simulation (EIZENBERG; SHACHAM; BRAUNER, 2006; RAONI; SECCHI; DEMICHELA, 2018; ŠVANDOVÁ, Z. *et al.*, 2005); expert based systems (CUI; ZHAO; ZHANG, 2010; VAIDHYANATHAN; VENKATASUBRAMANIAN, 1996), graph theory (KOŚCIELNY *et al.*, 2017; RODRÍGUEZ; DE LA MATA, 2012; VAIDHYANATHAN; VENKATASUBRAMANIAN, 1995), among others. A detailed review is presented by Dunjó *et al.* (DUNJÓ *et al.*, 2010). Particularly, for the purpose of this paper, it is convenient to discuss the use of graphs tools for HAZOP analysis.

Graph and digraph are represented by a set of vertices and lines. Digraphs contains directional lines (so the name directional-graphs or digraphs). A simple example is illustrated in the following Figure 2.1.

Figure 2.1 – Illustration of (A) graphs and (B) digraphs



Source: Author, 2018

In the above example, vertex 1 is connected to the vertex 2, which is connected to the vertex 3. In the example of Figure 2.1B, vertices 2 and 3 has a loop, since following the paths, one will return to the same point. For our purpose, the digraphs are more appealing. It is important to define the concepts:

- Loops – associated to undirected cycles (when direction of arrows is not considered);
- Circuit – loops in directed cycles, when a directed path is closed.

Digraphs can be represented by the adjacency matrix A , which indicates which vertex is connected and its direction. The matrix A can be understood as:

$$A_{i,j} = \begin{cases} 1 & \text{an arrow from vertex } i \text{ to vertex } j \text{ exists} \\ 0 & \text{no relation between edges} \end{cases} \quad (1)$$

For example, the case represented in Figure 2.1 can be expressed as:

$$A = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \begin{matrix} \text{Vertex 1} \\ \text{Vertex 2} \\ \text{Vertex 3} \end{matrix} \quad (2)$$

The influence of variables can be mutual for both positive and negative perturbations, or in a single direction, as illustrated in Table 2.1.

Table 2.1 – Illustration of influences between variables considered in the HAZOP

Representation	Meaning
$\Delta(x)^{+,-} \leftrightarrow \Delta(y)^{+,-}$	Mutual relation both for positive and negative perturbations. Perturbation in x will affect y and vice-

 versa.

$\Delta(x)^{+,-} \rightarrow \Delta(y)^{+,-}$ Relation for both positive and negative perturbations; the perturbations of x affects y , but the opposite is not true

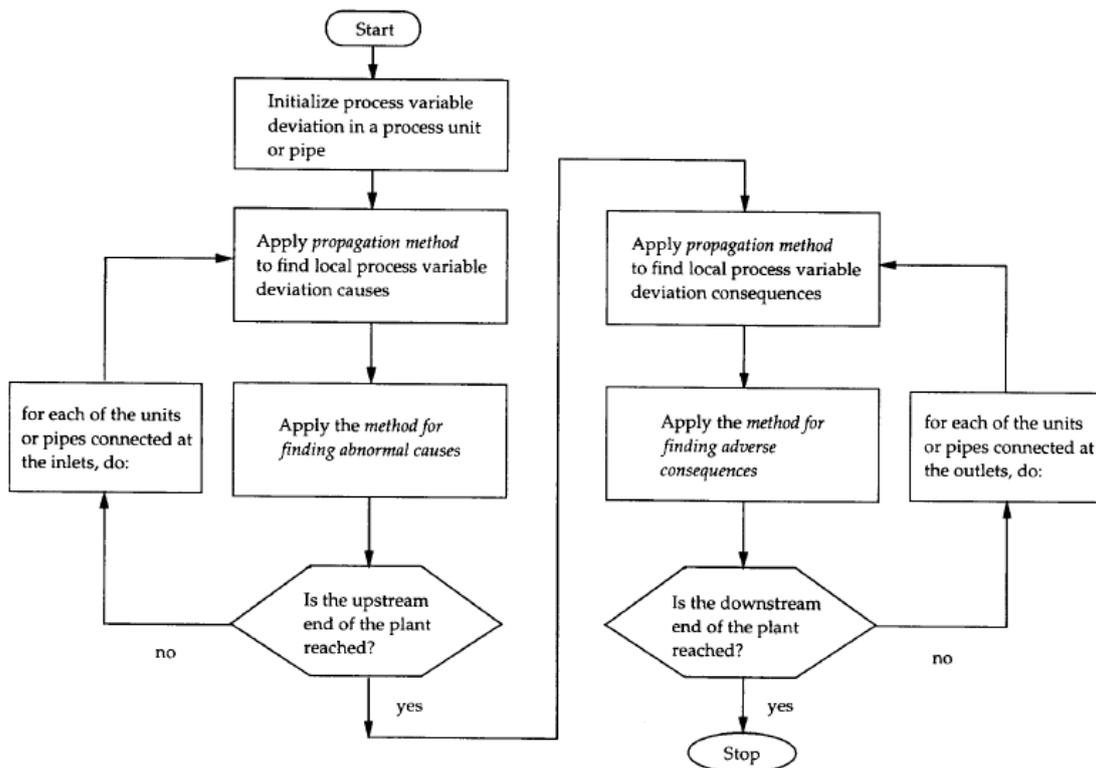
$\Delta(x)^{-} \rightarrow \Delta(y)^{+}$ Relation between x and y , where negative perturbation in x leads to positive perturbation in y , but the opposite is not true

Source: Author, 2018

As commented before, graph analysis has been applied to HAZOP studies.

Vaidhyathan and Venkatasubramanian (VAIDHYANATHAN; VENKATASUBRAMANIAN, 1995) proposed the use of digraph based models for automating HAZOP analysis. The procedure is illustrated in Figure 2.2. Firstly, they identify causes of perturbations; then, propagation method is applied to identify how such perturbations propagate to other units. Authors applied such methodology to industrial cases. Posterior work included languages specific for discrete events (SRINIVASAN; VENKATASUBRAMANIAN, 1996).

Figure 2.2 – Digraph based model for HAZOP analysis



Source: VAIDHYANATHAN; VENKATASUBRAMANIAN, 1995

Later, Vaidhyanathan and Venkatasubramanian (VAIDHYANATHAN; VENKATASUBRAMANIAN, 1996) proposed an improvement in the study presented by themselves in (VAIDHYANATHAN; VENKATASUBRAMANIAN, 1995). The authors stated that the methodology proposed to automate the HazOp analysis through the use of the HAZOPExpert platform has a significant gap, once among all the consequences identified, a significant amount is related to consequences that are not feasible to occur. They justified that it happens due to the completely qualitative nature of the platform, which always returns the worst-case scenario as a result. For instance, in a deviation of high temperature in a flammable chemical, the platform returns as consequence a possible fire and explosion, even if the fluid temperature cannot reach the auto-ignition temperature, as per a process limitation. To overcome this fact, the authors proposed a semi-quantitative filtering methodology to eliminate unfeasible results. This was achieved through the addition of known process parameters, such as maximum pressure and temperature a vessel can hold, operating pressure and temperature, auto-ignition temperature of chemicals, etc. Having those values declared with other tolerance limits, the HAZOPExpert shows only consequences physically possible to happen. For example, to define if a fire is possible to occur because of a high temperature in a flammable fluid, a fire hazard threshold was defined, which is the ratio between the auto-ignition temperature and operation temperature. Every time the consequences for high temperature are evaluated in a node, the software calculates the actual ratio and compares to the tolerance limit. The engine will return a fire case only if the tolerance is violated by the ratio calculated. With the use of this approach for this and other deviations, the number of unfeasible consequences was drastically reduced. The authors applied the semi-quantitative approach to an ethylene plant and compared the results to the ones obtained in a classical HazOp with a team of experts and the ones obtained with the use of the HAZOPExpert (fully qualitative modelling). They found that the semi-quantitative approach reduced in 50% the amount of consequences identified, comparing to the qualitative modelling, once the unreal consequences were not considered. In addition, the new approach obtained more complete results than the team of experts. The authors stated that methodology applied has a significant potential to provide automated HazOp studies, adding semi-quantitative reasoning to the use of graphs.

Maurya et al. (2003a) points out the importance of evaluating spurious relations from the use of digraph for representing relation of events in a chemical plant. They attracted attention to loops and incoherent information between cycles. In a second paper (MAURYA; RENGASWAMY; VENKATASUBRAMANIAN, 2003b), the authors developed models for

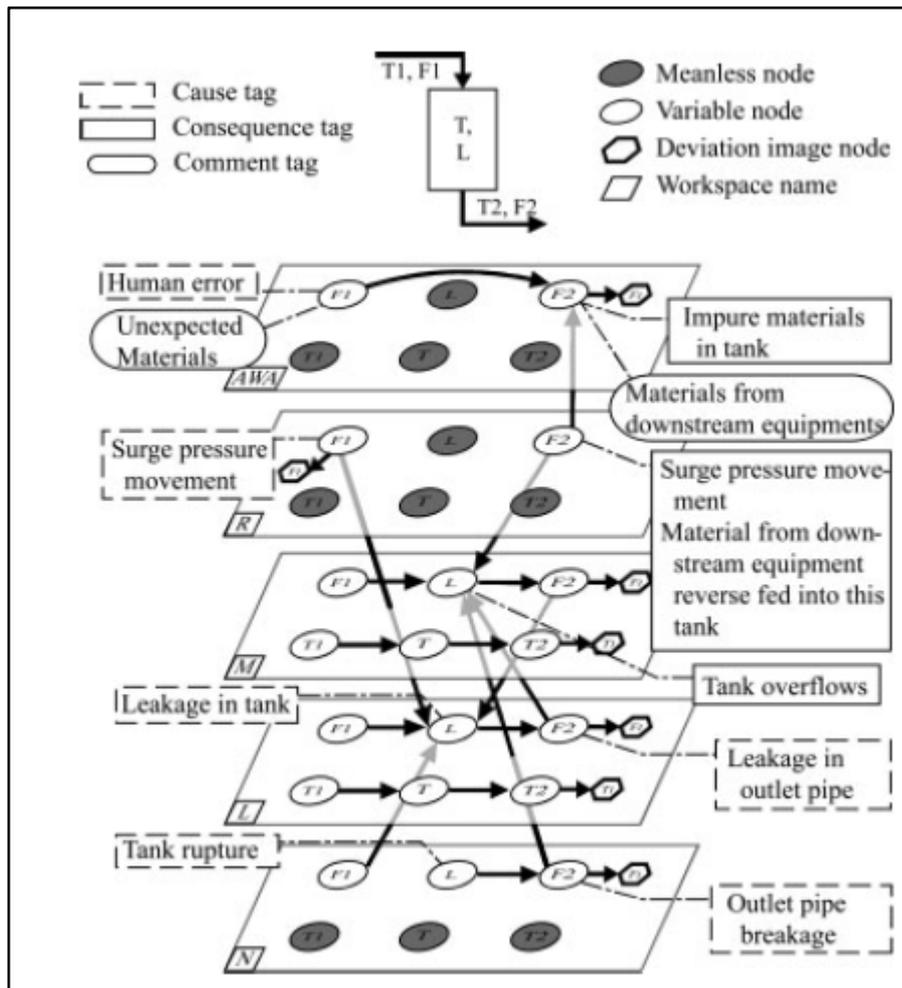
representing the flow rate of a toxic material. With this approach, the start and end path are set. With the goal of finding all the existing paths, an adjacency matrix is used, in which every row and column element represent a node of the SDG. The $a_{i,j}$ elements of the matrix are 0 or 1, where 1 indicates that there is a relation between variable in the row i and the variable in column j and 0 indicates that no relation exists. With the matrix and a computational algorithm, all the possible paths are found. In the next step, the authors calculate the influence type of each path from the start node to the end node. Then, the results can be presented in away very similar to a HazOp report. The authors state that the proposed methodology allows a forward and back forward approach, useful for HazOp studies, as most paths can be identified.

Kuo et al.(Kuo et al., 1997) use a tool called IHAS (Integrated Hazard Analysis System) to automatically perform a study that includes FTA, ETA and HazOp. Analogously to others works cited, standard SDGs of basic units are developed and combined to represent a bigger process through the IHAS. The authors provide the steps necessary to perform the analysis using the IHAS. Such steps include selecting a deviation, determining the guide word, construct a fault-tree using the selected deviation as the top event, determining the minimum cut-sets of the fault tree, constructing the event tree corresponding to a minimum cut set and enumerating the event sequences (consequences and safeguards actuation) associated with the event tree. The above obtained data will be plotted in the columns for deviations, causes, consequences and safeguards in a HazOp format.As the last step, recommendations are listed. The recommendations work as a rule-based system. For the causes, consequences and safeguards listed, the IHAS has recorded and its database a series of recommendations that may be applicable. It means that an action or actions can be found if a rule in the knowledge base is met. The authors applied the methodology to an olefin dimerization unit and concluded that the proposed methodology made it possible to find more hazardous scenarios and suggested more recommendations when compared to the HazOp study made by a team of experts for the same unit. In addition, they stated that as the time to find more common scenarios is saved, the team of experts can focus in the non-obvious and critical events.

Cui et al. (Cui et al., 2008) proposed a different graph methodology, called LDM (Layered Digraph Model). The authors state that SDGs are used as the main attempt to automate HazOp studies. However, in those qualitative models, only signals + and – are used in the graph representations, which limits the analysis to the HazOp keywords of “more”, “less” and “none”. Thus, the authors affirm that incomplete HazOps can be generate through

such automations, as other HazOp keywords are neglected, such as “reverse”, “as well as” and “other than”. To solve this gap, LDM is suggested. They explain that LDM consists in a series of workspaces stacked in layers, in which each layer corresponds to a HazOp keyword. Each layer also contains a series of nodes connected between themselves through arcs with no designation of signals + or -. Here the nodes represent process variables of interest, and the junction of a node and a layer corresponds to a unique deviation. An arc connecting a node in the workspace A to a node in the workspace B means that the deviation represented by the node in the workspace A causes the effect represented by the connected node in the workspace B. In addition, tags of cause, consequence and other comments can be added to the LDM for more complete information. An example of an LDM is shown in Figure 2.4 below.

Figure 2.4 - Example of an LDM



Source: CUI et al., 2008

An LDM of different equipment can be connected to represent a more complex process and then generate the automated hazard analysis intended. The authors emphasize the

flexibility that such methodology provides, as many keywords as needed can be used to identify different scenarios.

Sauk et al. (SAUK et al., 2015) used the graph concept not to automate HazOp studies, but to support it. The authors state that often a deviation originated in an upstream node can generate a given consequence in the node being studied. Thus, the deviation in the node being studied is a propagation of the same deviation in the upstream node. Considering that, the team often need to momentarily interrupt the study of a node to analyze the upstream one and assess if the deviation being discussed and its propagation are possible to happen. The authors considerer that this process can disrupt the HazOp study and make the team to miss hazardous scenarios. To mitigate this issue, they suggest a methodology to help selecting the optimal sequence of nodes to be evaluated, to not disrupt the logical sequence of the study. The graph concept is used. In the given context, each vertex represents a HazOp node and the vertices are connected with directional arcs. The graph is translated in a matrix where rows and columns indexes represent the nodes of the HazOp and the $a_{i,j}$ elements are given values of 0 or 1. If 1, then there is at least one process stream going from the node of row i to the node in the column j . With the obtained matrix and with the use of matrix operations involving the exclusion of empty columns and rows, the optimal node sequence is obtained. The author also state that this methodology is not limited to HazOp studies, being possible to be applied to other techniques involving the subdivision of a system into smaller units.

Kościelny et al. (KOŚCIELNY et al., 2017) follow a similar reasoning as (SAUK et al., 2015) and states that HazOp studies are subjected to incompleteness due to failure in the identification of all possible causes. This fact becomes more relevant in more complex processes, with multiple interfaces and feedbacks between nodes. To overcome this issue, the authors proposed the use of a GP, which is based on qualitative modelling. The GP proposed in their paper is a graph that takes in consideration the relation between process variables (physical variables), control signals from the control system, readings signals from control instruments sensors and failures affecting the process. The authors utilize a system called IAPS (Intelligent Accident Prevention System), which has a module for the creation of the GP and obtaining of the possible cause and effect interactions. In addition, they state emphasize that the use of the GP allows the visualization of the cause-effect relations in the form of a more complete graph and provides the opportunity of acknowledging the dependencies between nodes in a more structured way, including nodes feedback.

Other applications of HAZOP with graphs model were performed in other works (LÜ; WANG, 2007).

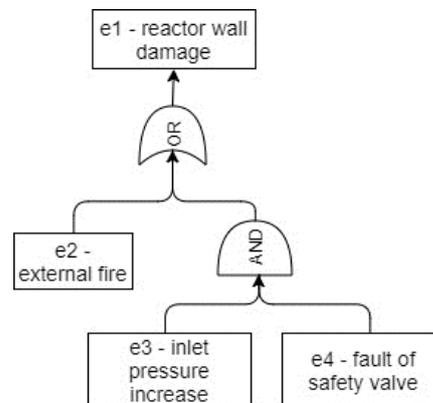
2.1.2. FTA and ETA

FTA and ETA are deductive techniques, which elaborate trees from a fault (FTA) or an original event (ETA). In FTA, one creates the conditions that leads to faults, while in ETA the subsequent events are derived from an original perturbation. Such systems can be written in terms of Boolean Algebra (that contains only 0 or 1). An event occurs if it is assigned by 1, and did not occur if it is assigned by 0, as follows.

$$e_i = \begin{cases} 1 & \text{event } i \text{ occurs} \\ 0 & \text{event } i \text{ does not occur} \end{cases} \quad (3)$$

According to logical representation, **OR** is represented sum (+), while **AND** is represented by multiplication (\cdot)¹. For example, considering the FTA represented in Figure 2.5.

Figure 2.5 – Illustration of FTA.



Source: Author, 2018

The FTA represented in Figure 2.5 can be represented in Boolean Algebra as the following relation:

$$e_1 = e_2 + e_3 \cdot e_4 \quad (4)$$

Then, for example, if there is no external fire, $e_2 = 0$, but occur an inlet pressure increase $e_3 = 1$ and fault of the safety valve $e_4 = 1$, then event $e_1 = 0 + 1 \cdot 1 = 1$, which means that reactor wall damage will occur. Since the events can assume only 0 or 1, if the sum is greater than one, it is assumed to be one (for example, if fire occurs and pressure inlet

¹ It is important to emphasize that in Boolean Algebra, sum is not a mathematical sum, but logical operation, representing the union of a True or False condition. For example, True + True = True, not 2*True.

and fault of safety valve also, then the sum of $e_1 = 2$, but since it can assume only 0 or 1, it means that the value 1 is assigned to e_1). So, considering for all individual events and combinations of two, the columns vector $\mathbf{e} = \{e_1; e_2; \dots, e_n\}$ can be written as according to the following logical operation:

$$\mathbf{e} = \mathbf{E}^{(0)} \cdot \mathbf{e} + \mathbf{e}^T \cdot \mathbf{E}^{(1)} \cdot \mathbf{e} \quad (5)$$

Where $\mathbf{E}^{(0)}, \mathbf{E}^{(1)}$ are square matrices of $n \times n$ containing 0 or 1. $\mathbf{E}^{(0)}$ corresponds to a single factor influence over others, while $\mathbf{E}^{(1)}$ contains the binary effects.

How to deal with loops in trees generation?

A problem occurs when a loop is found, then, it is not possible to represent trees in only single directions. Besides, contradictions can arise. Several works discuss this subject (DEMICHELA *et al.*, 2004; JUNG; HAN, 2005; MATSUOKA, 2009). Basically, the structure problem has no clear solution, being performed studies that propose avoid such loops, however somehow tie loops in weak or contradictory points.

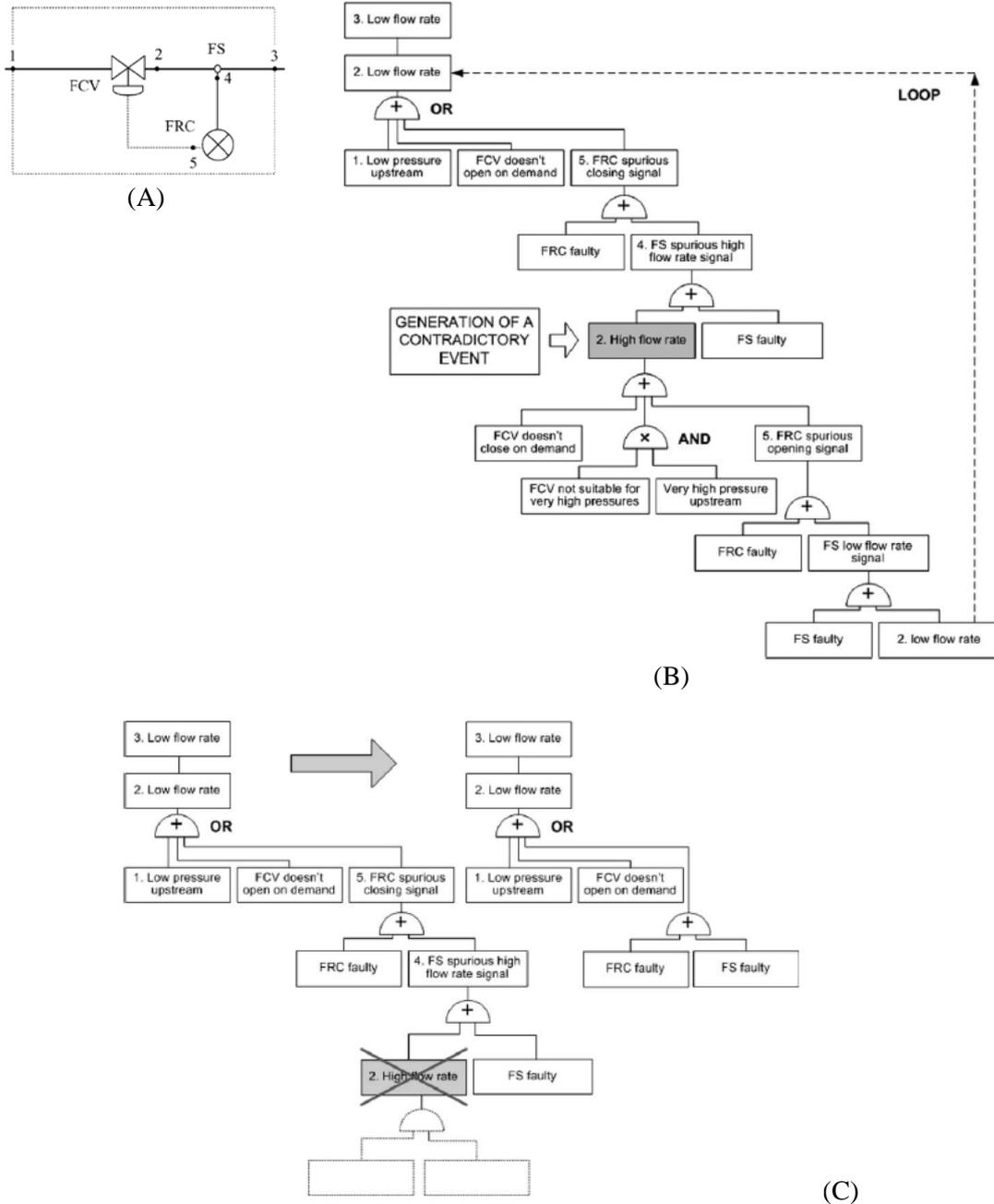
Demichela et al. (DEMICHELA *et al.*, 2004) pointed out that typically a contradictory fact can be avoided in some manners. First, starting from the top event, when get a contradictory event due a loop, simply remove such event is one form to avoid incoherence. Authors illustrates this case considering a valve system (Figure 2.6A), where a fault of low flow occurs; and possible cause is a spurious value of FRC and a High Flow Rate (Figure 2.6B). The solution is remove this branch, as shown in Figure 2.6C. A second approach is to use of a procedure called ROA (Recursive Operability Analysis) for obtaining FTAs, instead other traditional methodologies. According to the authors, such procedures seeks the “primary events”, so, loops are avoided in the generation of FTA.

Lim and Jang (LIM; JANG, 2007) proposed a solution to avoid logical loops considering Boolean equations, including a term δ_i associated to a particular event i . A meaningless event could be eliminated considering $\delta_i = 0$; so, the loop is broken with a personal choice that decides which event(s) should be ignored. In a posterior paper, Lim and Han (LIM; HAN, 2012) proposed to consider the initial condition for obtaining FTAs.

Matsuoka (MATSUOKA, 2009) proposed a treatment of Boolean equations to deal with logical loops, if without considering the time associated to each event. Interesting discussions are presented. For example, if there is one single loop, it is possible to lump these

parts of process or represent it at the same level of a tree. He also points out aspects about the time involving the events, and how it influences the sequence of events. However, in the examples of the author, the original structure has no incoherence.

Figure 2.6– Illustration of incoherent loop and a simple way to deal with it



Source: DEMICHELA *et al.*, 2004

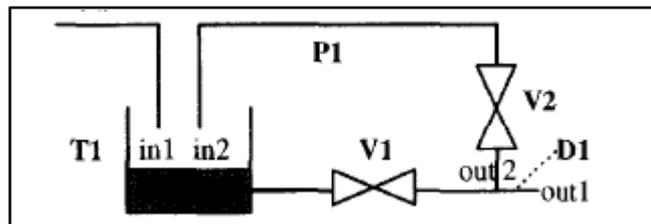
Palmer and Chung (PALMER; CHUNG, 1998) address the use of SDSs and the ambiguities that can arise after combining them to represent a larger process and study the

propagation of deviations. Basically, the authors state that these ambiguities exist due to multiple propagation paths that lead to:

- Final and initial effects influencing one another in a contradictory way inside a loop;
- Scenarios physically impossible to occur;
- A single cause leading to completely opposite consequences.

Considering these facts, the authors propose an approach to reduce the above-mentioned ambiguities, called modular modelling approach. Instead of connecting every unit in aSDG to represent the whole process, the authors create a simplified SDG module, in which the paths that leads to ambiguities are removed. To evidence this approach, the authors applied the concept into the plant loop showed in the Figure 2.7 below:

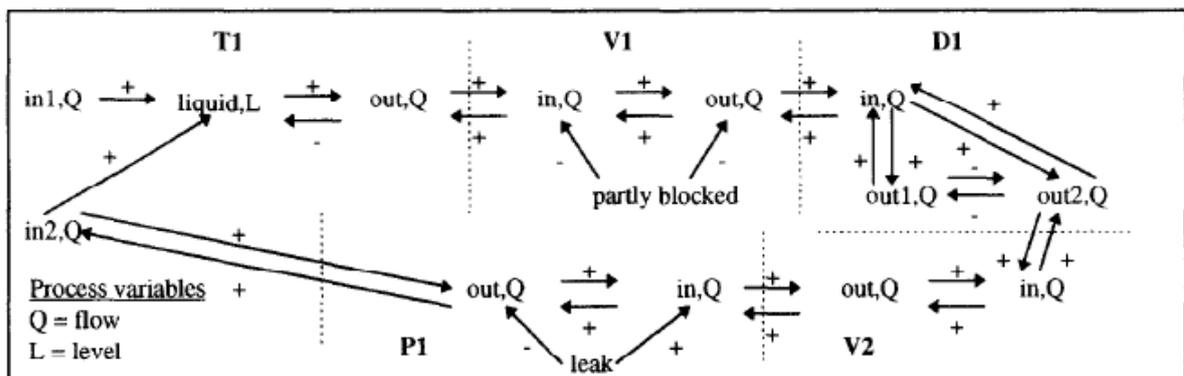
Figure 2.7 - Single plant loop



Source: PALMER;CHUNG, 1998

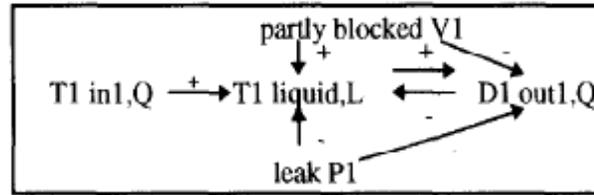
The Figures 2.8 and 2.9 below represent the above system in a unit-based SDG and in the modular approach SDG, respectively.

Figure 2.8 - SDG for a single plant loop



Source: PALMER;CHUNG, 1998

Figure 2.9 - Module SDG of a single plant loop



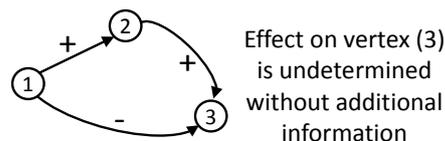
Source: PALMER;CHUNG, 1998

It's possible to notice that when the plant loop was made into a module, some of the propagations paths were removed. The authors stated that even with multiple paths still existing, a heuristic that consists in taking the shortest path leads to the correct results.

2.1.3. Risk of using the direct information of Boolean relations in loops of HAZOPs or trees

As commented before, this subject was emphasized by Maurya et al. (MAURYA; RENGASWAMY; VENKATASUBRAMANIAN, 2003a, b). The authors point out the importance of evaluating spurious relations from the use of digraph for representing relation of events in a chemical plant. They attained attention to loops and incoherent information between cycles. For example, consider three vertices, as shown in Figure 2.2, where vertex (1) influence positively (2) and negatively (3), and vertex (2) influence positively (3). Then, (3) suffers a positive and negative influence, but without quantification, the net result is unknown. Authors present an extensive discussion conceptual points an algorithm, alluding the use of original mathematical relations for reducing spurious information from graph representation.

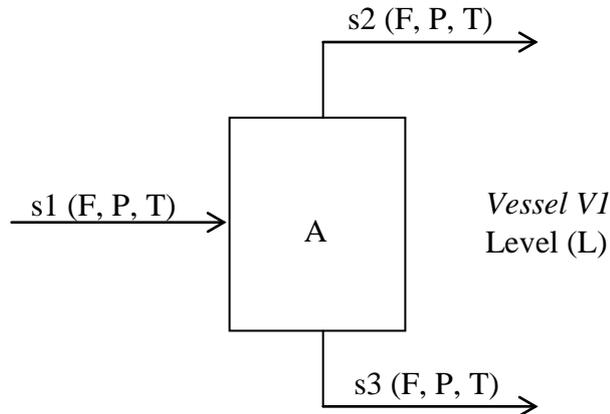
Figure 2.10 – Digraph based model for HAZOP analysis



Source: MAURYA; RENGASWAMY; VENKATASUBRAMANIAN, 2003a

For illustrating this risk even in only positive loops, consider for example a *flash system*, as illustrated in Figure 2.11

Figure 2.11 – Example of a flash system.



Source: Author, 2018

The original equation that relates level, inlet and liquid outlet flows is the following:

$$A \cdot \frac{d}{dt}(V1.L) = s1.F - s3.F \quad (6)$$

$$s3.F = \mathfrak{C} \cdot \sqrt{V1.L} \quad (7)$$

Where A is the area of the vessel, $V1.L$ is the liquid level of the vessel, $s1.F$ and $s3.F$ are the flows of the streams $s1, s3$ and \mathfrak{C} is a constant. Substituting the Equation (7) in Equation (6) we have:

$$A \cdot \frac{d}{dt}(V1.L) = s1.F - \mathfrak{C} \cdot \sqrt{V1.L} \quad (8)$$

An example of simple relation of a single direction perturbation is between level and inlet flow:

$$\Delta(s1.F)^{+,-} \rightarrow \Delta(V1.L)^{+,-}$$

Thus, $V1.L$ is affected by $s1.F$ but the opposite is not true (at least for a short time range). In terms of a matrix terms, one can represent as:

$$s1.F \quad V1.L$$

$$S^+ = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{matrix} s1.F^+ \\ V1.L^+ \end{matrix}$$

$$S^- = \begin{pmatrix} 0 & -1 \\ 0 & 0 \end{pmatrix} \begin{matrix} s1.F^- \\ V1.L^- \end{matrix}$$

An example of a mutual relation between variables can be associated to variables $V1.L$ and $s3.F$, according Equation (2). Since there is a direct mathematical relation, positive or negative variations of $s3.F$ will imply respectively in positive or negative variations of $V1.F$, which can be represented in the following form:

$$\Delta(s3.F)^{+,-} \leftrightarrow \Delta(V1.L)^{+,-}$$

In terms of a binary matrix of factors, it will imply in a symmetric matrix. Representing only $s3.F$ and $V1.L$ in a matrix, it will lead to:

$$\begin{array}{c}
 s3.F \quad V1.L \\
 S^+ = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{array}{l} s3.F^+ \\ V1.L^+ \end{array} \\
 S^- = \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix} \begin{array}{l} s3.F^- \\ V1.L^- \end{array}
 \end{array}$$

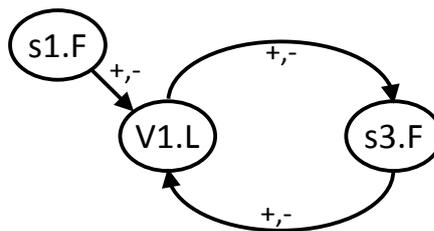
Which illustrates that those relations where the equation bellow is satisfied contains simple direct mathematical relation between variables.

$$S^+ = -S^-$$

This analysis does not allow affirming if such perturbations are self-sustainable. For example, in the above example, it is well known that it is not a self-sustainable perturbation, because the mathematical relation involves the derivative of level as a function of absolute value of the level, according to Equation (1). Then, the derivative of $V1.L$ is negatively related to the own value of $V1.L$, leading in this case to a self-controlled system. Although in this simple case the analysis is straightforward, it will lead to a complex problem for the most cases. Since the formal analysis of self-sustainable perturbations would require the mathematical modeling, one can argue that this analysis should not be further used to evaluate self-sustainable perturbations or long-time range effects.

In terms of representation, it will naturally lead to a cycle of relations between $s3.F$ and $V1.L$, and the variables $s1.F$ influencing $V1.L$, in the form of Figure 2.12.

Figure 2.12 – An example of relation of variables associated to a flash system.



Source: Author, 2018

More examples can be found in the works of Maurya et al. (MAURYA; RENGASWAMY; VENKATASUBRAMANIAN, 2003a, b).

2.1.4. Overall comments

One can argue that the literature presented relevant development about use of graphs representation of process and its use in HAZOP and FTA and ETA. In fact, tools have been developed for performing such analysis, like (RODRÍGUEZ; DE LA MATA, 2012): HAZOPExpert(VENKATASUBRAMANIAN; ZHAO; VISWANATHAN, 2000), PHA Suite (ZHAO; BHUSHAN; VENKATASUBRAMANIAN, 2005), Functional HAZOP assistant (ROSSING *et al.*, 2010a, b), Layered Digraph Model (CUI; ZHAO; ZHANG, 2010), among others

Nonetheless, it is noteworthy the fact that few of such tools are not easily accessible to the industrial and academic community, besides the fact that, when available, they allow few personalization of the code. Thus, it seems reasonable to continue studying and developing similar tools, ideally allowing in the future the development of free available to industrial and academic community.

Another point that deserves attention is how to evaluate the objectivity of HAZOP, quantifying possible incoherence. This last case is better performed carrying out case studies, observing how traditional HAZOP can lead to unfeasible real implications. This is in consonance with other discussion presented(MAURYA; RENGASWAMY; VENKATASUBRAMANIAN, 2003a, b, 2006).

In this context, the present paper has the objective to perform Graph analysis of typical HAZOP analysis on case studies, applying digraph tools, to evaluate how graph analysis can help HAZOP conclusions, and which incoherence arise from such study.

2.2 Methodology

We considered three case studies: (i) a simple flash-pot, (ii) a pumping system and (iii) a complex CO₂ separation plant. For each case study it was developed a HAZOP analysis. Then, such analysis was converted to an adjacency matrix (as shown in Equation (2)).

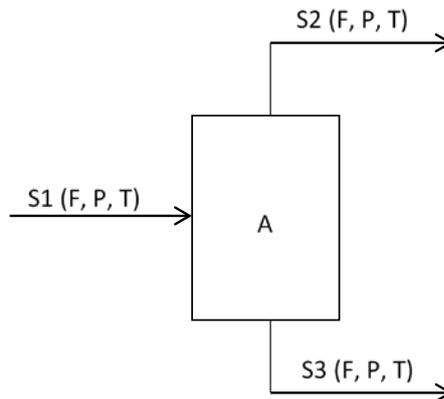
Objective matrix representations were generated, adapted from discussions raised in classic HazOps. Such matrices have been raised to industry-standard equipment such as heat

exchangers, gas-liquid separation vessels, centrifugal compressors, etc. which represent the individual nodes of a classic HazOp. To develop such matrices, the relationships between the inlet and outlet streams of each equipment were raised qualitatively, following the coding below:

- $a_{i,j} = 0$, there is no relation between the variables
- $a_{i,j} = 1$, there is an increase in the value of a given variable taking into account a given disturbance
- $a_{i,j} = -1$, there is a decrease in the value of a given variable taking into account a given disturbance.

Taking into account the generic equipment A of Figure 2.13, the obtained matrix can follow the shape indicated in Table 2.2.

Figure 2.13 – Example of generic equipment.



Source: Author, 2018

In the present methodology, only flow (F), pressure (P) and temperature (T) were considered for the streams variables. In addition, some equipment specific variables were considered as the level L.

Table 2.2 – Matrix of influences adapted from typical HAZOP

	S1 F	S1 P	S1 T	S2 F	S2 P	S2 T	S3 F	S3 P	S3 T
S1 F	a _{1,1}	a _{1,2}	a _{1,3}	a _{1,4}	a _{1,5}	a _{1,6}	a _{1,7}	a _{1,8}	a _{1,9}
S1 P	a _{2,1}	a _{2,2}	a _{2,3}	a _{2,4}	a _{2,5}	a _{2,6}	a _{2,7}	a _{2,8}	a _{2,9}
S1 T	a _{3,1}	a _{3,2}	a _{3,3}	a _{3,4}	a _{3,5}	a _{3,6}	a _{3,7}	a _{3,8}	a _{3,9}
S2 F	a _{4,1}	a _{4,2}	a _{4,3}	a _{4,4}	a _{4,5}	a _{4,6}	a _{4,7}	a _{4,8}	a _{4,9}
S2 P	a _{5,1}	a _{5,2}	a _{5,3}	a _{5,4}	a _{5,5}	a _{5,6}	a _{5,7}	a _{5,8}	a _{5,9}
S2 T	a _{6,1}	a _{6,2}	a _{6,3}	a _{6,4}	a _{6,5}	a _{6,6}	a _{6,7}	a _{6,8}	a _{6,9}
S3 F	a _{7,1}	a _{7,2}	a _{7,3}	a _{7,4}	a _{7,5}	a _{7,6}	a _{7,7}	a _{7,8}	a _{7,9}
S3 P	a _{8,1}	a _{8,2}	a _{8,3}	a _{8,4}	a _{8,5}	a _{8,6}	a _{8,7}	a _{8,8}	a _{8,9}
S3 T	a _{9,1}	a _{9,2}	a _{9,3}	a _{9,4}	a _{9,5}	a _{9,6}	a _{9,7}	a _{9,8}	a _{9,9}

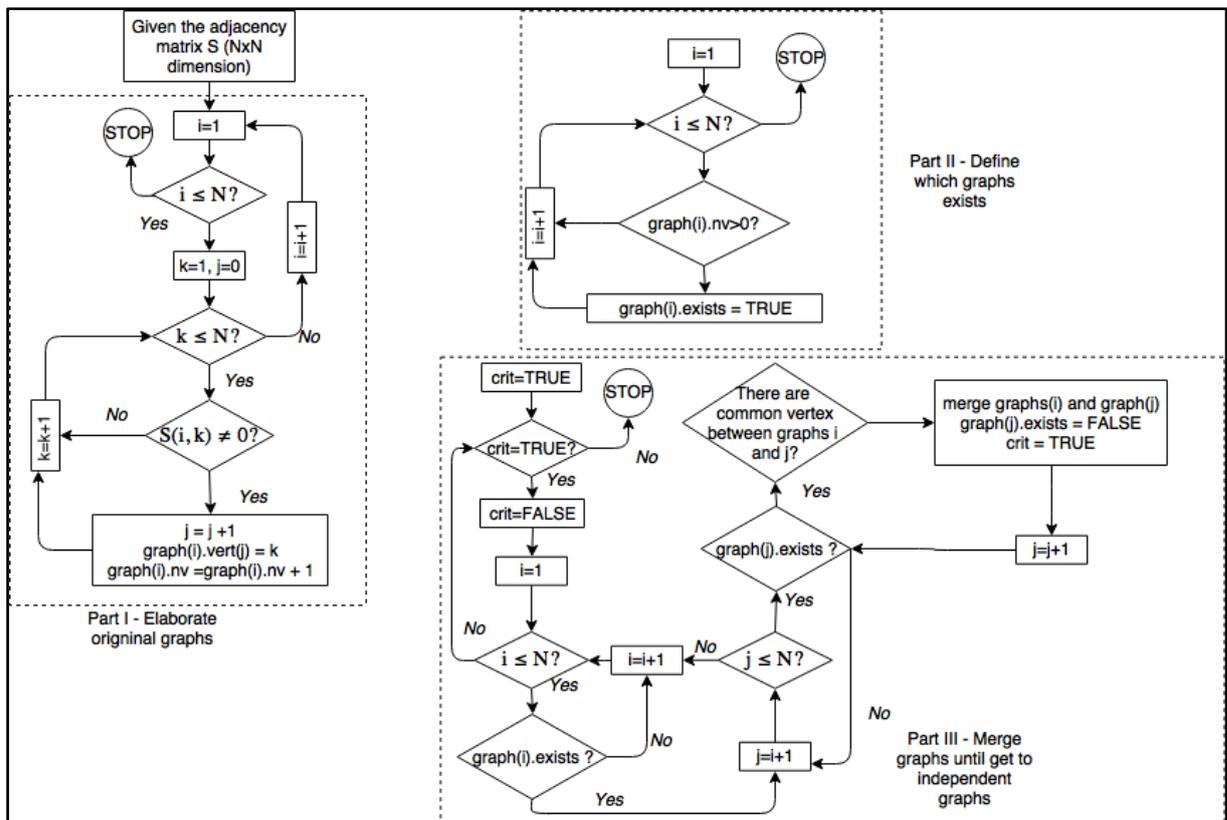
Source: Author, 2018

Two matrices following this pattern were developed for each equipment, one related to increases in disturbing variables and another related to the decreases of these same variables. The indices at the top represent all the variables included in the process and the elements of the matrix indicate the response of each of these variables to an increase or decrease of the disturbing variable of reference in line n , following the coding defined above.

In addition, four algorithms were developed to perform the proposed HazOp consistency analysis through graphs:

- Algorithm 1 – to identify interrelated variables (Figure 2.14);
- Algorithm 2 – to identify cycles that relate variables in a graph (Figure 2.17)
- Algorithm 3 – to join positive and negative perturbations matrices and verify inconsistencies (Figure 2.18 and Figure 2.19)
- Algorithm 4 – to generate an event tree from one initial informed disturbance (Figure 2.22)

Figure 2.14 – Algorithm 1, to identify interrelated variables.



Source: Author, 2018

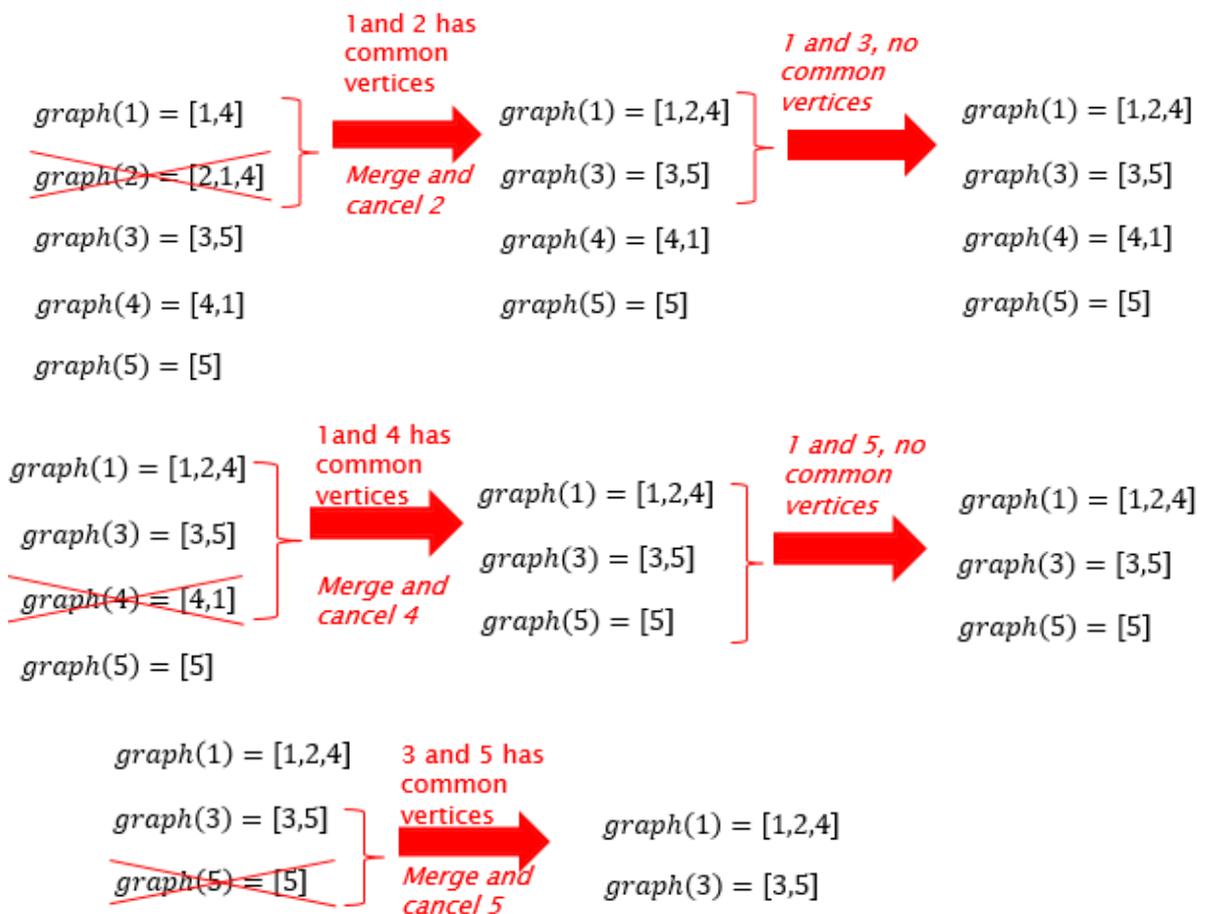
The application of the above flow chart can be understood more easily through the visualization of Figures 2.15 and 3.16 below, where the mentioned algorithm is applied to a hypothetical matrix.

Figure 2.15 - Algorithm 1 – Step 1 – Set the graphs

$$\mathbf{S} = \begin{pmatrix} v1 & v2 & v3 & v4 & v5 \\ 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{matrix} v1 \\ v2 \\ v3 \\ v4 \\ v5 \end{matrix} \begin{matrix} \rightarrow \\ \rightarrow \\ \rightarrow \\ \rightarrow \\ \rightarrow \end{matrix} \begin{matrix} graph(1) = [1,4] \\ graph(2) = [2,1,4] \\ graph(3) = [3,5] \\ graph(4) = [4,1] \\ graph(5) = [5] \end{matrix}$$

Source: Author, 2018

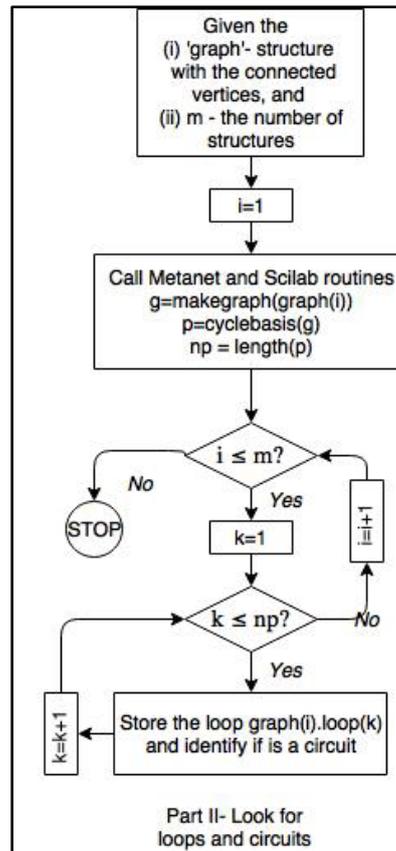
Figure 2.16 - Algorithm 1 – Step 2 – Compare and merge if there are common vertices



Source: Author, 2018

The algorithm delivers as a result the graphs and their interrelated variables. Basically, the matrix representation is transformed into a series of graphs.

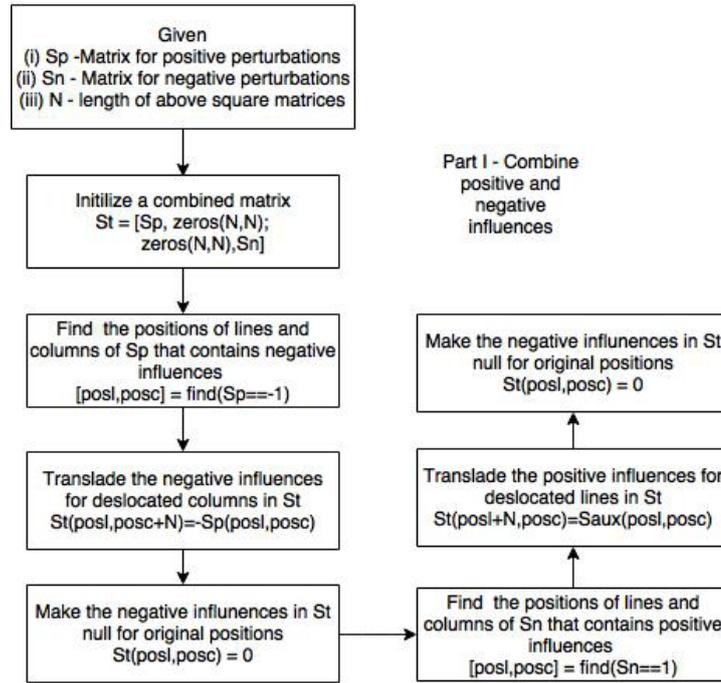
Figure 2.17 – Algorithm2, to identify cycles that relate variables in a graph



Source: Author, 2018

After identifying the connected vertices with the use of the algorithm 1, a Scilab routine and function, called Metanet and cycle_basis, respectively, were used to identify the loops throughout the graphs vertices.

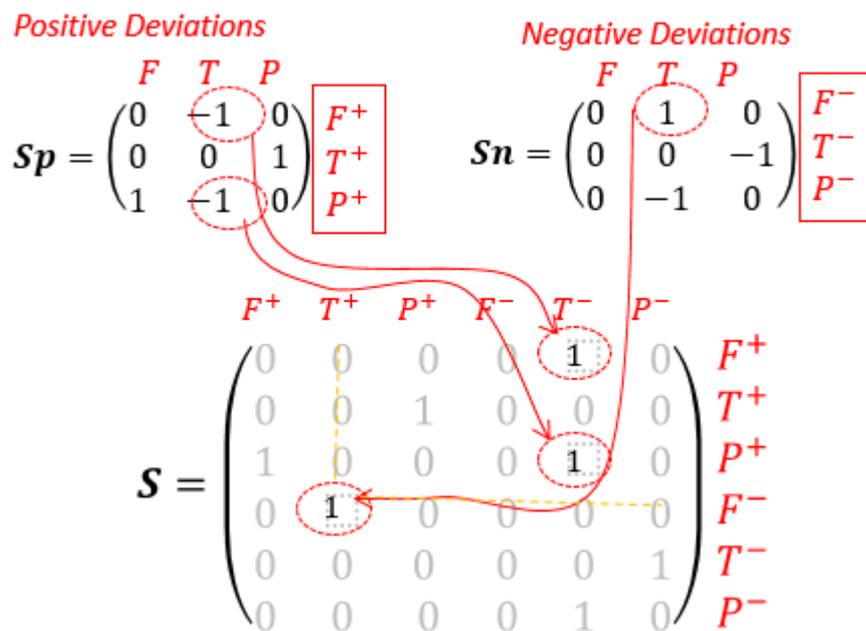
Figure 2.18 – Algorithm 3 part I, to join positive and negative deviations matrices



Source: Author, 2018

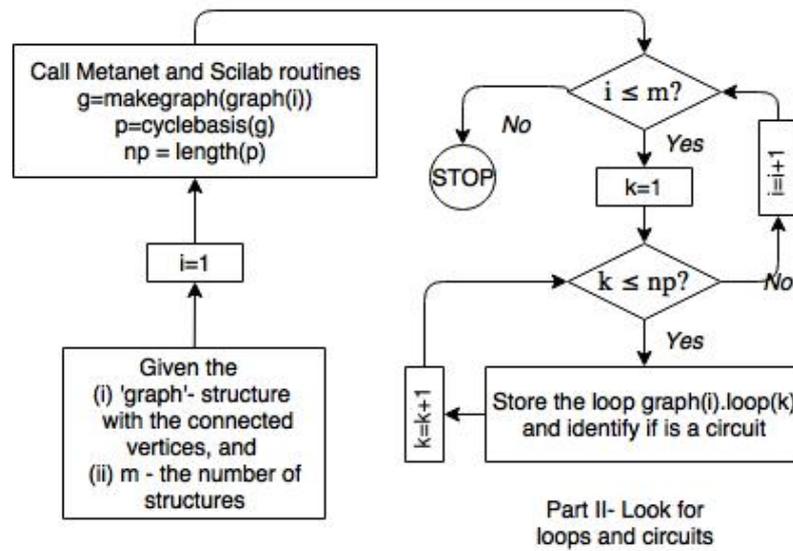
In algorithm 3, the positive and negative deviation matrices are firstly merged in a single matrix with all type of deviations. A practical example of the above work process is showed below in Figure 2.19.

Figure 2.19 - Algorithm 3 – Step 1 – Merge of positive and negative deviations



Source: Author, 2018

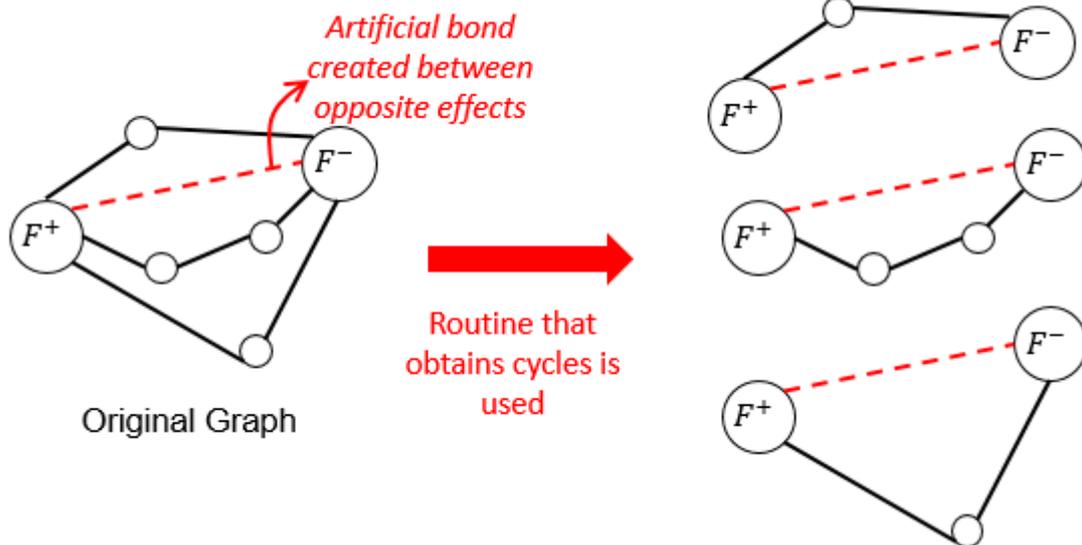
Figure 2.20 – Algorithm 3 part II, to verify inconsistencies



Source: Author, 2018

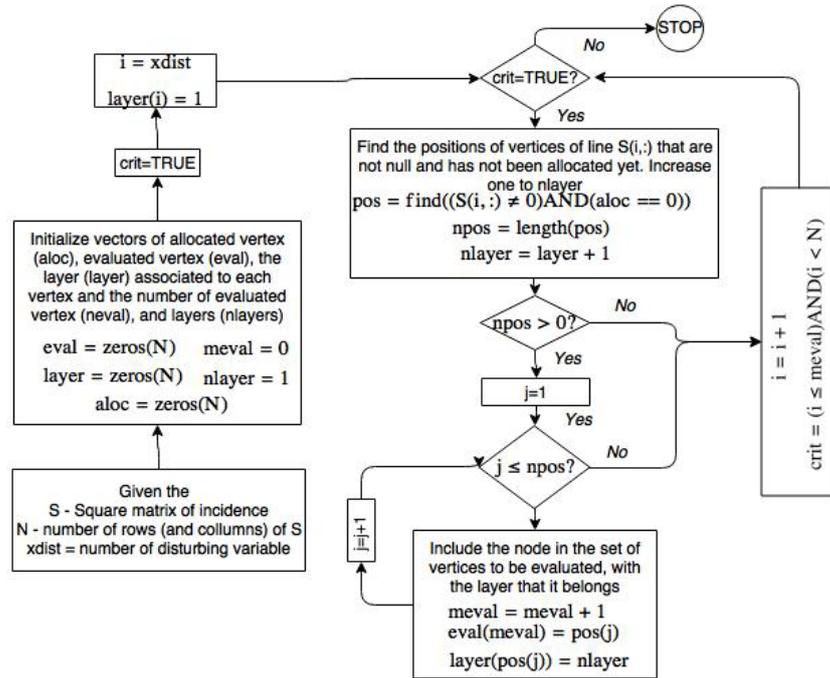
In step 2 of algorithm 3, artificial connections of opposite effects are created and the algorithm 2 is used to return the cycles. Figure 2.21 below exemplifies this methodology.

Figure 2.21 - Algorithm 3 – Step 2 – Approach to identify possible inconsistencies



Source: Author, 2018

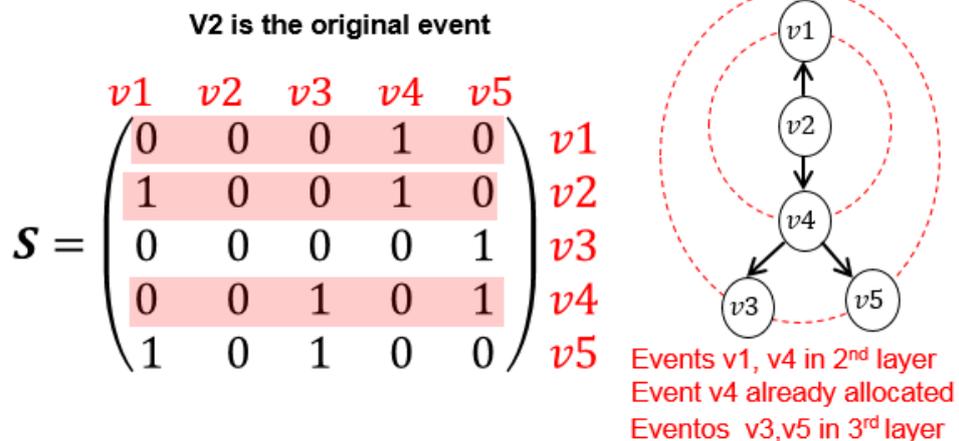
Figure 2.22 – Algorithm 4, to generate event trees



Source: Author, 2018

From an originally informed event, algorithm 4 stores the sequential effects and what variable they affect and adds to the next layer of events. If an event has already appeared, it is not considered again. In this way, the layers are built.

Figure 2.23 - Example of event tree generation



Source: Author, 2018

Once the matrices of individual equipment were developed, they were combined through a computational routine elaborated in Scilab. This routine, from the combination of

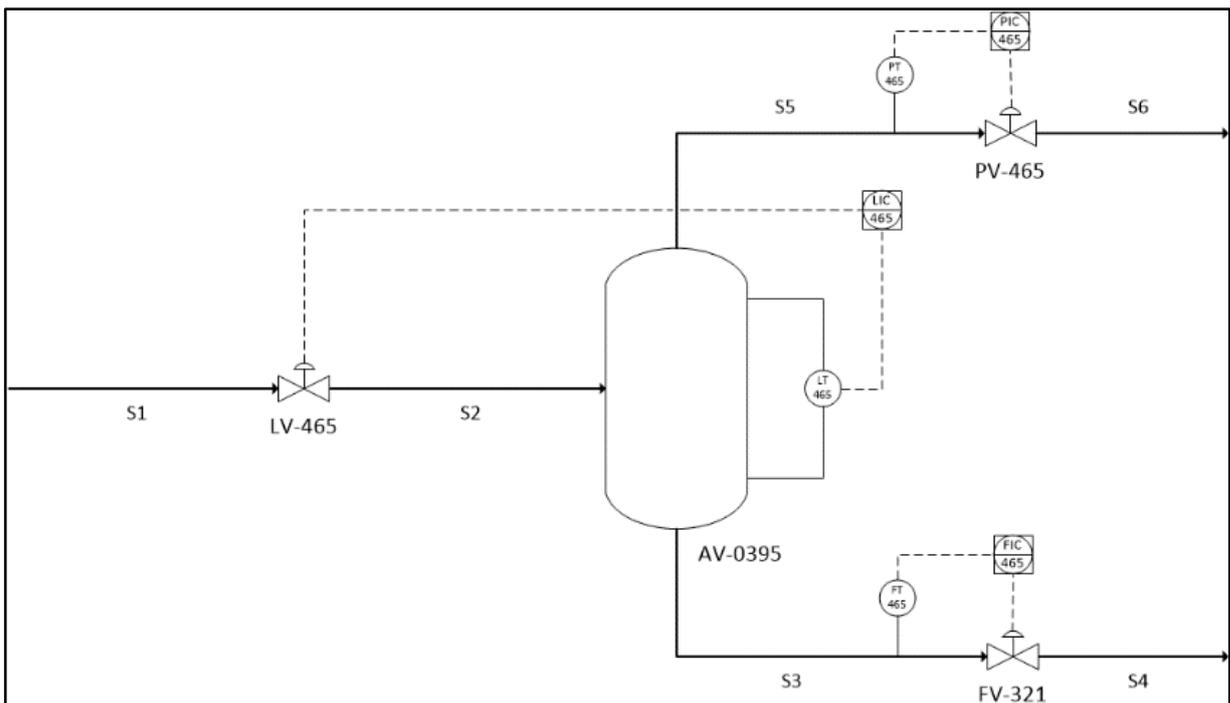
the individual matrices of each equipment, also generates a consequence tree, visually indicating the relationship between all variables studied in a system, and how the disturbances propagate through it. A comparison was then made between the approaches described in this section and the classic HazOp spreadsheet, showing the advantages and disadvantages of each approach.

2.3 Results

2.3.1. Case Study 1 – Flash Pot

In this process, a liquid nitrogen stream passes through an automatic valve and enters a flash vessel, from where there will be a withdrawal of nitrogen gas at the top and another of liquid nitrogen at the bottom. The process counts with a level control acting in the feeding of the vessel, a pressure control in the top gas stream and a flow control in the bottom outlet stream. Such system can be seen in a simplified way in Figure 2.24 and the classical HazOp analysis developed is shown in Table 2.3.

Figure 2.24 – Liquid nitrogen flash pot



Source: Author, 2018

Table 2.3 –HAZOP analysis for flash pot system

Deviation	Causes	Consequences	S	Indications	Protections	F	L
No Flow	1.1 No flow from upstream node	1.1.1 Low pressure and low level in the flash pot, with no product flow to the LN2 storage tank	5	1.1.1 LIC/LAL-465 indicates and alarms low level in the flash pot	None identified	4	4
				1.1.2 PIC/PAL-465 indicates and alarms low pressure in the flash pot			
				1.1.3 FI-321 will indicate no flow			
				1.1.4 TI-436 will indicate ambient temperature			
	1.2 Automatic valve LV-465 fails closed	1.2.1 Low pressure and low level in the flash pot, with no product flow to the LN2 storage tank	5	2.1 See 1.1.1, 1.1.2, 1.1.3, 1.1.4	4	4	
1.3 Automatic valve FV-321 fails closed	1.3.1. High liquid level in the flash pot, with possible overpressure in the vessel.	1	1.3.1 LIC/LAH-465 indicates and alarms high level	1.3.1 LIC-465 closes LV-465	5	4	
			1.3.2 PIC/PAH-465 indicates and alarms high pressure	1.3.2 PSV-465 @ 6,89 barg			
1.4. Automatic valve PV-465 fails closed	1.4.1 Pressure increase in the flash pot, with possible rupture in the vessel and possible high pressure in the downstream node	1	1.4.1 PIC/PAH-465 indicates and alarms high pressure	PSV-465 @ 6,89 barg	5	4	
High Flow	1.5 Automatic valve LV-465 overly opened	1.5.1. High level in the flash pot with possible overpressure.	1	1.5.1 See 1.3.1 e 1.3.2	1.5.1 LV-465 with opening limited to 80%	5	4
					1.5.2 Ver 1.3.1 e 1.3.2		

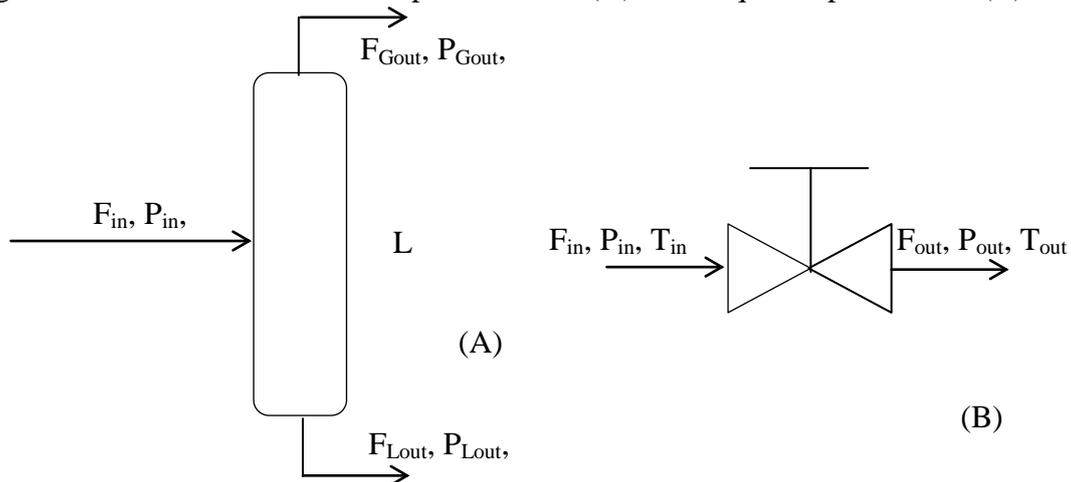
Deviation	Causes	Consequences	S	Indications	Protections	F	L
	1.6 Automatic valve FV-321 overly opened	1.6.1 Low level in the flash pot, without significant consequence					
	1.7 Automatic valve FV-321 overly opened	1.7.1 No significant consequence					
Misdirected Flow	1.8 Manual drain/vent valve improperly opened	1.8.1 Possible low level in the flash pot and product loss.	5	1.8.1 See 1.1.1	1.8.1 None Identified	4	4
		1.8.2 Possible O2 depleted atmosphere	3	1.8.2 Visual indication of mist formation	1.8.2 Drain valve directed to the drain manifold	4	4
	1.9 PSVs premature opening	1.9.1 See 1.8.1 and 1.8.2					
Abnormal Shutdown	1.10 FV-321 fails to close when required (low purity product) 1.11 Equipment shutdown with low pressure and improperly opening of drain/vent valve	1.10.1 Low purity product sent to the storage tank, product contamination. 1.11.1 Migration of atmospheric moist air into the flash pot	5	1.10.1 AE/AAHH-2B indicates low product purity in the lower column	1.10.1 ASHH-2B sends signal to close LV-465 1.11.1 None Identified	4 4	4 4
				1.10.2 QAAE-3 indicates low purity of the product in the tank			
				1.11.1 Visual indication of opened drain/vent with the flash pot without pressure			
Contamination	1.10 FV-321 fails to close when required (low purity product)	1.10.1 Low purity product sent to the storage tank, product contamination.	5	1.10.1 AE/AAHH-2B indicates low product purity in the lower column	1.10.1 ASHH-2B sends signal to close LV-465	4	4

Source: Author, 2018

Scenarios usually analyzed in HazOps, such as reverse flow, high / low level and high / low pressure were omitted from this worksheet, since it was considered that scenarios from these deviations had already been contemplated in others, such as no flow, high flow, contamination, etc.

However, according to the methodology adopted, this information from a classic HazOp analysis can be adapted to a matrix representation, through a series of basic relations between the variables of the streams that enter and leave the equipment. Below, such procedure can be demonstrated for the flash pot, considering separate arrays for the vessel and its inlet and outlet valves, based on the relation of the variables of the equipment, which will then be combined to represent the integration of these elements and their variables in a process as a whole.

Figure 2.25 – Variables of a HazOp Matrix of a (A) Gas-Liquid Separator and (B) Valves.



Source: Author, 2018

In Figure 2.25A, F_{in} , P_{in} , T_{in} respectively represent the flow, pressure and temperature of the vessel inlet stream, F_{Gout} , P_{Gout} , T_{Gout} , represent the flow, pressure and temperature of the gaseous outlet stream at the top and F_{Lout} , P_{Lout} , T_{Lout} , represent the flow, pressure, and temperature of the liquid outlet stream at the bottom and L is the equipment-specific level variable. In Figure 2.25B, F_{in} , P_{in} , T_{in} , respectively, represent the flow, pressure, and the temperature of valve inlet stream and F_{out} , P_{out} , T_{out} , the outlets. The following relationships can be declared for the gas-liquid separator.

- If the input disturbance is an increase of F_{in} : it will increase F_{Gout} , P_{Gout} , F_{Lout} , P_{Lout} and L

- If the input disturbance is an increase of T_{in} : it will increase T_{Gout} , T_{Lout} , and decrease L
- If the input disturbance is an increase of P_{in} : it will increase P_{Gout} and P_{Lout}
- If the input disturbance is an increase of F_{Gout} : it will decrease P_{Gout} and P_{Lout}
- If the input disturbance is an increase of F_{Lout} : it will decrease P_{Lout} and L
- If the input disturbance is a decrease of F_{in} : it will decrease P_{Gout} , P_{Lout} , L , F_{Gout} , F_{Lout} and P_{in}
- If the input disturbance is a decrease of T_{in} : it will increase L and decrease T_{Gout} and T_{Lout}
- If the input disturbance is a decrease of P_{in} : it will decrease P_{Gout} and P_{Lout}
- If the input disturbance is a decrease of F_{Gout} : it will increase P_{Gout} and P_{Lout}
- If the input disturbance is a decrease of F_{Lout} : it will increase L , P_{Gout} and P_{Lout}

Based on these direct causes and consequences relations, the following matrices were obtained:

Table 2.4 – Matrix from a HazOp study of a G / L Separator – Increase in the disturbing variables

	F_{in}	P_{in}	T_{in}	F_{Gout}	P_{Gout}	T_{Gout}	F_{Lout}	P_{Lout}	T_{Lout}	L
F_{in}	1	0	0	1	1	0	1	1	0	1
P_{in}	0	1	0	0	1	0	0	1	0	0
T_{in}	0	0	1	0	0	1	0	0	1	-1
F_{Gout}	0	0	0	1	-1	0	0	-1	0	0
P_{Gout}	0	0	0	0	1	0	0	0	0	0
T_{Gout}	0	0	0	0	0	1	0	0	0	0
F_{Lout}	0	0	0	0	0	0	1	-1	0	-1
P_{Lout}	0	0	0	0	0	0	0	1	0	0
T_{Lout}	0	0	0	0	0	0	0	0	1	0
L	0	0	0	0	0	0	0	0	0	1

Source: Author, 2018

Table 2.5 – Matrix from a HazOp study of a G / L Separator – Decrease in the disturbing variables

	F_{in}	P_{in}	T_{in}	F_{Gout}	P_{Gout}	T_{Gout}	F_{Lout}	P_{Lout}	T_{Lout}	L
F_{in}	-1	-1	0	-1	-1	0	-1	-1	0	-1
P_{in}	0	-1	0	0	-1	0	0	-1	0	0
T_{in}	0	0	-1	0	0	-1	0	0	-1	1
F_{Gout}	0	0	0	-1	1	0	0	1	0	0
P_{Gout}	0	0	0	0	-1	0	0	0	0	0
T_{Gout}	0	0	0	0	0	-1	0	0	0	0
F_{Lout}	0	0	0	0	1	0	-1	1	0	1
P_{Lout}	0	0	0	0	0	0	0	-1	0	0
T_{Lout}	0	0	0	0	0	0	0	0	-1	0
L	0	0	0	0	0	0	0	0	0	-1

Source: Author, 2018

The same procedure should be applied to the valves of Figure 2.25, since they exist in the process flow chart under analysis, in the inlets and outlets of the vessel. The following relationships can be declared:

- If the input disturbance is an increase of F_{in} : it will increase F_{out} and vice-versa
- If the input disturbance is an increase of P_{in} : it will increase P_{out} e vice-versa
- If the input disturbance is an increase of T_{in} : it will increase T_{out}
- If the input disturbance is a decrease of F_{in} : it will decrease F_{out} and vice-versa
- If the input disturbance is a decrease of P_{in} : it will decrease P_{out}
- If the input disturbance is a decrease of T_{in} : it will decrease T_{out}

Based on these direct causes and consequences, the following matrices were obtained for a generic valve:

Table 2.6 – Matrix adapted from a HazOp study of a valve – Increase in disturbing variables

	F_{in}	P_{in}	T_{in}	F_{out}	P_{out}	T_{out}
F_{in}	1	0	0	1	0	0
P_{in}	0	1	0	0	1	0
T_{in}	0	0	1	0	0	1
F_{out}	1	0	0	1	0	0
P_{out}	0	0	0	0	1	0
T_{out}	0	0	0	0	0	1

Source: Author, 2018

Table 2.7 – Matrix adapted from a HazOp study of a valve – Decrease in disturbing variables

	Fin	Pin	Tin	Fout	Pout	Tout
Fin	-1	0	0	-1	0	0
Pin	0	-1	0	0	-1	0
Tin	0	0	-1	0	0	-1
Fout	-1	0	0	-1	0	0
Pout	0	0	0	0	-1	0
Tout	0	0	0	0	0	-1

Source: Author, 2018

As detailed in the methodology, such matrices were combined to represent the interaction of the process and its elements as a whole, and from that, consequence trees were also raised for each of the initiating events. Firstly, however, let us present and discuss the complexity of resultant relations.

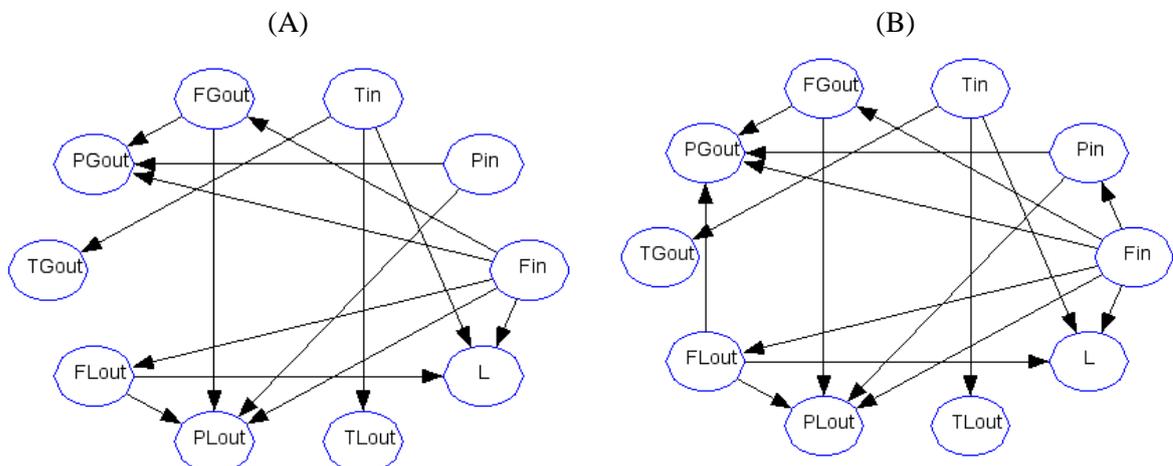
General graphs and cycles

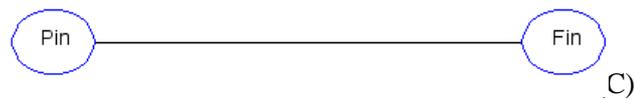
In this section, it was developed the analysis based on graphs for the vessel only and all the system.

For the vessel only

Figure 2.26 presents the relations of graph for vessel. It can be seen that several loops are formed. As can be seen in Figure 2.26C, there is only one difference between positive and negative disturbance matrices, associated to Pin and Fin relation.

Figure 2.26 – Graph from HAZOP matrix of flash system for: (A) positive disturbances (Table 2.6), (B) negative disturbances and (C) for the difference between positive and negative (actually the sum of previous matrices).

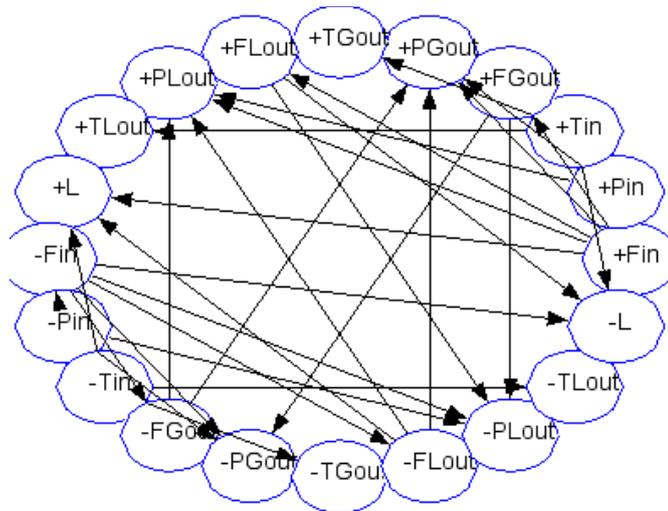




Source: Author, 2018

When joining both positive and negative disturbance, it was obtained several loops, as can be seen in Figure 2.27.

Figure 2.27 – Relations for flash vase considering positive and negative perturbations.



Source: Author, 2018

The analysis showed 11 loops, as show in Table 2.8.

Table 2.8 – Loops and circuits considering both positive and negative perturbations in HAZOP matrices for flash vessel.

Loop number	Variables
1	+Fin +Pin +PGout +PLout
2	-Fin -Pin -PLout
3	+Fin +PGout +PLout -FGout
4	+Fin +FGout +PGout -Fin -FGout -PLout
5	+FGout -Fin -PGout -PLout
6	+FGout -Pin -PGout -PLout
7	+Fin +PGout +PLout -FLout
8	+Fin +PGout +L -FLout
9	+Fin +FGout +PGout -Fin -FLout -PLout

10	+Fin +FGout +FLout -PLout
11	+Fin +FGout +FLout -Fin -PLout -L

Source: Author, 2018

It was also observed 6 suspicious sequences allowed according to HAZOP matrix, as shown in Table 2.9. All these sequences are suspicious since simultaneous increase and decrease of flow of inlet (Fin) lead to same results. In this particular case, these sequences are not necessarily inconsistent, since Fin contains original disturbances, not result from other disturbances.

Table 2.9 – Number suspicious or inconsistent sequences allowed according to HAZOP matrices.

Loop number	Variables
1	+Fin +FGout -Fin -Pin -PLout
2	+Fin +PGout -Fin -FGout
3	+Fin +FGout -Fin -PGout
4	+Fin +PGout -Fin -Flout
5	+Fin +FGout -Fin -PLout
6	+Fin +FLout -Fin -L

Source: Author, 2018

For the entire process

When considering all the system it was observed 13 suspicious sequences, shown in Table 2.10.

Table 2.10 – Number suspicious or inconsistent sequences allowed according to HAZOP matrices for flash system.

Loop number	Variables
1	+S1F +S2F +S5P -S1F -S2F -S5F
2	+S1F +S2F +S5F -S1F -S2F -S5P
3	+S1F +S2F +S5P -S1F -S2F -S3F
4	+S1F +S2F +S3F -S1F -S2F -S3P
5	+S1F +S2F +S3F -S1F -S2F -S2P -S3P
6	+S1F +S2F +S3F -S1F -S2F -L
7	+S2F +S5P -S2F -S5F
8	+S2F +S5F -S2F -S5P

9	+S2F +S5F -S2F -S2P -S5P
10	+S2F +S5P -S2F -S3F
11	+S2F +S5F -S2F -S3P

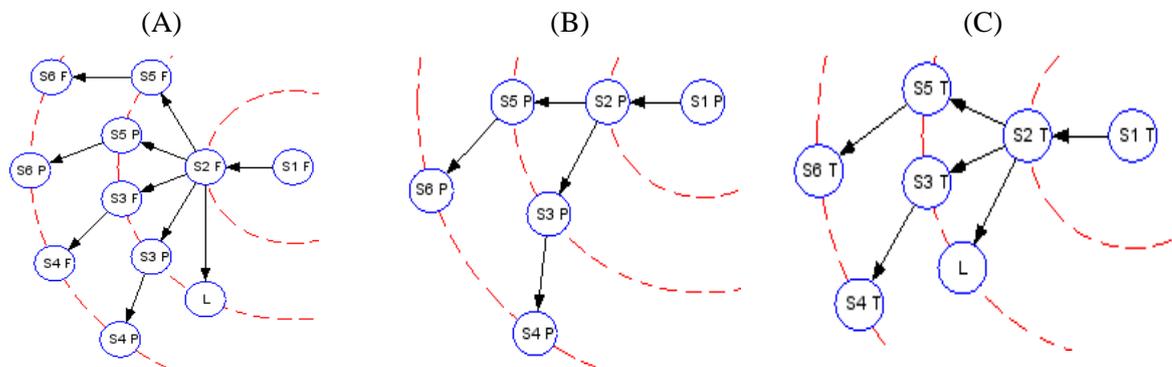
Source: Author, 2018

The suspicious sequences presented previously in Table 2.9 propagated to the system, including some more sequences. All these are associated to simultaneous increase and decrease of flow of inlet streams, suggesting that those sequences of events should be revisited. It proves that was clear that it becomes clear that the developed tool in this work can be helpful for evaluating if HAZOP analysis is consistent or not.

Event tree analysis

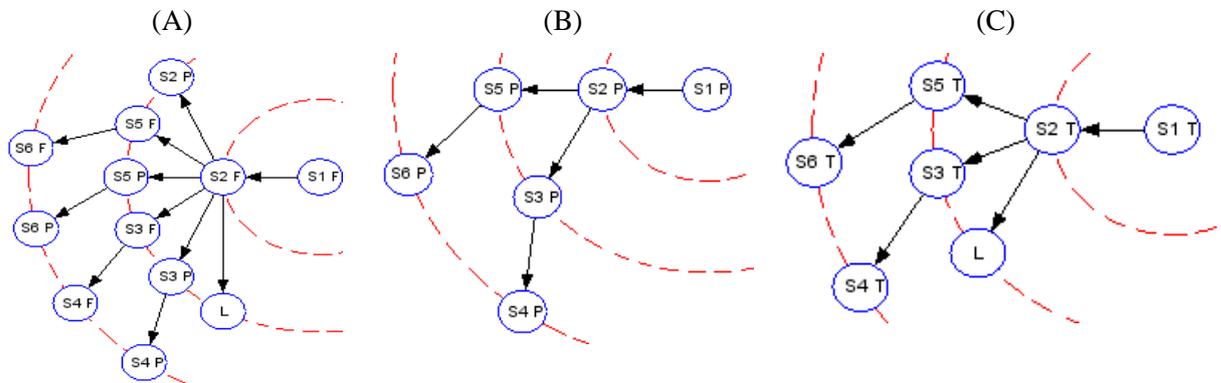
The event tree analysis was generated with algorithm Alg4. It generates one of the several possible event trees. Figure 2.28 and Figure 2.29 contains the increase and decrease of S1 variables event tree analysis

Figure 2.28 – Possible HAZOP Trees – Increase in S1 (A) flow, (B) pressure and (C) temperature.



Source: Author, 2018

Figure 2.29 – Possible HAZOP Trees – Decrease in S1 (A) flow, (B) pressure and (C) temperature.



Source: Author, 2018

From this collection of data, detailed analysis of each procedure can be done.

Related to the increase of the feed flow, the HazOp matrix showed an influence in the outlet stream flows, pressures and equipment level. Once it was developed with data generated from a classical analysis, this result is in agreement with the one shown in scenario 1.5 of Table 2.3, where a high flow, caused by a larger than expected opening of LV-465, is studied. This high flow through the LV-465 is analogous to an increase in the feed rate studied in the matrix.

A similar discussion can be conducted when considering a decrease in the feed flow. The HazOp matrix indicated that it will impact the flows, pressures and level, but, as expected, in the opposite direction of the feed increase. It is also according to the results shown in Table 2.3 in cause 1.2, where a failure of LV-465 is studied. This loss of flow due to this valve failure is similar to the disturbance of S1F decrease.

As it is a more complete analysis of the whole system, the classic HazOp study shows all the protections, severity and frequency for the studied scenario, which is not addressed in matrices, which focus only on a cause and consequence relation. It is important to point out that even though it does not show 100% identical results to a classic HazOp for these scenarios of increase and decrease of S1F, the matrices obtained by the adaptation of the classic HazOp are contained in these results and help to demonstrate how much some of the variables are affected by the perturbation in question, reducing the dependency on the team experience. When changing the inlet pressure, the propagations were also as expected. It is important to mention that, in this methodology, a deviation can be included in all streams, and not only the inlet ones. In addition, it is important to note that similar trees were obtained for the pairs S1F increase/decrease, S1P increase/decrease and S1T increase/decrease. It

happened because the trees shows influences, and according to the matrices developed for these equipment, the ones for positive disturbances were equal to the negative disturbances in module.

It is possible also to note in the trees generated that a change in the temperature of the inlet stream can affect the flash pot level. This consequence was not mentioned in the real HAZOP study, probably because the team did not consider this consequence feasible. However, this result shows the potential of the methodology to less the dependency of the HAZOP team experience, once already known process relations can be included in the matrices. One can argue that the base relations of the matrices are also human dependent. However, it is a more controlled dependency, once standard matrices can be developed by an experienced professional and used as basis for future projects, helping HazOp teams, no matter the experience of the participants. that will

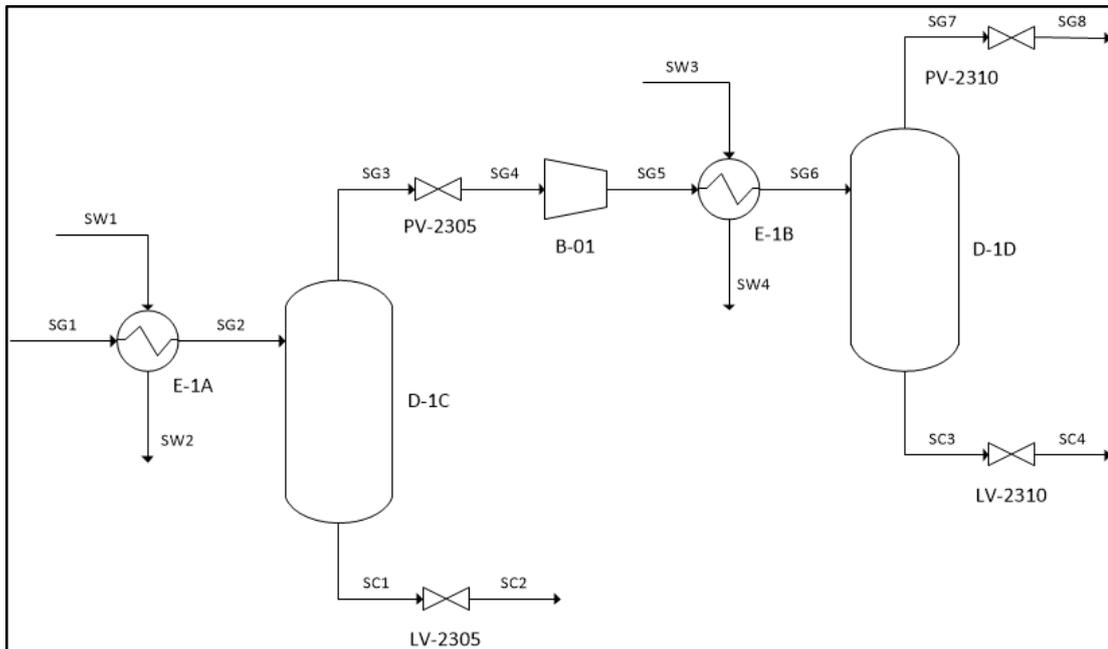
Another important aspect is that scenarios related to operational issues could be captured only by classic HAZOP, not by the matrices. This could be evidenced from causes 1.8, 1.9, 1.10 and 1.11 of Table 2.3, where deviations resulting from actions of control logics and human action were studied. The following case presents a greater degree of complexity, where other aspects can be noticed.

2.3.2. Case Study 2 – Raw Gas Pumping System

In this system, a gaseous stream rich in CO₂ and water vapor is received from a source at low pressure, but at elevated temperature. This stream flows through the shell-and-tube heat exchanger E-1A, where it is cooled with a stream of water. Such cooling will condense part of the water vapor contained in the stream, which will then be collected and separated from the gaseous stream in the separating vessel D-1C. The condensate will be withdrawn by the automatic valve LV-2305 and the gas stream will continue in the process through the PV-2305, passing through the centrifugal blower B-01, which will raise the pressure of this stream. With increasing pressure, there will also be an increase in temperature, and that heat will be removed in the E-1B heat exchanger, also with cooling water. This second cooling stage will cause another portion of the water vapor to condense and then to be withdrawn into

the D-1D vessel, equally to the D-1C operation. The CO₂ enriched stream, yet with other non-condensable contaminants, will follow a gas pipeline to a purification and liquefaction plant. Thus, the main purpose of this pumping system is to supply pressure and remove moisture from the raw gas and then feed this gas to the pipeline that will follow to a CO₂ production unit. This process can be seen in Figure 2.30 below, in a simplified manner, omitting controls and manual and safety valves, for ease of viewing.

Figure 2.30 – Raw gas pump system



Source: Author, 2018

A classical HazOp analysis was developed for this system, as can be seen below. This analysis is also based on a real study carried out in the industry in which two nodes were considered. The first, taking into account the raw gas feed, through the E-1A exchanger and the D-1C separation vessel, to the PV-2305 and LV-2305. The second, from the outlet of the PV-2305, through the blower B-00, heat exchanger E-1B, separation vessel D-1D, to the valves PV-2310 and LV-2310. Minor modifications to the original study were performed to retain data and information from the source company.

Table 2.11 – Classical HazOp – Pumping System – Node 1

Deviation	Cause	Consequence	S	Indication/Protection	L	R
No/Low Flow	1.1 Manual valve X-2320K improperly closed	1.1.1 No gas flow to exchanger E-1A and vessel D-1C, with possible vacuum formation due to blower J-1C operation in the downstream node and equipment damage.	2	1.1.1 PSL-2300 will shut down blower J-1C in case of low pressure	5	4
				1.1.2 Vessels E-1A and D-1C are rated for full vacuum.		
				1.1.3 PSL-2301 will shut down blower J-1C in case of low pressure		
	1.2. No raw gas flow from upstream node	1.2.1 See 1.1.1	2	1.2.1 See 1.1.1, 1.1.2 and 1.1.3	5	4
Misdirected Flow	1.3 Vents improperly opened or premature opening of PSV-2301	1.3.1 Raw gas leaking to atmosphere with possible O ₂ depleted atmosphere formation	1	1.3.1 Vents located in an opened space and directed for a safe place	5	4
High Temperature	1.4 No cooling water flow	1.4.1 Raw gas temperature increase in inlet of D-1C with possible equipment damage.	4	1.4.1 TSHH-2300 will shut down blower J-1C	5	4
				1.4.2 PSL-8461 will shut down blower J-1C		
High Pressure	1.5 High pressure from upstream node	1.5.1 High pressure in E1-A and D1-C with possible equipment damage, energy release and personnel injury.	1	1.5.1 PSV in the gas supply station at 0.3 barg limits the inlet pressure in the system	5	4
Low Level	1.6 Condensate valve fails opened	1.6.1 No significant consequence for this node	5			
High Level	1.7 Consensate valve fails closed.	1.7.1 Possible high level in D-1C with possible moisture carryover to downstream node (blower)	4	1.7.1 LSHH-2300 will shut down blower J-1C	4	4
				1.7.2 LI/LAH/LAHH- 2300 indicates and alarms high level in D-1C.		
Contamination	1.8 Raw gas contaminated with hydrogen	1.8.1 No significant consequence for this node	5			
	1.9 Hole in the tubes of heat exchanger E-1A.	1.9.1 Water ingress in raw gas stream, with possible level increase in D-1C and water carryover to the blower J-1C.	4	1.9.1 See 1.7.1 and 1.7.2	5	4
Abnormal Startup	1.10 New pumping system startup without isolating the old pumping plant.	1.10.1 Pressurization of previous system without having it operating. Not a significant consequence.	5			

Source: Author, 2018

Table 2.12 – Classical HazOp – Pumping System – Node 2

Deviation	Cause	Consequence	S	Indication/Protection	L	R
No / Low Flow	2.1 Automatic valve PV-2300 fails closed	2.1.1 No raw gas flow to blower J-1C, with possible extreme vacuum formation in the suction line and possible damage to the machine.	4	2.1.1 PSL-2301 will shut down the blower due to low suction pressure.	4	4
				2.1.2 Compressor anti-surge control		
				2.1.3 PI/PAL/PALL- 2301 indicates and alarms low suction pressure		
	2.2 Manual valve improperly closed in the blower discharge	2.2.1 High pressure in the downstream system, including E-1B and D-1D, blower surge, with possible damages to the machine. It is not possible to damage the equipments by overpressure because the system MAWP is higher than the maximum pressure the blower can give.	4	2.2.1 See 2.1.2	4	4
				2.2.2 PI-2320 indicates high pressure		
	2.3 No flow from upstream node	2.3.1 See 2.1.1		2.3.1 See 2.1.1, 2.1.2 and 2.1.3		
High Flow	2.4 Automatic valve PV-2300 sticking opened	2.4.1 Blower will work without flow control, in full capacity, high a increase in the power consumption.	4	2.4.1 JSHH-2310 will shut down the blower for high current	4	4
Reverse Flow	2.5 New pumping system operating with a manual valve opened in the discharge of the old pumping unit and vice versa.	2.5.1 Raw gas flow to the discharge of the existing pumping, with consequent pressurization of that	5	2.5.1 Check valves in the existing system	4	4
				2.5.2 Check valves in the discharge of the existing system.		
Misdirected Flow	2.6 Vents improperly opened or premature opening of a PSV.	2.6.1 Gas leaking to atmosphere with possible formation of a O2 depleted atmosphere.	4	2.6.1 Vents located in an opened space	4	4
				2.6.2 PSV discharge routed to a safe place, at least 3.0m from the ground.		
High Temperature	2.7 No cooling water flow	2.7.1 Gas temperature increase in the inlet of D-1D with possible equipment damage.	4	2.7.1 TSHH-2312 will shut down blower J-1C	4	4
				2.7.2 PSL-8461 will shut down blower J-1C		
	2.8 High temperature from upstream node	2.8.1 Temperature increase in the blower discharge, with possible	4	2.8.1 TSHH-2311 will shut down blower J-1C for high discharge temperature	4	4

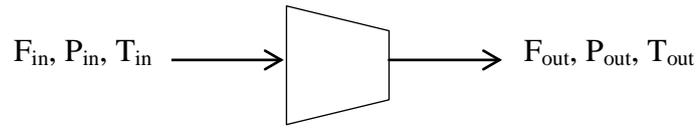
Deviation	Cause	Consequence	S	Indication/Protection	L	R
		equipment damage in vessels E-1B and D-1D.		2.8.2 TSHH-2312 will shut down blower J-1C for high temperature after E-1B.		
High Pressure	2.9 High pressure from upstream node	2.9.1 Possible increase in the blower suction, above the maximum allowed, with possible damages to the dynamics components of the machine. Possible damages to E-1B and D-1D.	4	2.9.1 Customer PSV @ 0.3 barg.	4	4
				2.9.2 Customer shutdown at 0.09 barg		
Low Level	2.10 Condensate valve fails opened	2.10.1 No significant consequence	5			
High Level	2.11 Condensate valve fails closed	2.11.1 Possible high level in vessel D-1D with possible water carryover do downstream system.	4	2.11.1 LSHH-2310 will shut down the blower	4	4
Contamination	2.12 Raw gas contaminated with hydrogen	2.12.1 Possible flammable mixture in the system with possible ignition once the electrical equipment are not rated for classified areas.	1	2.12.1 Hydrogen analyzer in the raw gas stream	5	4
	2.13 Hole in exchanger E-1B tubes	2.13.1 Water ingress in the raw gas stream, possible level increase in D-1D and water carryover for the downstream system.	4	2.13.1 Ver 2.11.1 2.13.2 LSH-2310 opens the drain valve	4	4

Source: Author, 2018

Scenarios usually analyzed in HazOps, such as reverse flow, low pressure, low temperature were omitted from this worksheet, since it was considered that scenarios from these deviations had already been contemplated in others, such as no flow, high flow, contamination, etc., or because they were considered as not applicable.

For the matrix representation of a classical HazOp analysis, matrices will be considered for the following equipment: valves, gas-liquid separator, centrifugal compressor and heat exchanger. For gas-liquid valves and separators, the same matrices as those developed in the case of the flash pot will be used. For the centrifugal compressor, and for the heat exchanger, the development is as follows:

Figure 2.31 - Variables of a HazOp Matrix of a centrifugal compressor



Source: Author, 2018

The following relations can be declared:

- If the input disturbance is an increase of F_{in} : it will increase F_{out}
- If the input disturbance is an increase of P_{in} : it will increase P_{out} and T_{out}
- If the input disturbance is an increase of T_{in} : it will increase T_{out}
- If the input disturbance is an increase of F_{out} : it will increase F_{in}
- If the input disturbance is a decrease of F_{in} : it will decrease F_{out} , P_{in} , P_{out} and T_{out}
- If the input disturbance is a decrease of P_{in} : it will decrease P_{out} and T_{out}
- If the input disturbance is a decrease of T_{in} : it will decrease T_{out}
- If the input disturbance is a decrease of F_{out} : it will decrease F_{in} and increase P_{out} and T_{out}

Based on these relations above, the following matrices were obtained:

Table 2.13 – Matrix adapted from a Compressor HazOp – Increase in the disturbing variables.

	F_{in}	P_{in}	T_{in}	F_{out}	P_{out}	T_{out}
F_{in}	1	0	0	1	0	0
P_{in}	0	1	0	0	1	1
T_{in}	0	0	1	0	0	1
F_{out}	1	0	0	1	0	0
P_{out}	0	0	0	0	1	1
T_{out}	0	0	0	0	0	1

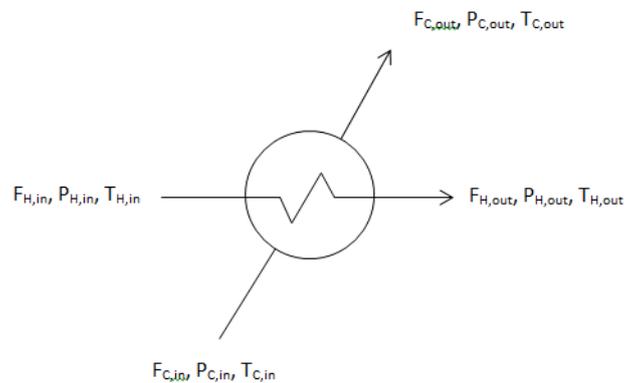
Source: Author, 2018

Table 2.14 – Matrix adapted from a Compressor HazOp – Decrease in the disturbing variables

	F_{in}	P_{in}	T_{in}	F_{out}	P_{out}	T_{out}
F_{in}	-1	-1	0	-1	-1	-1
P_{in}	0	-1	0	0	-1	-1
T_{in}	0	0	-1	0	0	-1
F_{out}	-1	0	0	-1	1	1
P_{out}	0	0	0	0	-1	-1
T_{out}	0	0	0	0	0	-1

Source: Author, 2018

Figure 2.32 - Variables of a HazOp Matrix of a heat exchanger



Source: Author, 2018

$F_{H,in}$, $P_{H,in}$, $T_{H,in}$, represents respectively the flow, pressure and temperature of the hot stream inlet, and $F_{H,out}$, $P_{H,out}$, $T_{H,out}$, the hot stream outlet. The same consideration can be done for the cold stream, which is represented by the index “c”. The following relations can be declared:

- If the input disturbance is an increase of $F_{H,in}$: it will increase $F_{H,out}$, $T_{H,out}$ and $T_{C,out}$
- If the input disturbance is a decrease of $F_{H,in}$: it will decrease $F_{H,out}$, $T_{H,out}$, $T_{C,out}$ and $P_{H,out}$
- If the input disturbance is an increase of $F_{H,out}$: it will increase $F_{H,in}$, $T_{H,out}$ and $T_{C,out}$
- If the input disturbance is a decrease of $F_{H,out}$: it will decrease $F_{H,in}$, $T_{H,out}$, $T_{C,out}$ and increase $P_{H,out}$
- If the input disturbance is an increase of $T_{H,in}$: it will increase $T_{H,out}$ and $T_{C,out}$
- If the input disturbance is a decrease of $T_{H,in}$: it will decrease $T_{H,out}$ and $T_{C,out}$

- If the input disturbance is an increase of FC_{in} : it will increase FC_{out} and decrease TH_{out} and TC_{out}
- If the input disturbance is a decrease of FC_{in} : it will decrease FC_{out} and increase TH_{out} , TC_{out} and PC_{out}
- If the input disturbance is an increase of FC_{out} : it will increase FC_{in} , and decrease TH_{out} and TC_{out}
- If the input disturbance is a decrease of FC_{out} : it will decrease FC_{in} and increase TH_{out} , TC_{out} and PC_{out}
- If the input disturbance is an increase of TC_{in} : it will increase TH_{out} and TC_{out}
- If the input disturbance is a decrease of TC_{in} : it will decrease TH_{out} and TC_{out}

The following matrices were obtained:

Table 2.15 – Matrix adapted from a Heat Exchanger HazOp – Increase in the disturbing variables.

	$F_{H,in}$	$P_{H,in}$	$T_{H,in}$	$F_{H,out}$	$P_{H,out}$	$T_{H,out}$	$F_{C,in}$	$P_{C,in}$	$T_{C,in}$	$F_{C,out}$	$P_{C,out}$	$T_{C,out}$
$F_{H,in}$	1	0	0	1	0	1	0	0	0	0	0	1
$P_{H,in}$	0	1	0	0	1	0	0	0	0	0	0	0
$T_{H,in}$	0	0	1	0	0	1	0	0	0	0	0	1
$F_{H,out}$	1	0	0	1	0	1	0	0	0	0	0	1
$P_{H,out}$	0	0	0	0	1	0	0	0	0	0	0	0
$T_{H,out}$	0	0	0	0	0	1	0	0	0	0	0	0
$F_{C,in}$	0	0	0	0	0	-1	1	0	0	1	0	-1
$P_{C,in}$	0	0	0	0	0	0	0	1	0	0	1	0
$T_{C,in}$	0	0	0	0	0	1	0	0	1	0	0	1
$F_{C,out}$	0	0	0	0	0	-1	1	0	0	1	0	-1
$P_{C,out}$	0	0	0	0	0	0	0	0	0	0	1	0
$T_{C,out}$	0	0	0	0	0	0	0	0	0	0	0	1

Source: Author, 2018

Table 2.16 – Matrix from a Heat Exchanger HazOp – Decrease in the disturbing variables.

	$F_{H,in}$	$P_{H,in}$	$P_{H,in}$	$F_{H,out}$	$P_{H,out}$	$T_{H,out}$	$F_{C,in}$	$P_{C,in}$	$T_{C,in}$	$F_{C,out}$	$P_{C,out}$	$T_{C,out}$
$F_{H,in}$	-1	0	0	-1	-1	-1	0	0	0	0	0	-1
$P_{H,in}$	0	-1	0	0	0	0	0	0	0	0	0	0
$T_{H,in}$	0	0	-1	0	0	-1	0	0	0	0	0	-1
$F_{H,out}$	-1	0	0	-1	1	-1	0	0	0	0	0	-1
$P_{H,out}$	0	0	0	0	-1	0	0	0	0	0	0	0
$T_{H,out}$	0	0	0	0	0	-1	0	0	0	0	0	0
$F_{C,in}$	0	0	0	0	0	1	-1	0	0	-1	-1	1
$P_{C,in}$	0	0	0	0	0	0	0	-1	0	0	0	0
$T_{C,in}$	0	0	0	0	0	-1	0	0	-1	0	0	-1
$F_{C,out}$	-1	0	0	0	0	1	0	0	0	-1	1	1
$P_{C,out}$	0	0	0	0	0	0	0	0	0	0	-1	0
$T_{C,out}$	0	0	0	0	0	0	0	0	0	0	0	-1

Source: Author, 2018

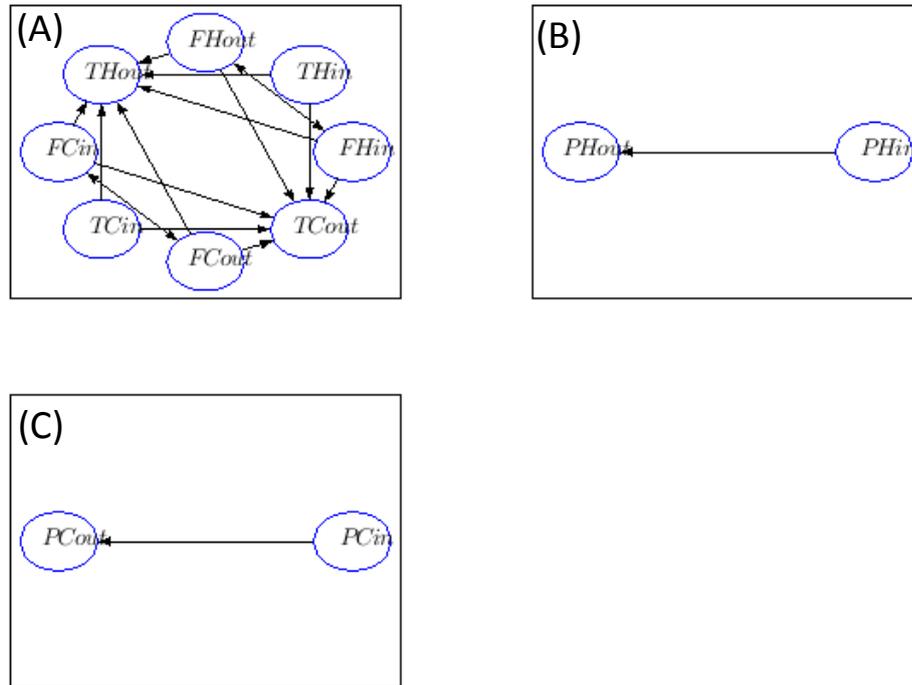
General graphs and cycles

In this section, it was developed the analysis based on graphs for the heat exchanger only and all the system. It was chosen the heat exchanger since it has 4 streams and a greater number of variables.

For the heat exchanger only

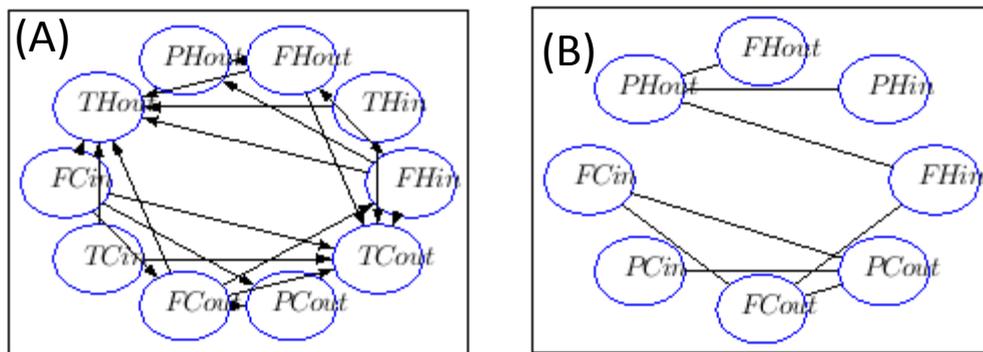
Let us consider the loops arising from Heat Exchanger equipment only (Figure 2.33).

Figure 2.33 – Graph from HAZOP matrix of heat exchanger for positive perturbation matrix Table 2.15: (A) set 1, (B) set 2, and (C) set 3 of connected vertices



Source: Author, 2018

Figure 2.34 – Loops from HAZOP matrix for heat exchanger: (A) for negative perturbation matrix (Table 2.16) and (B) summing the two matrices to study the asymmetry

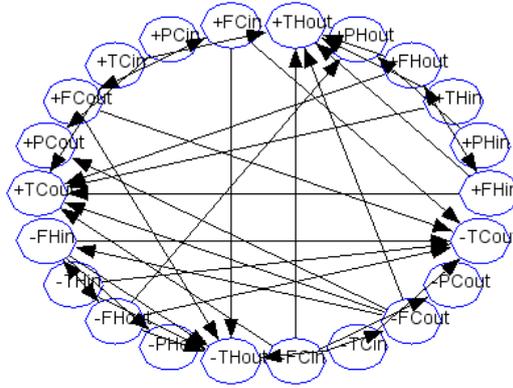


Source: Author, 2018

As can be seen in Figure 2.33, positive perturbations lead to 3 sets of connected vertices; while in Figure 2.34A, one can observe that for negative perturbations only one set connects all variables. This reveals the asymmetry of such analysis; which becomes more clear observing Figure 2.34B, where the connections arising from summing the two matrices connect several vertices.

The combined relations for both positive and negative perturbations is presented below.

Figure 2.35 – Relations for heat exchanger considering positive and negative perturbations



Source: Author, 2018

Regarding cycles, Table 2.17 shows the loops and circuits for heat exchanger according to HAZOP matrices for both positive and negative relations. It can be seen that 14 loops become from HAZOP analysis. These are not inconsistent but can be used to map which are the original perturbations variables, reducing the number of original causes of disturbances.

Table 2.17 – Loops and circuits considering both positive and negative perturbations in HAZOP matrices for pumping system.

Loop number	Variables
1	+FHin +FHout +THout
2	+FCin +FCout -THout
3	+FHin +THin +THout +TCout
4	+FHin +FHout +TCout
5	+FHin +THout +TCin +TCout
6	-FHin -FHout -THout
7	+FHin +THout +TCout -FCin
8	+FHin +THout +TCout -FCout
9	+THout -FCin -FCout
10	+FCin -FHin -THout -TCout
11	+FCout -FHin -THout -TCout

12	-FHin -THin -THout -TCout
13	-FHin -FHout -TCout
14	-FHin -THout -TCin -TCout

Source: Author, 2018

Table 2.18 shows suspicious or inconsistency sequences allowed by HAZOP, which is only one associated to an increase and decrease of the inlet flow in the same relation. Again, the suspicious or inconsistency relation suggest that the original proposed relation should be evaluated more carefully.

Table 2.18 – Suspicious or inconsistency sequences allowed for HAZOP matrices for heat exchanger

Loop number	Variables
1	+FHin+THout-FHin-FCout

Source: Author, 2018

For the entire process

Table 2.19 presents loops and circuits arising from the entire process of raw gas pumping system.

Table 2.19 – Loops and circuits considering both positive and negative perturbations in HAZOP matrices for pumping system

Loop number	Variables
1	+SG1F,+SG2F,+SG2T
2	+SW1F,+SW2F,-SG2T
3	+SG1F,+SG1T,+SG2T,+SW2T
4	+SG1F,+SG2F,+SW2T
5	+SG1F,+SG2T,+SW1T,+SW2T
6	+SG2F,+SG2P,+SG3P,+SC1P
7	+SG1F,+SG2F,+SG2T,+SG3F,+SG3T,+SG4F,+SG4T,+SG5F,+SG5T,+SW4T
8	+SG5F,+SG5T,+SG6T,+SW4T
9	+SG5F,+SG6F,+SG6T
10	+SG5F,+SG6T,+SW3T,+SW4T
11	+SW3F,+SW4F,-SG6T

12	+SG5F,+SG6F,+SW4T
13	+SG2F,+SG3F,+SG3P,+SG4F,+SG4P,+SG5F,+SG5P,+SG6F,+SG7F,-SG5F,-SG6F,-SG7P
14	+SG2F,+SG3F,+SG3P,+SG4F,+SG4P,+SG5F,+SG5P,+SG6F,+SG7P,-SG5F,-SG6F,-SG7F
15	+SG5P,+SG6P,+SG7P,-SG5F,-SG6F,-SG7F
16	+SG2F,+SG3F,+SG3P,+SG4F,+SG4P,+SG5F,+SG5P,+SG6F,+SC3F,-SG5F,-SG6F,-SC3P
17	+SG2F,+SG3F,+SG3P,+SG4F,+SG4P,+SG5F,+SG5P,+SG6F,+SC3P,-SG5F,-SG6F,-SG7F
18	+SG5P,+SG6P,+SC3P,-SG5F,-SG6F,-SG7F
19	+SG2F,+SG3F,+SG3P,+SG4F,+SG4P,+SG5F,+SG5P,+SG6F,+L,-SG5F,-SG6T
20	+SG1F,+SG2F,+SG2T,+L,-SG1F,-SG2F,-SG2T,-L
21	+SG2F,+SC1F,+L,-SG1F,-SG2P,-SG2T,-SC1P
22	+SG1F,+SG2F,+SG2T,+SC1F,-SG2F,-SG2P,-SC1P,-L
23	+SG1F,+SG2F,+SG2T,+L,-SG2F,-SG2T,-L
24	+SG1F,+SG2T,+SW2T,-SW1F
25	+SG1F,+SG2T,+SW2T,-SW2F
26	+SG1F,+SG2F,+SG2T,+L,-SG1F,-SG2T,-SW2F
27	+SG2T,-SW1F,-SW2F
28	+SG1F,+SG2F,+SG2T,+SW1F,+L,-SG2F,-SG2T,-SW2T,-L
29	+SG1F,+SG2F,+SG2T,+SW2F,+L,-SG2F,-SG2T,-SW2T,-L
30	+SG1F,+SG2F,+SG2T,+L,-SG1F,-SG2F,-SG2T,-SW2T,-L
31	+SG1F,+SG2F,+SG2T,+L,-SG1T,-SG2F,-SG2T,-SW2T,-L
32	+SG1F,+SG2F,+SG2T,+L,-SG2F,-SG2T,-SW1T,-SW2T,-L
33	+SG2F,+SG3P,+SC1P,-SG3F
34	+SG1F,+SG2F,+SG2T,+SC1P,-SG2F,-SG3F,-L
35	+SG1F,+SG2F,+SG2T,+SG3F,-SG2F,-SG3P,-L
36	+SG2F,+SG3F,+SC1F,-SG2P,-SG3P,-SC1P
37	+SG2F,+SG3P,+SC1P,-SC1F
38	+SG2F,+SC1P,+L,-SC1F
39	+SG1F,+SG2F,+SG2T,+SC1P,-SG2F,-SC1F,-L
40	+SG2F,+SG3F,+SC1F,-SC1P
41	+SG1F,+SG2F,+SG2T,+SC1F,-SG2F,-SC1P,-L
42	+SG1F,+SG2F,+SG2T,+SC1F,-L
43	+SG2F,+SG3P,+SC1P,+SG4P,+SG5P,-SG3F,-SG4F,-SG5F

44	+SG2F,+SG3F,+SG3P,+SG4P,+SG5P,-SG3P,-SG4F,-SG4P,-SG5F
45	+SG2F,+SG3P,+L,+SG4P,+SG5P,-SG2T,-SG3T,-SG4F,-SG4T,-SG5F,-SG5T
46	+SG2F,+SG3F,+SG3P,+SG4F,+SG4P,+SG5F,+SG5P,+SG5T,+SW4T,-SG5F
47	-SG4F,-SG4P,-SG5P
48	-SG4F,-SG4P,-SG5T
49	-SG4F,-SG5P,-SG5T
50	-SG5F,-SG6F,-SG6P
51	-SG4F,-SG5F,-SG5T,-SG6T
52	-SG5F,-SG6F,-SG6T
53	+SG5F,+SG6T,+SW4T,-SW3F
54	+SG5F,+SG6T,+SW4T,-SW4F
55	+SW4T,-SW3F,-SW4F
56	+SW3F,-SG5F,-SG6T,-SW4T
57	+SW4F,-SG5F,-SG6T,-SW4T
58	-SG4F,-SG5F,-SG5T,-SW4T
59	-SG5F,-SG6F,-SW4T
60	-SG5F,-SG6T,-SW3T,-SW4T
61	-SG5F,-SG6F,-SG6P,-SG7P
62	+SG7P,-SG6F,-SG7F,-SC3F
63	+SC3P,-SG6F,-SG7F,-SC3F
64	+L,-SG5F,-SG6F,-SG6T,-SC3F
65	+SG7F,-SG6F,-SG7P,-SC3P
66	-SG5F,-SG6F,-SG6P,-SC3P
67	+SG2F,+SG3F,+SG3P,+SG4F,+SG4P,+SG5F,+SG5P,+SG6T,-SG5F,-SG6F,-L
68	+SC3F,-SG6F,-SC3P,-L

Source: Author, 2018

As can be seen in Table 2.19, the system presented 68 loops. As commented before, such loops are not inconsistent; but reveal a cascade effect or could be used to reduce the disturbance events to those ones that really could be imitating events. Table 2.20 shows possible suspicious or incoherent relations from HAZOP.

Table 2.20–Suspicious or inconsistency sequences allowed for HAZOP matrices for entire pumping system

N°	Events
----	--------

1	+SG1F,+SG2T,-SG1F,-SG2F,-L
2	+SG1F,+SG2F,+SC1F,-SG1F,-SG2P,-SC1P
3	+SG1F,+SG2F,+L,-SG1F,-SG2T
4	+SG1F,+SG2T,-SG1F,-SW2F
5	+SG1F,+SG2F,+L,-SG1F,-SG2T,-SW1T,-SW2T
6	+SG2F,+SC1F,-SG2F,-SG2P,-SC1P
7	+SG2F,+L,-SG2F,-SG2T
8	+SG2F,+L,-SG2F,-SG2T,-SW1T,-SW2T
9	+SG2F,+SC1P,-SG2F,-SG3F
10	+SG2F,+SG3F,-SG2F,-SG3P
11	+SG2F,+SC1P,-SG2F,-SC1F
12	+SG2F,+SC1F,-SG2F,-SC1P
13	+SG4F,+SG5F,+SG6F,+SG7P,-SG4F,-SG5F,-SG6F,-SG7F
14	+SG4F,+SG5F,+SG6T,-SG4F,-SG5F,-SG6F,-L
15	+SG5F,+SG6F,+SG7F,-SG5F,-SG6F,-SG7P
16	+SG5F,+SG6F,+SG7P,-SG5F,-SG6F,-SG7F
17	+SG5F,+SG6F,+SC3F,-SG5F,-SG6F,-SC3P
18	+SG5F,+SG6F,+SC3P,-SG5F,-SG6F,-SG7F
19	+SG5F,+SG6F,+L,-SG5F,-SG6T
20	+SG5F,+SG6T,-SG5F,-SG6F,-L
21	+SG5P,-SG5F,-SG5P,-SG5T,-SG6T
22	+SG5P,-SG5F,-SG5P,-SG5T,-SW4T
23	+SG2F,+SG3F,+SG3P,+SG4F,+SG4P,+SG5F,+SG5P,+SG6F,+SG7F,-SG5F,-SG6F,-SG7P
24	+SG2F,+SG3F,+SG3P,+SG4F,+SG4P,+SG5F,+SG5P,+SG6F,+SG7P,-SG5F,-SG6F,-SG7F
25	+SG2F,+SG3F,+SG3P,+SG4F,+SG4P,+SG5F,+SG5P,+SG6F,+SC3F,-SG5F,-SG6F,-SC3P
26	+SG2F,+SG3F,+SG3P,+SG4F,+SG4P,+SG5F,+SG5P,+SG6F,+SC3P,-SG5F,-SG6F,-SG7F

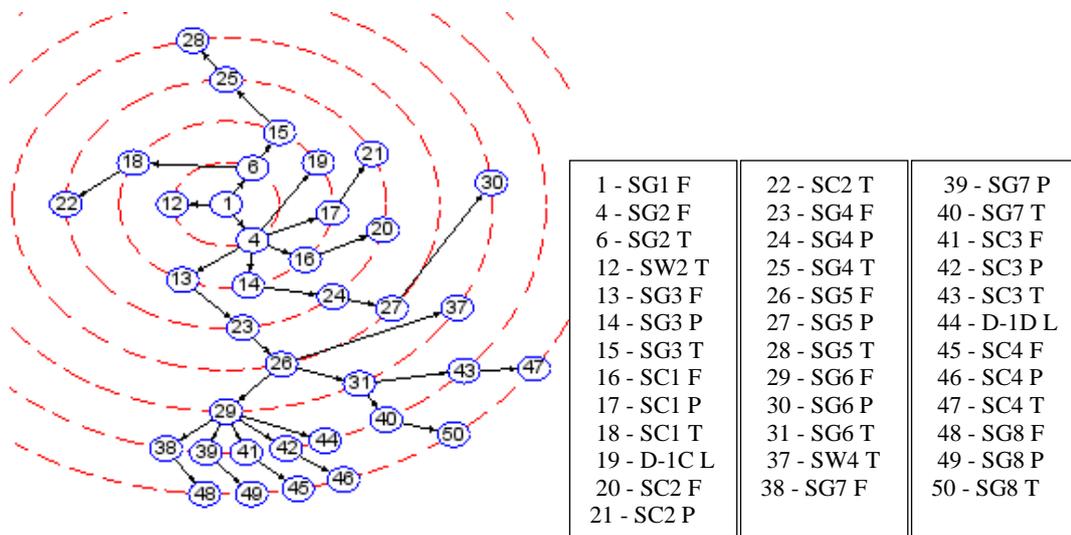
Source: Author, 2018

As can be seen in Table 2.20, the most of them are associated to increase and decrease of flow in the same stream. Only two cases (lines 21 and 22 of Table 2.20) showed problem in the pressure of a stream. These results suggest that the relations associated to flow must be prepared more carefully or revisited.

Elaborating trees from HAZOP events

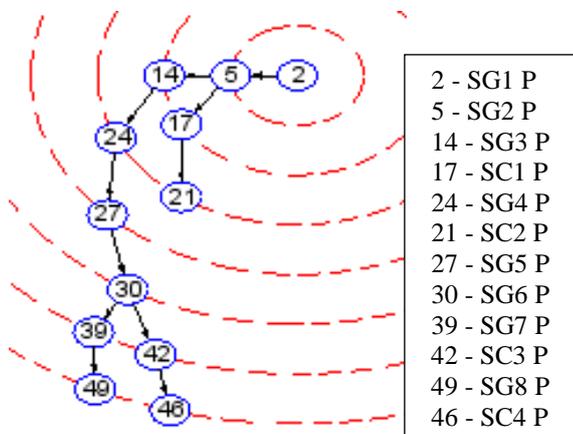
Having declared all the matrices related to the raw gas pump system, they can then be combined according to the process equipment sequence, and then consequence trees can be obtained for the entire system. As the range of results is significantly large, only a few will be chosen as being of greater relevance for exemplifying the proposed methodology. These results can be seen below:

Figure 2.36 – HazOp Tree – SG1F Increase – Pumping System



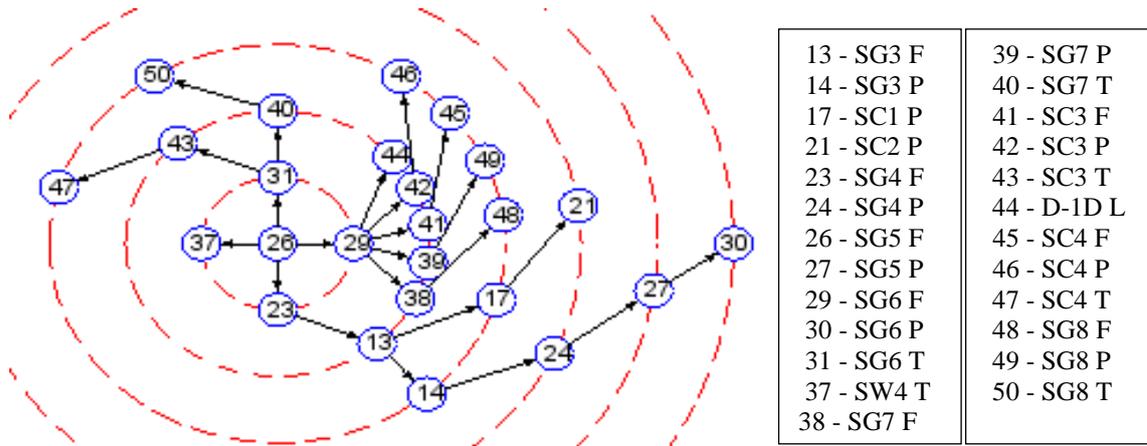
Source: Author, 2018

Figure 2.37 – HazOp Tree – SG1P Increase – Pumping System



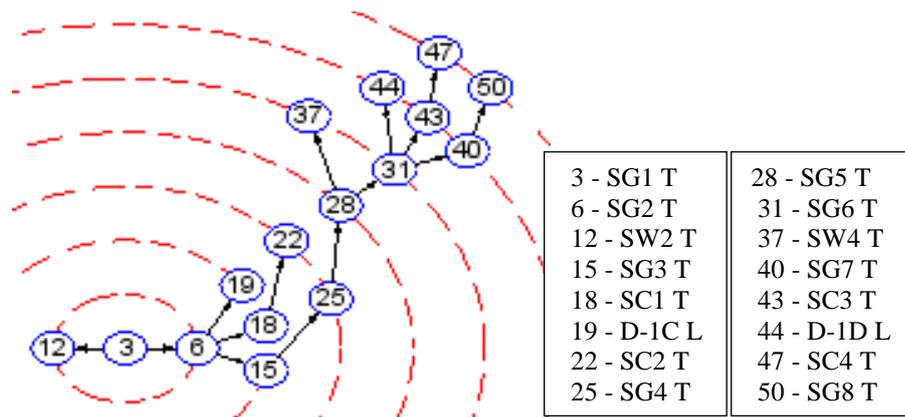
Source: Author, 2018

Figure 2.38 – HazOp Tree – SG1F Increase – Pumping System



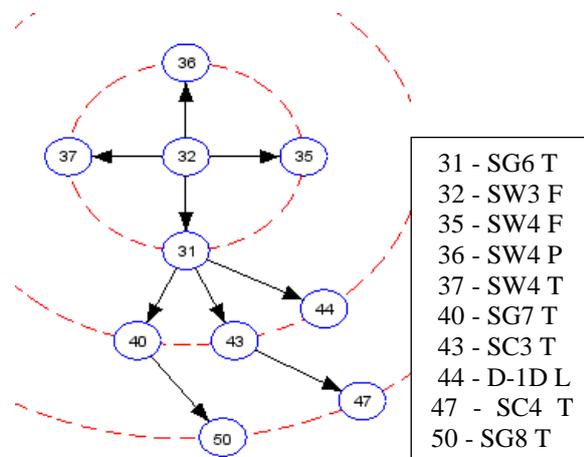
Source: Author, 2018

Figure 2.39 – HazOp Tree – SG1 T Decrease – Pumping System



Source: Author, 2018

Figure 2.40 – HazOp Tree – SW3 F Decrease – Pumping System



Source: Author, 2018

In Figure 2.36 it can be observed that an increase in the gas flow at the system inlet, SG1F, generates a large chain of events in the process sequence. It can be noticed a direct influence on the temperature of the cooling water, and on the flows and temperatures of the downstream streams. In the generated tree, one of the branches starts the propagation of a temperature increase until the stream SG5. It was expected that this temperature increase in the stream SG5 could have been propagated to the streams after SG5, nevertheless this happened by the flow increase of the own stream SG5. The influence on the temperatures was correctly established, however, from a given moment, by the flows of the system. It is noted in the generated trees that it is possible that one variable influences two or more variables, but the opposite does not occur, that is, two different variables influence one. This fact probably explains why from a given moment the temperatures have been influenced by the flows, and not by other temperatures. This scenario of increase of the gas flow at the entrance of the system was not considered by the HazOp team, although it is included in the generic equipment matrix. Probably, the original HazOp team did not identify this hazard as possible. However, from the use and combination of the generic matrices, it is possible to show that, depending on the system, a given hazard may exist and the project team should evaluate whether or not it should be considered. This aspect shows the possibility that the approach has to decrease the dependence of participants in HazOp studies.

With respect to an increase in gas inlet pressure (SG1P), it can be seen from the tree generated in Figure 2.37 that this increase was propagated to the entire downstream system, according to the relation of the matrices. However, by this analysis, it is not possible to see how far this pressure increase will be sensitive, ie how far the pressure increase will be perceivable by the system. It can be said that the results generated were the most conservative possible, leading to an increased pressure to the process outlets.

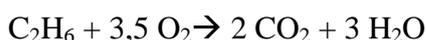
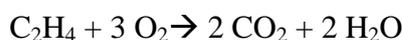
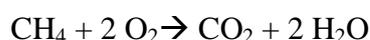
As mentioned before in the flash pot study case, it is also possible to apply deviations in the middle of the process, and not only in their initial ends. This is possible to show from Figure 2.38, which is related to an increase in flow rate of the SG5F current. This increase in this flow was propagated to downstream temperatures and upstream and downstream flows, as expected through the generated matrices. This is an important aspect and increases the flexibility of the approach, since deviations can be generated in any chains, such as in a classic HazOp study.

Figure 2.39 and Figure 2.40 show the results for a decrease of SG1T and SW3F, respectively. The first was not captured in the HazOp study, but the deviation equivalent to a decrease in SW3F can be seen in cause 2.7 in Table 2.11, showing consistency of the matrix

approach with the classical study for this specific deviation. However, deviations not related to the variables involved in the matrices cannot be captured by them, such as deviations related to contamination or operational questions.

2.3.3. Case Study 3 – CO₂ plant

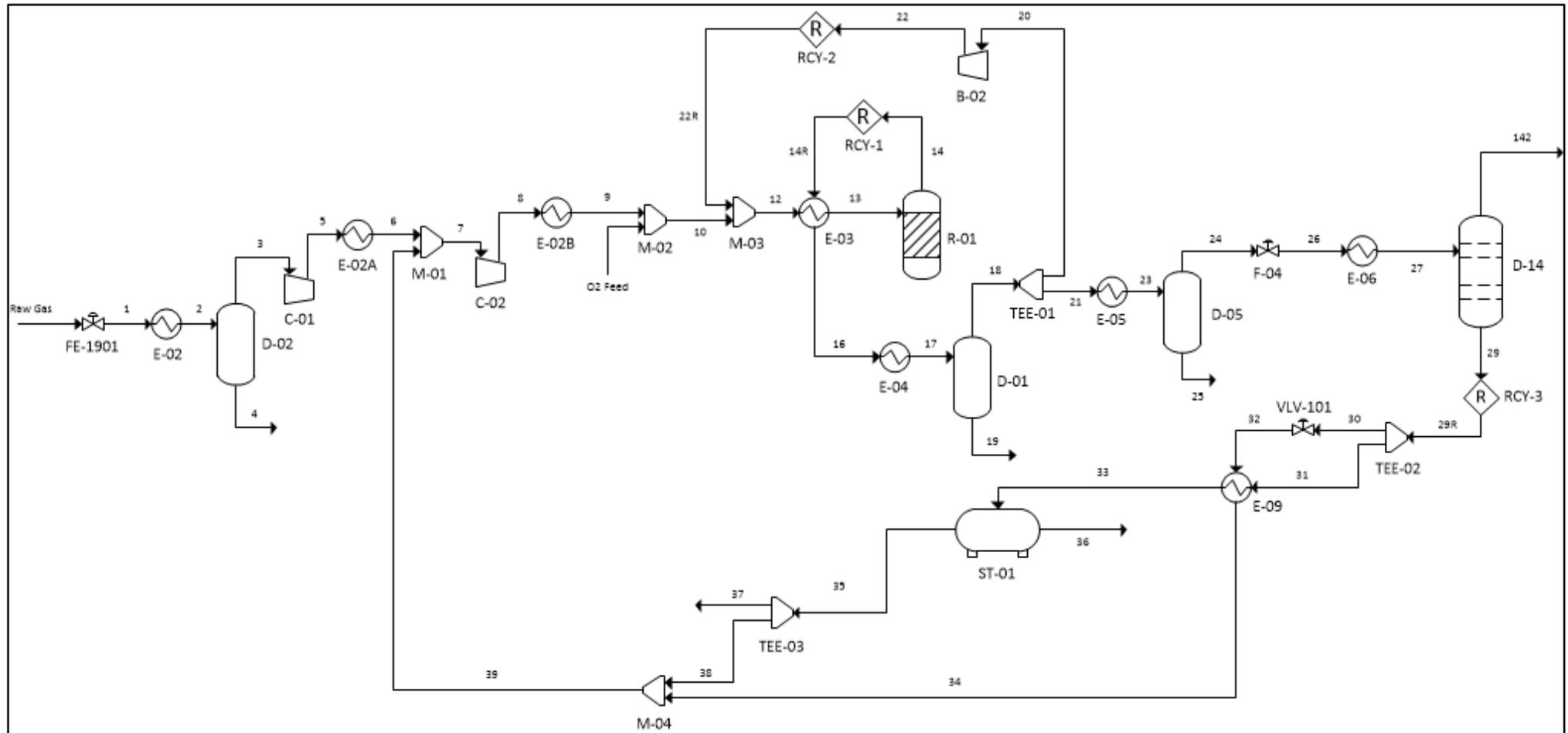
In this plant (Figure 2.41), a gaseous stream enriched in CO₂ flows through a cooler in order to condensate part of the water in the stream. After that, the water will be collected in a collector vessel, with the gaseous stream flowing on the top. This gas is compressed and then mixed with a 99,9% gaseous oxygen stream. This mixture is fed to a catalytic oxidizer reactor (catox), which is filled with a catalyst which will promote the oxidation reaction of some hydrocarbons present in the stream. With this, more CO₂ will be formed, with water being the by-product. The main reactions considered are the following.



All the above reactions are exothermic, and then the outlet stream, now with a temperature above 400 ° C, is then used to preheat the charge of this reactor in the E-03, the cross heater. Even with this thermal exchange after the exit of the catox, a second stage of cooling is necessary, and it is done in the E-4 heat exchanger, the catox aftercooler. Similarly to the beginning of the process, some of the water present in the stream is condensed. and collected in a new collector vessel. Part of the gaseous stream leaving this last vessel is then divided: part is fed to the catox recycle blower, and another that will pass through another cooling battery. The purpose of the recycle blower is to assist in the temperature adjustment of the catox, since its inlet stream has a lower temperature and will mix with the inlet stream of the catox, previous to the cross heater. The other stream, which passed through the cooling battery, is then sent to the distillation column D-14, where liquid CO₂ is obtained in the bottom, and gaseous CO₂, along with some contaminants, such as oxygen, methane, and water, is vented into the top. The liquid CO₂ is then cooled in the subcooler to be stored in the

ST-01 tank. Part of the bottom stream of the distillation column is vaporized and returns to the beginning of the process. Ammonia is coolant used in this process. The following figure demonstrates a simplified process flow diagram for this process.

A classical HazOp analysis was also developed for this system. However, for this particular case, only some portions of the study will be presented, once the original source HazOp is very large, making it not reasonable to be fully presented in this paper. It was decided to show some scenarios related to two nodes: the first one comprises the raw gas inlet, the precooler E-02, the knockout drum E-02 and downstream CO₂ compressors. The second node comprises the cross heater E-03, the catox vessel, the aftercooler E-04, water separator D-01 and recycle blower B-02. This analysis presented is also based on a real study carried out in the industry.

Figure 2.41 – CO₂ separation and liquefaction plant

Source: Author, 2018

Table 2.21 –Classical HazOp – Node 1: raw gas inlet, the precooler E-02, the knockout drum E-02 and downstream CO₂ compressors

Deviation	Causes	Consequences	S	Indications/Protections	L	R
No Flow	1.1 Manual valve closed in the inlet pipeline	1.1.1 Vacuum to the pipeline and to the equipment E-02, D02 (with CO ₂ compressor running), air into the process and consequent high oxygen content in the raw gas and possible explosion due to contact with compressor lube oil	1	1.1.1 Shutdown of the CO ₂ compressors in case of low suction pressure	5	4
				1.1.2 E-02(Precooler 2) is designed to vacuum condition		
				1.1.3 D02 (knockout drum 2) is designed for full vacuum		
Low Flow	1.2 E02 fouled on process gas side	1.2.1 Loss of exchanger performance, possible loss of cooling, temperature increase at outlet of E02.	4	1.2.1 None identified	4	4
High Flow	1.3 High flow through D-02 bottom	1.3.1 High condensate and possible CO ₂ carry over the SO drain line, possible personal injury due to hazardous atmosphere	2	1.3.1 None Identified	4	4
				1.3.2 Low Level at E-02		

Deviation	Causes	Consequences	S	Indications/Protections	L	R
High Temperature	1.4 High temperature from upstream node	1.4.1 Increase amount of moisture on the feed gas and possible moisture carryover to the pipeline, possible pressure drop	5	1.4.1 Demister inside D-02	4	4
	1.5 Lack of Ammonia at E-02 (Shell side)	1.5.1 Loss of exchanger performance and possible temperature increase at outlet of E02 process side	5	1.5.1 None Identified		
Low Temperature	1.6 Low pressure of ammonia to E02 on the shell side	1.6.1 Possible freeze moisture content in the feed gas and possible plugging tubes of E02, damaging the equipment and possible high pressure on upstream system	1	1.6.1 PSV will protect the system against overpressure 1.6.2 High pressure shutdown in the upstream system	5	4
	1.7 Low temperature of feed gas from upstream node	1.7.1 Possible high level in D-02	4	1.7.1 Shutdown due to high level in the D-02	4	4
		1.7.2 Water carry over to the process lines and possible plug/damage instruments	4	1.7.2 Demister in D02 and pipeline purge	4	
Low Pressure	1.8 Loss of feed to E-02 while compressor is operating	1.8.1 E-02 possible collapse possible CO2 leak, possible localized CO2 atmosphere,	1	1.8.1 E-02 tube side is rated for -14.5 psig (0.2 psia) 1.8.2 PSV-7451A/B vacuum will operate 1.8.3 PSL-4100 will shut down compressor on low suction pressure	5	4

Deviation	Causes	Consequences	S	Indications/Protections	L	R
		possible ammonia release from E-2, possible employee injury				
High Pressure	1.9 Ammonia leak into E-02 process side	1.9.1 Possible formation of ammonium carbamate salts, possible basic water, possible plugging of the cooler, high pressure upstream heat exchanger E-02	1	1.9.1 Normal operating procedure to periodically check ammonia level in receiver 1.9.2 PSV will protect against overpressure 1.9.3 High pressure shutdown	5	4

Source: Author, 2018

Table 2.22 –Classical HazOp – Node 2: Cross heater E-03, catox vessel, aftercooler E-04, water separator D-01 and recycle blower B-02

Deviation	Causes	Consequences	S	Indications/Protections	L	R
No Flow	2.1 No flow from upstream node	2.1.1 No/Low flow to this node, low pressure to this node, possible high temperature at E-03 and possible equipment damage	1	2.1.1 High temperature shutdown in place	5	4
	2.2 Block in the downstream system	2.2.1 Possible overpressure of catox cross exchanger (E-03), catox vessel, (R-01) aftercooler (E-04), catoxwater separator (D01)and blower by deadheading of CO2 compressor,possible trapping of oil in piping	1	2.2.1 PSV-4110 will protect against overpressure 2.2.2. High pressure shutdown in place	5	4
	2.3 Valve improperly closed in the outlet of catox water separator	2.3.1 Possible high level in catox moisture separator, possible watercarryover in downstreamnode, possible CATOX recycle blower damage	2	2.3.1 LSHH-5130 will shut down plant on high level 2.3.2 Blower B-02 high vibration shutdown	4	4

Deviation	Causes	Consequences	S	Indications/Protections	L	R
	2.4 Manual valve improperly closed in the B-02 suction	2.4.1 Possible loss of gas supply to blower B-02 leading to possible vacuum on suction, possible leak into the system (air enter in the blower through the seals), possible low flow to downstream node	4	2.4.1 PSL5160 shuts down blower on low suction pressure	4	4
	2.5 1. Manual valve improperly closed in the B-02 discharge	2.5.1 If blower is necessary: Loss of raw gas dilution leading to high conversion in the catox leading to high temperature scenarios to CATOX and possible energy release	1	2.5.1 AE2 will shutdown the plant in case of high O2 content 2.5.2 High temperature shutdowns on Catox system	5	4
High Temperature	2.6 High temperature from upstream node	2.6.1 Possible high temperature in catox and possible runaway reaction in the catox, possible violation of MAWT of vessel, possible blower internal damage.	1	2.6.1 See 2.5.2	5	4
	2.7 Loss of ammonia refrigerant to aftercooler (E-04)	2.7.1 Possible exceed MAWT of downstream equipment, possible damage to equipment, possible leak	4	2.7.1 TAH5140 will shut down plant on high temperature from aftercooler	4	4

Deviation	Causes	Consequences	S	Indications/Protections	L	R
		of CO2 dueto failure				
Low Temperature	2.8 Oxygen valve fails open during normal operation	2.8.1 Cold gas to catox cross exchanger and catox, possible process inefficiency, possible product contamination, QA issue,no hazardous consequences	5			

Source: Author, 2018

The matrices of HAZOP will be omitted for simplicity, since it is a very complex system; however, such tables can be found in the supplementary material, containing the files with the matrices. From the tables, it is possible to perform the evaluation of loops and suspicious sequences, as follows.

Table 2.23 shows loops and circuits arising from CO₂ plant. As can be seen, there are 128 loops. Such loops analysis can help HAZOP team to evaluate which are some of original causes for disturbances.

Table 2.23 – Loops and circuits considering both positive and negative perturbations in HAZOP matrices for entire CO₂ plant

Loop n°	Variables
1	+10F,+12F,+29F,+29RF,+30F,+32F,+34F,+39F,+7F,+8F,+9F,-13T,-16F,-17F,-18F,-21F,-23F,-24F,-26F,-27F,-D-14L
2	+12F,+13F,-13T,-14RF,-16F,-16T
3	+12T,+13T,+16T,-12F,-13F
4	+13F,+13T,+14P,-12F,-13F,-13T,-14P,-14RF,-16F,-16T
5	+13F,+13P,+14P,+14T
6	+13F,+13T,+14T,-12F,-13F,-13T,-14P,-14RF,-16F,-16T
7	+13T,+14RF,+16T,-12F,-13F
8	+13F,+14F,+14RF,+16T,-13F,-13T,-14P,-14RF,-16F,-16T
9	+13F,+14P,+14RP,+16P,+17P,+19P,-14RF,-16F,-16T,-17F,-18F
10	+13T,+14RT,+16T,-12F,-13F
11	+13F,+14T,+14RT,+16T,-13F,-13T,-14P,-14RF,-16F,-16T
12	+13T,+14RF,+16F,+16T,-12F,-13F
13	+14RF,+16F,+16T,+17F,+19P,-13F,-13T,-14P,-16F,-17F,-18F
14	+14RF,+16F,+16T,+17T
15	+17F,+18F,+19P,-17F,-18F,-19P
16	+17F,+18P,+19P,-19F
17	+17P,+18P,+19P,-19F
18	+16T,+17T,+18T,+21T,+23T,-13F,-13T,-14P,-16F,-17F,-18F,-21F,-23F,-D-05L
19	+17F,+19F,+19P,-17F,-18F,-19P
20	+18F,+21F,+23T,-17F,-18F,-19P,-21F,-23F,-D-05L
21	+18P,+19P,+21P,+23P,+24P,-18F,-19F,-21F,-23F,-25F
22	+12F,+18F,+20F,+22F,+22RF,-13T,-16F,-17F,-19P
23	+12P,+13F,+13P,+14P,+18P,+19P,+20P,+22P,+22RP,-14RF,-16F,-16T,-17F,-

	18F,-19F
24	+21F,+23F,+23T,+24F,-23F,-25P,-D-05L
25	+21F,+23F,+23T,+24P,-23F,-25F,-D-05L
26	+21F,+23F,+23T,+25F,-D-05L
27	+21F,+23F,+23T,+25P,-23F,-24F,-D-05L
28	+23P,+24P,+25P,-23F,-24F,-25F
29	+24F,+26F,+27T,-23F,-24F,-25P,-26F,-27F,-D-14L
30	+2F,+24P,+26P,+27P,+29F,+29P,+29RF,+29RP,+3F,+3P,+30F,+30P,+32F,+32P, +34F,+34P,+39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P,-23F,-24F,-25F,-26F,-27F,-D- 14L
31	+23T,+24T,+26T,+27T,-23F,-24F,-26F,-27F,-D-05L,-D-14L
32	+142F,+27F,+29F,-142P,-27F,-D-14L
33	+142P,+2F,+27F,+27P,+29F,+29P,+29RF,+29RP,+3F,+3P,+30F,+30P,+32F,+32 P,+34F,+34P,+39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P
34	+26F,+27F,+27T,+29F,-D-14L
35	+2F,+27F,+29F,+29P,+29RF,+29RP,+3F,+3P,+30F,+30P,+32F,+32P,+34F,+34P, +39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P
36	+27T,+29F,+29T,+29RF,+29RT,+31F,+31T,+33T,-D-14L
37	+31F,+31T,+33T,+34T
38	+31F,+32T,+33T,+34T
39	+31F,+33F,+34T
40	+2F,+29RF,+3F,+3P,+30F,+31F,+32F,+33F,+34F,+35P,+38P,+39F,+39P,+5F,+5 P,+6F,+6P,+7F,+7P
41	+2F,+2P,+3P,+4P
42	+1F,+2F,+2T,+3P,+3T,+5T
43	+2F,+3F,+3P,+5F,+5T,+6T
44	+29RF,+30F,+31F,+32F,+33T,+34F,+35T,+38T,+39F,+39T,+5F,+6F,+6T,+7F,+ 7T
45	+2F,+3F,+3P,+5F,+5P,+6P,+6T,+7P,+7T,+8T
46	+10P,+12P,+13F,+13P,+14P,+2F,+29F,+29RF,+3F,+3P,+30F,+32F,+34F,+39F,+ 5F,+5P,+6F,+6P,+7F,+7P,+8P,+9P,-14RF,-16F,-16T,-17F,-18F,-21F,-23F,-24F,- 26F,-27F,-D-14L
47	+10T,+12T,+16T,+29F,+29RF,+30F,+32F,+34F,+39F,+7F,+8F,+9T,-13F,-13T,- 14P,-16F,-17F,-18F,-21F,-23F,-24F,-26F,-27F,-D-14
48	+10T,+12T,+16T,+2F,+29F,+29RF,+3F,+3P,+30F,+32F,+34F,+39F,+5F,+5P,+6F ,+6P,+7F,+7P,+8T,+9T,-13F,-13T,-14P,-16F,-17F,-18F,-21F,-23F,-24F,-26F,-

	27F,-D-14L
49	+17F,+19P,+D-01L,-16F,-17F,-17T,-18F
50	+21F,+23F,+23T,+D-05L,-23F,-25F,-D-05L
51	+142P,+2F,+27F,+27P,+29F,+29P,+29RF,+29RP,+3F,+3P,+30F,+30P,+32F,+32P,+34F,+34P,+39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P,+D-14L,-29F
52	+16T,-12F,-13F
53	-12F,-13F,-13P,-14P
54	-13F,-13T,-14F,-14P,-14RF,-16F
55	-13F,-13T,-14P,-14T
56	-13P,-13T,-14P,-14T
57	+142P,+27P,+29P,-142F
58	-13T,-14RF,-16F
59	-13T,-14T,-14RT
60	-14RF,-16F,-16P,-17F,-17P
61	+12F,-13T,-14RF,-16F,-16T
62	-12T,-13T,-14RF,-16F,-16T
63	-13T,-14RF,-14RT,-16F,-16T
64	-14RF,-16F,-16T,-17T
65	-17F,-18F,-18P,-21F,-21P,-23F,-23P
66	-17F,-17P,-18F,-18P,-21F,-21P,-23F,-23P
67	+19P,+D-01L,-16F,-17F,-17T,-18F,-19F
68	+19P,-17F,-18F,-19F
69	-17F,-17P,-19P
70	+2F,+4P,+D-02L,-1F,-2F,-2P,-2T,-3F,-3P
71	-18F,-18P,-20F,-20P,-21F,-21P,-23F,-23P
72	-20F,-20P,-22P
73	-20F,-20P,-22T
74	-12F,-13F,-13T,-14P,-16F,-17F,-18F,-20F,-22F,-22RF
75	+D-05L,-21F,-23F,-23T,-25F
76	-16F,-17F,-17T,-18F,-18T,-21F,-21T,-23T
77	-23F,-23P,-24P
78	+25P,-23F,-24F,-25F
79	+25F,-23F,-25P,-D-05L
80	-23F,-23P,-25P
81	-23F,-24F,-24P,-26F,-26P,-27F,-27P

82	+2F,+29F,+29P,+29RF,+29RP,+3F,+3P,+30F,+30P,+32F,+32P,+34F,+34P,+39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P,-142F,-27F,-D-14L
83	-142P,-27F,-27P
84	+142P,+2F,+27P,+29F,+29P,+29RF,+29RP,+3F,+3P,+30F,+30P,+32F,+32P,+34F,+34P,+39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P,+D-14L,-26F,-27F,-27T,-29F,-D-14L
85	-21F,-23F,-23T,-24F,-24T,-26F,-26T,-27T
86	+142P,+2F,+27P,+29F,+29P,+29RF,+29RP,+3F,+3P,+30F,+30P,+32F,+32P,+34F,+34P,+39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P,-27F,-29F,-D-14L
87	+142F,-142P,-27F,-29P
88	-27F,-27P,-29P
89	+29F,+29RF,+30F,+32F,+34F,-26F,-27F,-27T,-29T,-29RT,-31T,-33T,-D-14L
90	+31F,+33T,+34T,-32F
91	+142P,+2F,+27P,+29P,+29RF,+29RP,+3F,+3P,+30F,+30P,+31F,+32F,+32P,+33T,+34F,+34P,+39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P,-29F,-29RF,-30F,-32F
92	+142P,+2F,+27P,+29P,+29RP,+3F,+3P,+30P,+32P,+34P,+35F,+38F,+39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P,-29F,-29RF,-31F,-33F,-ST-01L
93	+142P,+2F,+27P,+29P,+29RP,+3F,+3P,+30P,+32P,+34P,+35F,+38F,+39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P,-29F,-29RF,-31F,-33F,-33P,-ST-01L
94	+32F,+34F,-33T
95	+142P,+2F,+27P,+29P,+29RP,+3F,+3P,+30P,+32P,+34F,+34P,+39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P,-29F,-29RF,-31F,-33T
96	+31F,+33T,+34T,-34F
97	+33T,-32F,-34F
98	+32F,+34F,-34T
99	+142P,+2F,+27P,+29P,+29RP,+3F,+3P,+30P,+32P,+34F,+34P,+39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P,-29F,-29RF,-31F,-34T
100	+34F,-31T,-33T,-34T
101	+34F,-32T,-33T,-34T
102	+34F,+35F,+38F,+39F,-33F,-34T,-ST-01L
103	+2F,+29RF,+29RP,+3F,+3P,+30F,+30P,+31F,+31P,+32F,+32P,+33F,+33P,+34F,+34P,+39F,+39P,+5F,+5P,+6F,+6P,+7F,+7P,+ST-01L,-35F
104	+29RF,+30F,+31F,+32F,+33F,+34F,+35F,+38F,+39F,+ST-01L,-33F,-35F,-ST-01L
105	+31F,+33F,+33T,+ST-01L,-34F,-35F,-38F,-39F
106	+29RF,+30F,+31F,+32F,+33T,+34F,+35F,+38F,+39F,-32F,-33F,-34P,-35P,-38P,-

	39P,-ST-01L
107	+2F,+3P,+4P,-4F
108	+2F,+3P,+D-02L,-4F
109	+2F,+3F,+4F,-4P
110	+2F,+3F,+4P,-2P,-3F,-3P,-4P
111	-3F,-3P,-5P
112	-3F,-3P,-5T
113	-1F,-2F,-2P,-2T,-3F,-3P,-3T,-5T
114	-3F,-5F,-5T,-6T
115	+2F,+29RF,+3F,+30F,+31F,+32F,+33T,+34F,+39F,+4P,+5F,+6F,+7F,-3F,-34F,- 39F,-5F,-6F,-7F
116	+2F,+29RF,+3F,+30F,+31F,+32F,+33T,+34F,+39F,+4P,+5F,+6F,+7F,-3F,-32F,- 34P,-39P,-5P,-6P,-7P
117	+33T,-32F,-34F,-34P,-39F,-39P,-7F,-7P
118	+2F,+3F,+34F,+39F,+4P,+5F,+6F,+7F,-3F,-33T,-35T,-38T,-39T,-5F,-6T,-7T
119	+33T,-32F,-34F,-34P,-39F,-39P,-7F,-7P,-8P
120	+33T,-32F,-34F,-34P,-39F,-39P,-7F,-7P,-8T
121	+29RF,+30F,+31F,+32F,+33T,+34F,-33T,-34F,-35T,-38T,-39F,-39T,-7F,-7T,-8T
122	+29F,+29RF,+31F,+33T,-10F,-12F,-13F,-13T,-14P,-16F,-17F,-18F,-21F,-23F,- 24F,-26F,-27F,-34F,-39F,-7F,-8F,-9F,-D-14L
123	+29F,+29RF,+31F,+33T,-10P,-12P,-18F,-20F,-21F,-22P,-22RP,-23F,-24F,-26F,- 27F,-34F,-39F,-7F,-8P,-9P,-D-14L
124	+29F,+29RF,+31F,+33T,-10T,-12T,-13T,-16F,-17F,-18F,-21F,-23F,-24F,-26F,- 27F,-34F,-39F,-7F,-8F,-9T,-D-14L
125	+29F,+29RF,+31F,+33T,-10T,-12T,-13T,-16F,-17F,-18F,-21F,-23F,-24F,-26F,- 27F,-34F,-39F,-7F,-8T,-9T,-D-14L
126	+16T,+17T,-13F,-13T,-14P,-16F,-17F,-D-01L
127	+19F,-17F,-19P,-D-01L
128	+1F,+2F,+2T,+4F,-D-02L

Source: Author, 2018

Table 2.24 presents the suspicious or inconsistent sequences obtained from HAZOP analysis. It can be seen that the most cases are associated to flow of stream, however, temperature of streams also presents incoherence (cases 10 to 14 of Table 2.24).

Table 2.24– Suspicious or inconsistency sequences allowed for HAZOP matrices for entire CO₂ plant

N°	Events
1	+1F,+2F,+D-02L,-1F,-2T
2	+1F,+2F,+4P,-1F,-2F,-2P,-3F,-3P
3	+1F,+2F,+3F,-1F,-2F,-2P,-4P
4	+1F,+2F,+4P,-1F,-2F,-2P,-3F,-3P,-5P
5	+1F,+2F,+4P,-1F,-2T,-3F,-3T,-5T
6	+1F,+2F,+4P,-1F,-2T,-3F,-3T,-5F,-5T,-6T
7	+10F,+12F,-10F,-12F,-13F,-13T,-14P
8	+10T,+12T,+16T,-10T,-12T,-13F,-13T,-14P
9	+12F,-12F,-13F,-13T,-14P
10	+12T,+13T,-12F,-12T,-13F,-13T,-14P
11	+12T,+16T,-12T,-13F,-13T,-14P
12	+13T,+14RF,+16T,-13F,-13T,-14P
13	+13T,+14RT,+16T,-13F,-13T,-14P
14	+13T,-12F,-13F,-13T,-14P
15	+14RF,+16F,+17F,+19P,-14RF,-16F,-17F,-18F
16	+14RF,+16F,+17T,+18T,+21T,+23T,-14RF,-16F,-17F,-18F,-21F,-23F,-D-05L
17	+14RF,+16F,+17T,-14RF,-16F,-17F,-D-01L
18	+16F,+17F,+19P,-16F,-17F,-18F
19	+16F,+17T,+18T,+21T,+23T,-16F,-17F,-18F,-21F,-23F,-D-05L
20	+16F,+17T,-16F,-17F,-D-01L
21	+14RF,+16F,+16T,+17F,+19P,-13F,-13T,-14P,-16F,-17F,-18F
22	+17F,+18F,+19P,-17F,-18F,-19P
23	+17F,+19F,+19P,-17F,-18F,-19P
24	+17F,+19P,+D-01L,-16F,-17F,-17T,-18F
25	+17F,+19P,-17F,-18F
26	+18F,+21F,+23T,-18F,-21F,-23F,-D-05L

Source: Author, 2018

2.4 Conclusions

As the classical HazOp is performed by a team during brainstorming sessions, lack of objectivity or incorrect conclusions may arise, depending on the experience of the team,

complexity of the process, time and money constrains and other factors. Therefore, a way to evaluate the consistency of the findings of a HazOp analysis in an objective form seems to be valuable. This evaluation can allow the team to find inconsistencies and close possible gaps in a timely manner. In this context, graph tools were successfully developed and applied in this paper to allow the evaluation of HazOp analysis. Several loops and circuits were found throughout the propagation paths based on typical HazOps propositions. Most of these loops and circuits are related to the flow of streams. This is an expected result as most of HazOps scenarios are usually related to flow deviations. This endorse the philosophy of integrating HazOp with mathematical tools to reduce inconsistencies. Routines for trees of events were also developed, and they allowed linking the events between units. The presentation of consequences in a tree shape makes it easier to identify the sequence of events from the original cause to the end point. In addition, it also helps identifying if there is any unfeasible path in the study, which can be corrected.

3 EVENT TREES OBTAINED FROM SENSITIVE ANALYSIS STATIONARY SIMULATIONS USING COMMERCIAL SOFTWARES: CASE STUDIES

Abstract

HAZOP is one of the most important techniques for evaluating potential risks of the plants. It is made from a holistic team, where individual knowledges play a very important role. Although a systematic technic is applied, the results, may be however, subjected to the team experience. In this context, some opportunities for improvement arise, as the use of process simulations in order to add information and help teams develop HazOp studies. Through process simulation, a sensitivity analysis was carried out, supported by computational routine created to generate disturbances in process streams. This methodology was applied to three cases: a Flash Pot System, a Pumping System and a CO₂ separation system. Event trees from the sensitivity analysis were generated and evaluated for the examples. The paper endorse the use of computational tools as a potential approach to support HazOp studies.

Keywords:HazOp, Process Safety, Event Tree, Simulation

3.1 Introduction

Several works presents an integration of HAZOP or trees employing simulations and sensitivity analysis, including chemical plants (LABOVSKÝ *et al.*, 2007), analysis of accidents (ISIMITE; RUBINI, 2016); supply chain systems (ADHITYA; SRINIVASAN; KARIMI, 2008). Besides, specific systems are target of such studies, like exothermic reactions (BERDOUZI *et al.*, 2018); distillation columns (MARENCO *et al.*, 2010; MATOS; FRUTUOSO E MELO; NELE, 2012; RAMZAN; COMPART; WITT, 2007); reactive distillation columns (ŠVANDOVÁ, ZUZANA *et al.*, 2009), among several others.

In many works, simulations propagate the influences of an original disturbance to other variables in process, through sensitive analysis or tree events. There is a continuous proposition of new methodologies for adapting HAZOP with simulations, generally adapting one or other step of the methodology. For example, Raoni et al. (RAONI; SECCHI; DEMICHELA, 2018) proposed divide simulation results in two steps, first performing analysis based on simulation results and posterior performing typical HAZOP procedures based on heuristics. The authors illustrated their procedures with two case studies, concluding that it was possible to achieve more coherent conclusions, and mapping some original perturbations that can propagate to other parts of the systems. A similar proposition has been presented by Chen et al. (2016). Kang and Guo (KANG; GUO, 2016) proposed HAZOP analysis based on sensitivity matrix using dynamic simulation, applying to case studies showing which perturbations would lead to inadmissible values of other variables, requiring safeguards.

The most basic sensitivity analysis consists in determining how an output variable y vary with an input variable x . Thus, derivative is a such direct measure $s_{y,x} = \left(\frac{\partial y}{\partial x} \right)$. Since the value of derivative depends on the value of y , usually normalization is performed as follows:

$$s_{y,x} = \frac{1}{y} \cdot \frac{\partial y}{\partial x} \quad (6)$$

It presumes that both variables are continuous and y is a smooth function of x ; otherwise, derivative is not defined. Other definitions use normalization of both x and y variables in the form $s_{y,x} = \frac{x}{y} \cdot \frac{\partial y}{\partial x}$.

Sensitive analysis can be used to generate trees of events. One problem with tree event analysis is associated to fast increase of branches, which grows exponentially with the number of possibilities in each level. To rank the events that should be represented in trees, other approach to verify the impact of failures is the use of risk measures.

Jonkman et al. (JONKMAN; VAN GELDER; VRIJLING, 2003) summarizes some measures of risk as:

- Fatalities
 - Individual risk
 - Societalrisk
- Economicdamage
- Environmental damage
- Integrated risk measures: considering various types of consequences
- Potentialdamage

Besides, risks models can take into account organizational factors, for which models have being developed, such as Technique for Human Error Rate Prediction, A Technique for Human Event Analysis, Systems-Theoretic Accident Model and Process; Functional Resonance Analysis Method, among others (ALVARENGA; FRUTUOSO E MELO; FONSECA, 2014).

Then, in considering failure probabilities $\mathbf{p} = \{p_1, p_2, \dots, p_n\}$ of independent events, and defining a function risk $R(\mathbf{p})$ in terms of such independent events, the derivative of risk can be written as (FULLWOOD; FULLWOOD, 2000):

$$dR = \left(\frac{\partial R}{\partial p_1}\right) dp_1 + \left(\frac{\partial R}{\partial p_2}\right) dp_2 + \dots + \left(\frac{\partial R}{\partial p_n}\right) dp_n = \sum_{i=1}^n r_{R,p_i} \cdot dp_i \quad (7)$$

Where the sensitivity of risk regard to the event i is defined as:

$$r_{R,p_i} = \left(\frac{\partial R}{\partial p_i}\right) \quad (8)$$

Importance measures based on such approach are defined in the literature, some of them presented in Table 3.1.

Table 3.1 – Importance measures of risk

Importance index	Description	Formula
Birnbaum	Risk for change in failure probability	$\left(\frac{\partial R}{\partial p_i}\right)$
Inspection Importance	Birnbaum index multiplied by probability	$p_i \cdot \left(\frac{\partial R}{\partial p_i}\right)$
Fussell-Veesly Importance	Similar to Birnbaum, but normalizing the risk function and probability	$\frac{p_i}{R} \cdot \left(\frac{\partial R}{\partial p_i}\right)$
Risk Achievement Worth Ratio	Risk if component i failed (R_i) divided by risk if no component fails (R)	$\frac{R_i}{R}$
Risk Achievement Worth Increment	Incremental change in risk if component i fail	$R_i - R$
Differential Important Measure	Normalized importance of each event	$\frac{\left(\frac{\partial R}{\partial p_i}\right) dp_i}{\sum_k \left(\frac{\partial R}{\partial p_k}\right) dp_k}$

Source: CONTINI; FABBRI; MATUZAS, 2010; FULLWOOD; FULLWOOD, 2000; JANBU, 2009

Other measures like Risk Reduction Worth Ratio and Risk Reduction Worth Increment are simply the opposite of Risk Achievement Worth Ratio and Risk Achievement Worth Increment.

In other approaches used FMEA/FMECA procedures, events are classified according to *Risk Priority Number (RPN)*, to determine which failures deserves more attention. As presented previously in this document, *RPN* is defined as (BARENDS *et al.*, 2012):

$$RPN = \left(\text{Probability of failure}\right) \times \left(\text{Severity of failure}\right) \times \left(\text{Severity of failure}\right) \quad (9)$$

To determine risk or *RPN*, several approaches have been proposed, as summarized by Liu et al. (LIU; LIU; LIU, 2013) in categories and approaches as follows:

- Multi-criteria decision making - Evidence theory; Grey theory; Fuzzy TOPSIS; AHP/ANP; ME-MCDM

- Mathematical programming - Linear programming, DEA /Fuzzy DEA
- Artificial intelligence - Rule-base system; Fuzzy rule-base system
- Integrated approaches - Fuzzy ART algorithm; Fuzzy cognitive map; WLSM-MOI-Partial ranking method; OWGA operator-DEMATEL; IFS-DEMATEL; among others
- Other approaches: Monte Carlo simulation; Boolean representation method; Digraph and matrix approach, among others.

In a more simple form, branches of trees can be eliminated according to the probabilities to such events, eliminating branches with low risk to the plant. The logical relations OR/AND defines how probabilities of events must be considered to get to a final incident (or accident). For example, considering that a final event C depends on two previous events A and B simultaneously ($A \cap B$), which means the use of the logical relation *AND*. Then, the probability becomes $p_{A \cap B} = p_A \cdot p_{B|A}$, where $p_{B|A}$ is the probability of B given A . If the events are independent, then, B does not depends on A , and $p_{B|A} = p_B$. Thus, in terms of probability p_C becomes:

$$\begin{aligned} A .AND. B \rightarrow C &\Rightarrow p_C = p_{A \cap B} \\ &p_C = p_A \cdot p_B \end{aligned} \quad (10)$$

Otherwise, if any of two original events A, B leads to C , then logical relation OR can be used. In this case, it is a union of events ($A \cup B$). In terms of probability, the final event C becomes:

$$\begin{aligned} A .OR. B \rightarrow C &\Rightarrow p_C = p_{A \cup B} \\ &\Rightarrow p_C = p_A + p_B - p_{A \cap B} \end{aligned} \quad (11)$$

It becomes clear from the above relations that, if C is related to logical relation *AND* of original events A, B , then its probability is much lower compared to C be related to logical relation *OR* of original events A, B . It also allows calculating how the inclusion of security layers impacts the probability of an accident, since for the accident must occur, besides the original fail, the security layers must also fail.

3.1.1. Overall comments

Literature presents several works integrating mathematical or simulation computations for helping the build of HAZOP or trees of events. Such approaches can help reducing events

in trees and in HAZOP analysis. Several techniques will require adapting efforts for specific systems. This feature limits the use of such tools. Then, using very common simulation tools is appealing. In fact, one can emphasize that almost all industrial projects contain stationary simulations in commercial softwares. The dynamic simulation is undoubtedly the most proper method for helping HAZOP analysis. However, it demands significant efforts to convert stationary simulations to dynamic mode. Hence, using stationary simulations is appealing, since it is available for almost every project in commercial simulations.

Another point that deserves attention is the wide propositions for risk quantification, which makes the choice of risk function not trivial. Therefore, one can argue that is preferable to work based on direct results on simulations.

In this context, the objective of this work is to develop a tool to generate automatically a sensitivity analysis from steady-state simulations and to generate event trees, in order to support HazOp studies.

3.2 Methodology

Steady state simulations of different systems were performed with the use of industry recognized softwares such as UniSim and Aspen HySys. After performing the simulations, computational routines in VBA were developed with the aim of automatically generating disturbances in the simulated process and, after the software recalculates the steady state, verify the changes in the other variables of the system as a whole. In the adopted approach, the disturbances contemplated increases and decreases in pressures, temperatures and flows of inlet streams of each process, since they were the only ones accessible, by a factor of $\pm 2\%$. The results of these perturbations were compiled in the form of a sensitivity analysis S , and were represented in a matrix form, where the response of each variable to a given perturbation was calculated as follows:

$$S_{i,j} = \frac{x_j - x_{j,0}}{f \times x_{j,0}}$$

Where,

$S_{i,j}$ –sensitivity of variable j regard to a disturbance of variable i ;

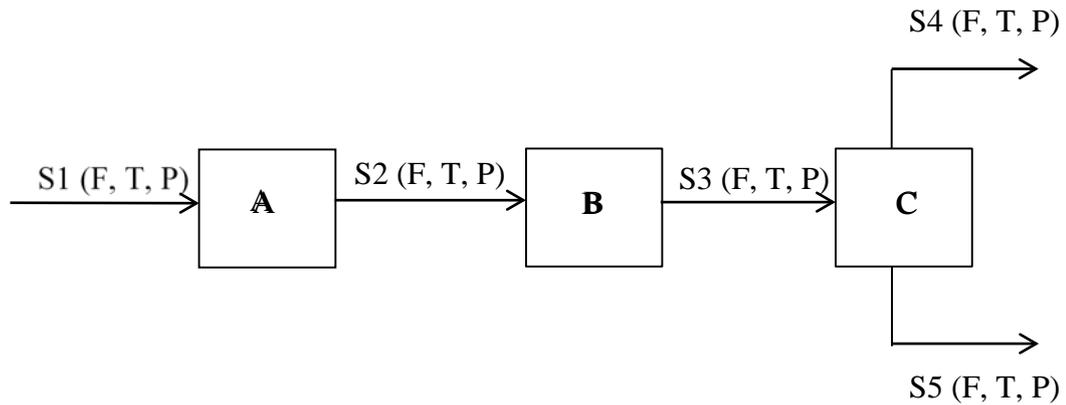
x_j - new value of the variable x_j after process disturbance

$x_{j,0}$ = original value of the variable x_j in the steady state simulation

f = disturbance factor

To visualize this procedure, the Figure 3.1 below, that represents a generic process, can be taken as an example.

Figure 3.1 – System with three equipment



Source: Author, 2018

In a state simulation, only the stream S1 could have its pressure (P), temperature (T) and mass flow (F) modified. The other streams and equipment downstream are a response to the process inlet stream. With this, the matrix representation of the sensitivity for this system can be represented in the following way:

Table 3.2 – An example matrix of sensitivity

	S1 F	S1 P	S1 T	S2 F	S2 P	S2 T	S3 F	S3 P	S3 T	S4 F	S4 P	S4 T	S5 F	S5 P	S5 T
S1 F	a _{1,1}	a _{1,2}	a _{1,3}	a _{1,4}	a _{1,5}	a _{1,6}	a _{1,7}	a _{1,8}	a _{1,9}	a _{1,10}	a _{1,11}	a _{1,12}	a _{1,13}	a _{1,14}	a _{1,15}
S1 P	a _{2,1}	a _{2,2}	a _{2,3}	a _{2,4}	a _{2,5}	a _{2,6}	a _{2,7}	a _{2,8}	a _{2,9}	a _{2,10}	a _{2,11}	a _{2,12}	a _{2,13}	a _{2,14}	a _{2,15}
S1 T	a _{3,1}	a _{3,2}	a _{3,3}	a _{3,4}	a _{3,5}	a _{3,6}	a _{3,7}	a _{3,8}	a _{3,9}	a _{3,10}	a _{3,11}	a _{3,12}	a _{3,13}	a _{3,14}	a _{3,15}

Source: Author, 2018

In the above representation, the indices on the left represent the variables that were disturbed (positive or negative variation) and the indices at the top represent the measured variables in each process stream. The terms of the matrix are the sensitivity values that show the order of magnitude of the variation of a given variable x in response to an input disturbance. Thus, assuming a process such as that of Figure 3.1, the sensitivity matrix would have a 3x15 dimension, considering F, P, and T in each stream. This occurs, as explained, because only the S1 stream variables could be changed, since the streams S2, S3, S4 and S5 are responses of this input in a steady state simulation and cannot be modified. Using the data obtained, other graphic representations that relate the responses of the variables after the

disturbances were elaborated, facilitating the identification of which variables are most impacted by a given variation.

In addition to the above approach, a computational routine was developed in Scilab, to generate a consequence tree, based on the obtained sensitivity matrix. Such a tree generates ramifications that indicate influence relations between the variables.

For the generation of the trees showing the relationships through layers, an earlier computational step is necessary to reorganize the matrix obtained by the software. This organization is given, firstly, by rewriting the sensitivity matrix in the square form (number of variables x number of variables), zeroing the other positions. In addition, it is necessary to create an incidence matrix, which provides information on the connections between the currents.

Based on the example of Figure 3.1, the square sensitivity matrix would have dimensions 15 x 15. The incidence matrix is the matrix that connects the streams of a given process to the equipment involved. The following coding has been established:

- a) $a_{i,j} = 0$, there is no relation between the stream and the equipment
- b) $a_{i,j} = 1$, the stream is the inlet of the equipment
- c) $a_{i,j} = -1$, the stream is the outlet of the equipment

The elaboration of the incidence matrix for Figure 4.1 can be illustrated by Table 3.3 below.

Table 3.3 – Incidence matrix for Figure 4.1

	S 1	S 2	S 3	S 4	S 5
Eq. A	1	-1	0	0	0
Eq. B	0	1	-1	0	0
Eq. C	0	0	1	-1	-1

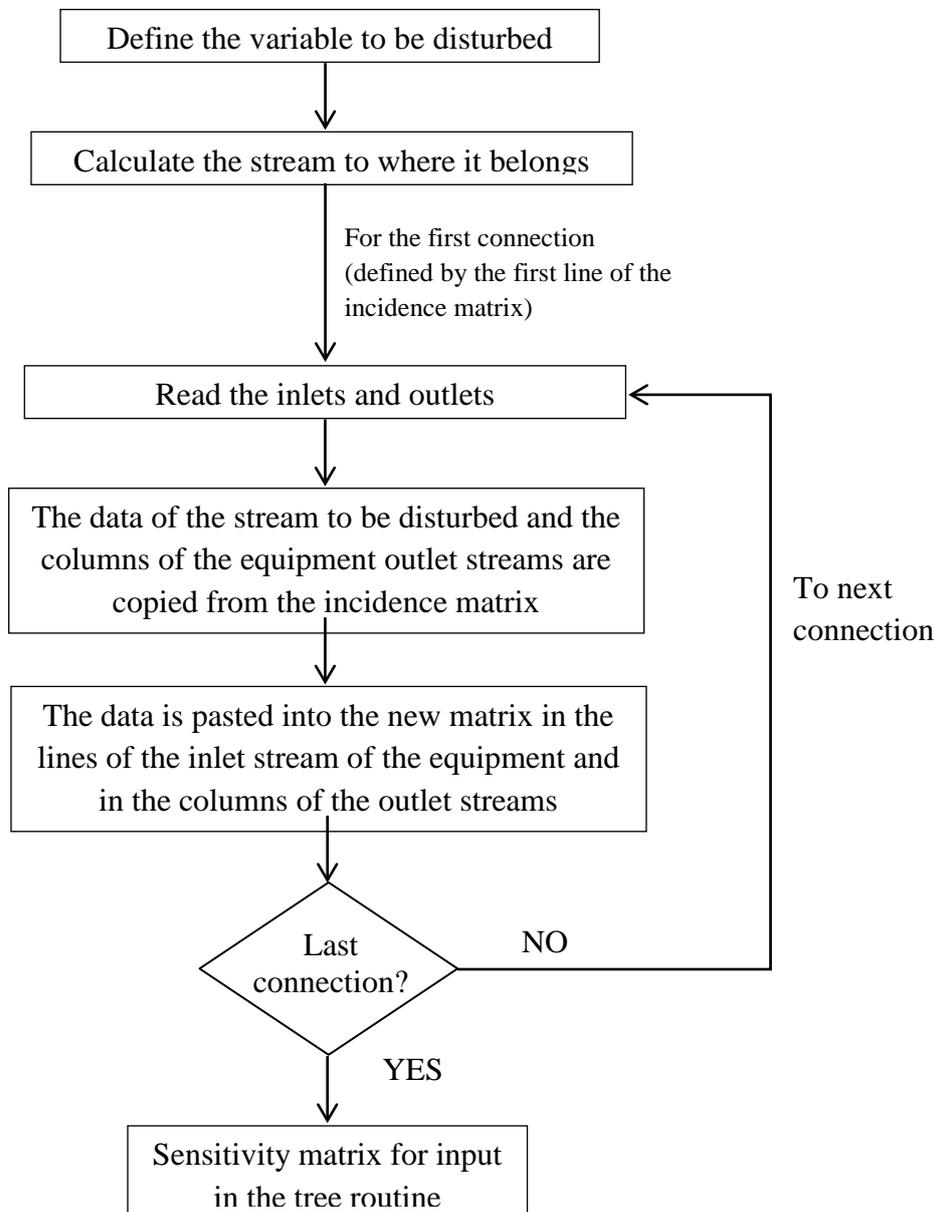
Source: Author, 2018

The flowchart Figure 3.2 below summarizes this procedure for reorganization of the sensitivity matrix and elaboration of the incidence matrix.

Exemplifying for the Figure 3.1 example, the stream S1 arrives at the equipment A, and the stream S2 leaves it. With this information, the program will search the squared sensitivity matrix for the streams to be disturbed, in this case the stream S1 (lines S1F, S1P and S1T), since it is the only one that can be altered. After identifying such lines, the program will record all the responses of the stream S2 to the disturbances generated in the stream S1.

As a matter of organization, these data are reallocated in a new matrix of dimension equal to the sensitivity matrix.

Figure 3.2 – Procedure for reorganization of the sensitivity matrix



Source: Author, 2018

The program then returns to the incidence matrix, searching for the next equipment in the sequence, which in this case will be Equipment B. It can be seen that stream S2 enters and stream S3 leaves this same equipment. The program will now look in the square sensitivity matrix for the S3 stream responses. These responses will then be allocated in the final matrix in the lines referring to stream 2. In practice, it is a cascading process, where layers of

influence will be obtained, from the disturbance to the final output of the process. The resulting matrix is used so that the computational code generates the influence trees.

A comparison was then made between the approach described in this section and the classic HazOp spreadsheet, showing the advantages and disadvantages of each approach and how they can be integrated to generate a more complete hazard analysis. The procedures described in this section were applied to three systems:

- a) A liquid nitrogen flash pot (system described in section 2.3.1)
- b) A raw gas pumping system(system described in section2.3.2)
- c) A complex CO₂ purification and liquefaction unit (system described in section2.3.3)

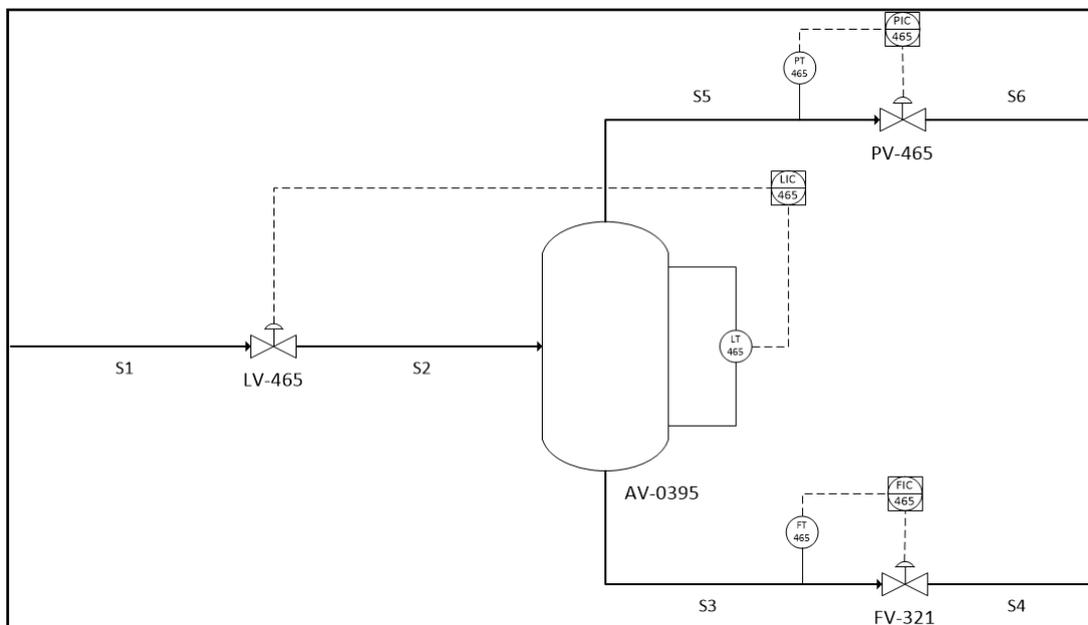
Trees generation was also performed with algorithm described previously in Figure 2.22.

3.3 Results

3.3.1. Case Study 1 – Liquid Nitrogen Flash Pot

This process was described in section 2.3.1. For clarity, some information are presented here again. In this process, a liquid nitrogen stream passes through an automatic valve and enters a flash vessel, from where there will be a withdrawal of nitrogen gas at the top and another of liquid nitrogen at the bottom. The process counts with a level control acting in the feeding of the vessel, a pressure control in the top gas stream and a flow control in the bottom outlet stream. Such system can be seen in Figure 2.24.

Figure 2.24 – Liquid Nitrogen Flash Pot



Source: Author, 2018

A classical HazOp analysis was developed for this system, and was presented in 2.3.1, in Table 2.3.

As mentioned before, the objective was to identify through the use of a process software if the same qualitative relations raised in classical HazOp analyzes were covered by mathematically calculated results. The following sensitivity matrices (Table 3.4 and Table 4.5) were obtained from sensitivity analysis of the system, according to the procedure detailed in the previous chapter.

Table 3.4 – Sensitivity Matrix – LN2 Flash Pot – Positive Disturbances

S1 T	S1 P	S1 F	S2 T	S2 P	S2 F	S5 T	S5 P	S5 F
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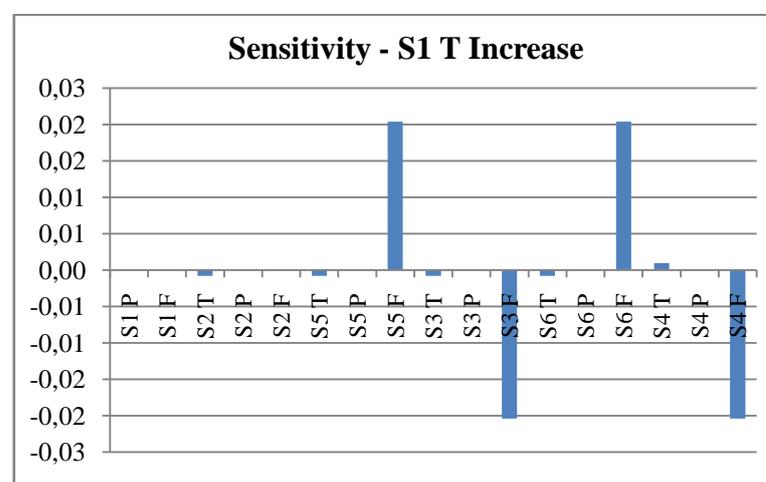
S1 T	1,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02
S1 P	0,00	1,00	0,00	0,06	1,00	0,00	0,06	1,00	0,00
S1 F	0,00	0,00	1,00	0,00	0,00	1,00	0,00	0,00	0,15
	S3 T	S3 P	S3 F	S6 T	S6 P	S6 F	S4 T	S4 P	S4 F
S1 T	0,00	0,00	-0,02	0,00	0,00	0,02	0,00	0,00	-0,02
S1 P	0,06	1,00	0,00	0,07	1,00	0,00	0,11	1,00	0,00
S1 F	0,00	0,00	0,85	0,00	0,00	0,15	0,00	0,00	0,85

Table 3.5 – Sensitivity Matrix – LN2 Flash Pot – Negative Disturbances

	S1 T	S1 P	S1 F	S2 T	S2 P	S2 F	S5 T	S5 P	S5 F
S1 T	-1,00	0,00	0,00	-3,09	0,00	0,00	-3,09	0,00	-0,44
S1 P	0,00	-1,00	0,00	0,69	-1,00	0,00	0,69	-1,00	0,15
S1 F	0,00	0,00	-1,00	0,00	0,00	-1,00	0,00	0,00	-0,15
	S3 T	S3 P	S3 F	S6 T	S6 P	S6 F	S4 T	S4 P	S4 F
S1 T	-3,09	0,00	0,44	-3,11	0,00	-0,44	0,00	0,00	0,44
S1 P	0,69	-1,00	-0,15	0,70	-1,00	0,15	-0,12	-1,00	-0,15
S1 F	0,00	0,00	-0,85	0,00	0,00	-0,15	0,00	0,00	-0,85

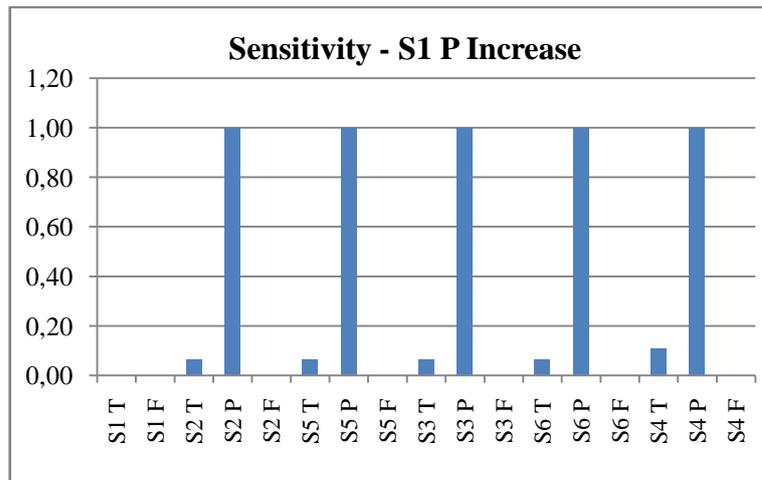
The results of these matrices can also be represented graphically, as follows in Figure 3.3 to Figure 3.5.

Figure 3.3 – Sensitivity for S1T increase



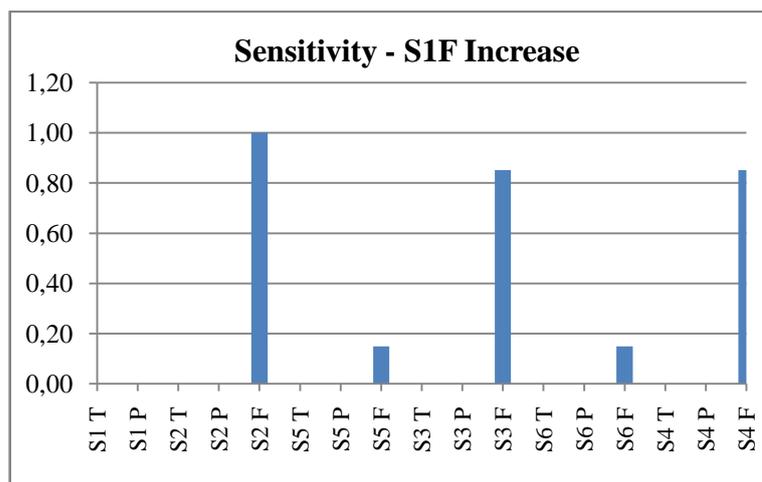
Source: Author, 2018

Figure 3.4 – Sensitivity for S1P increase



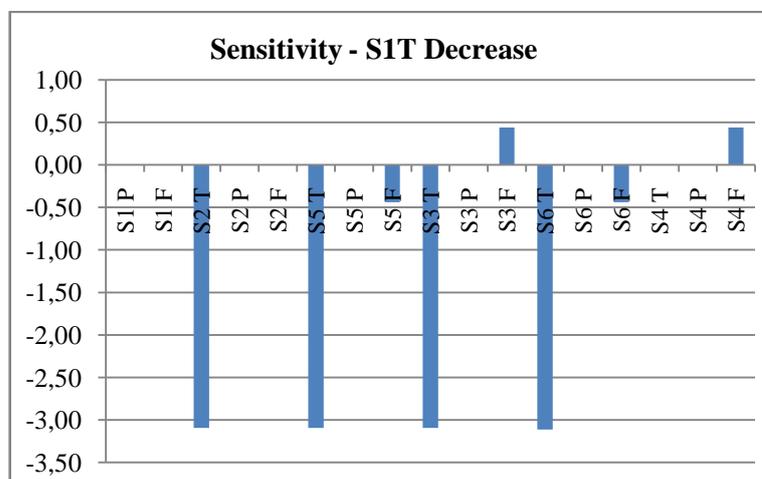
Source: Author, 2018

Figure 3.5 – Sensitivity for S1F increase



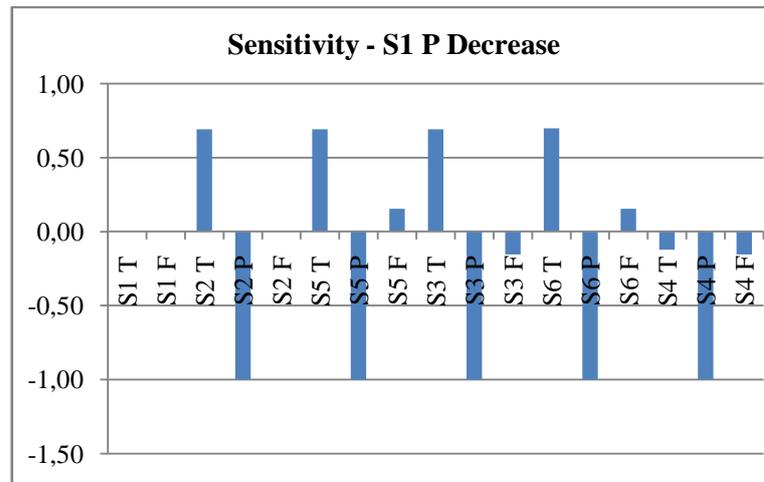
Source: Author, 2018

Figure 3.6 – Sensitivity for S1T decrease



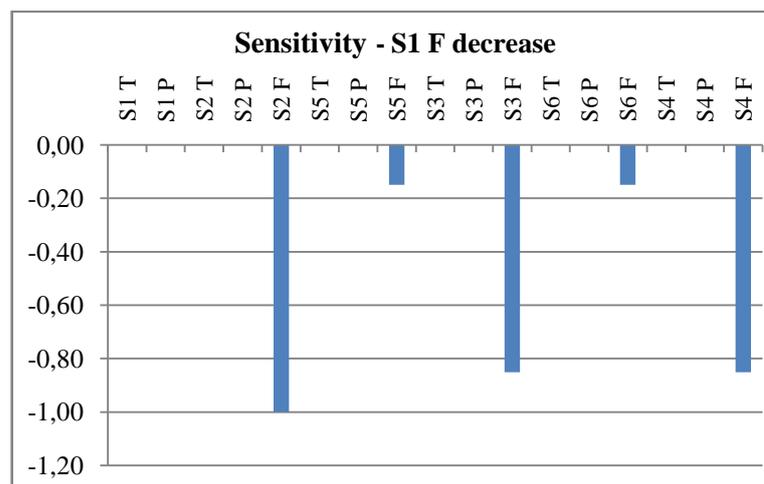
Source: Author, 2018

Figure 3.7 – Sensitivity for S1Pdecrease



Source: Author, 2018

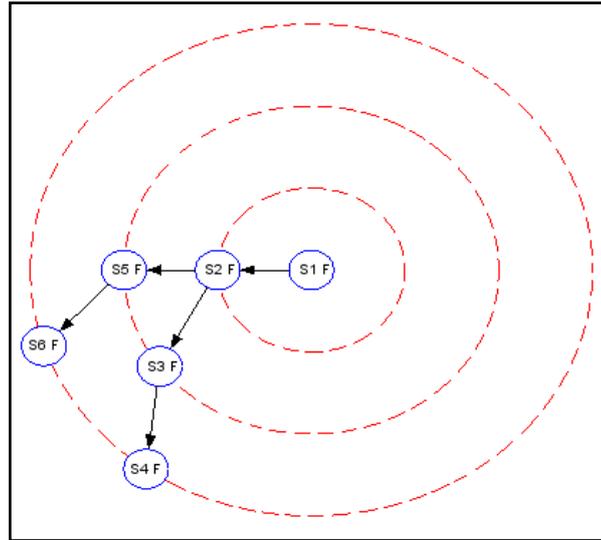
Figure 3.8 – Sensitivity for S1Fdecrease



Source: Author, 2018

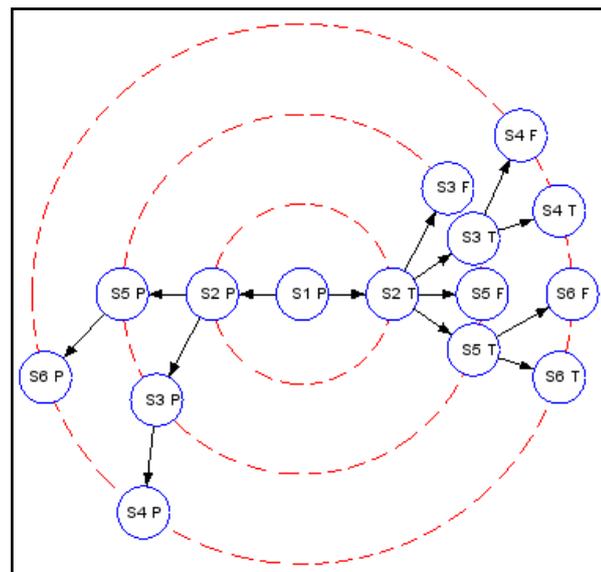
In addition, consequence trees can be obtained automatically with the developed computational routine (Figure 3.9 to Figure 3.14).

Figure 3.9 – S1F Increase – Flash Pot



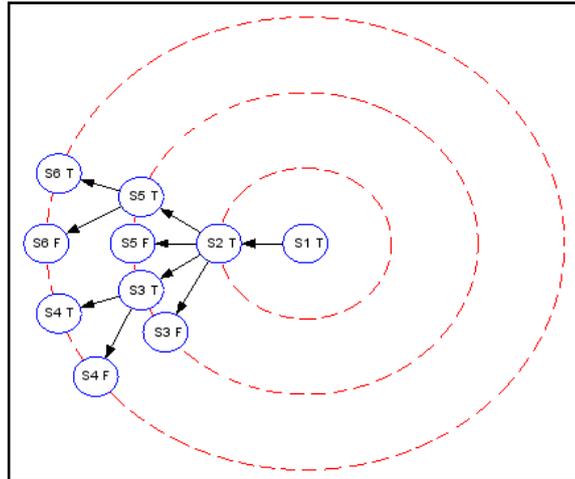
Source: Author, 2018

Figure 3.10 – S1P Increase – Flash Pot



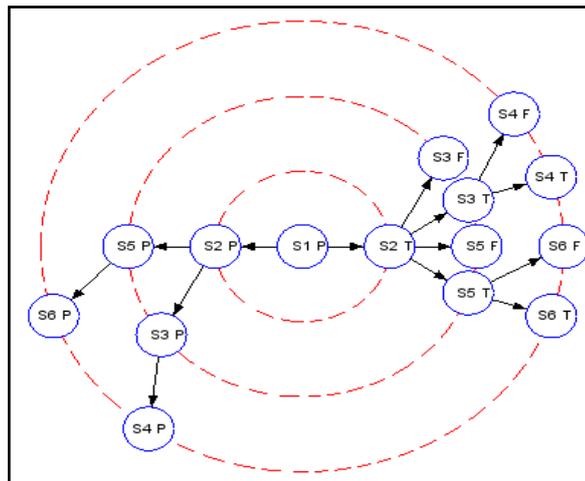
Source: Author, 2018

Figure 3.11 – S1T Increase – Flash Pot



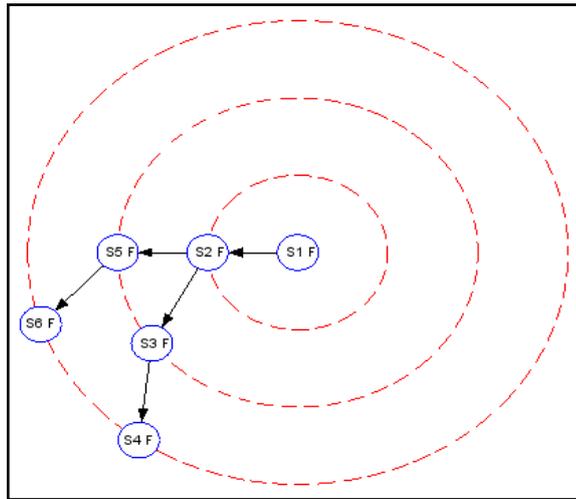
Source: Author, 2018

Figure 3.12 – S1P Increase – Flash Pot



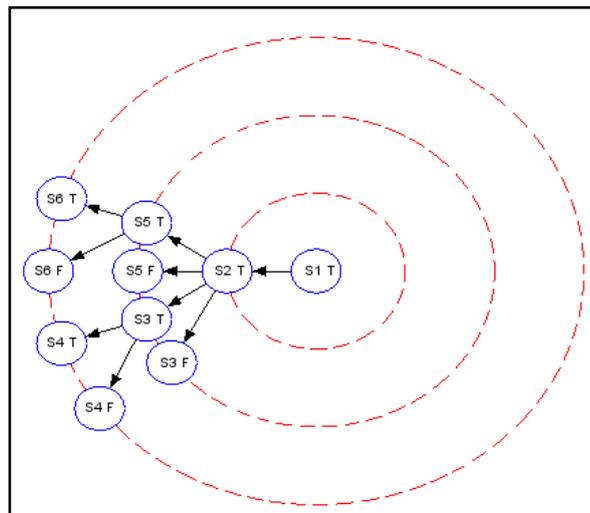
Source: Author, 2018

Figure 3.13 – S1F Decrease – Flash Pot



Source: Author, 2018

Figure 3.14 – S1T Decrease – Flash Pot



Source: Author, 2018

From this collection of data, detailed analysis of each procedure can be done.

With respect to an increase in feed rate, the sensitivity matrix obtained through the stationary simulation showed influence only on the liquid and gas outlet flows in the flash pot, with the liquid outlet being the most sensitive to this disturbance. By the simulation, there would be no variations in the pressure and level in case of a sudden increase in inlet flow. This is a disadvantage of the steady state simulation, which does not allow an observation of the change of pressure and level of equipment. This deviation is equivalent to the one discussed in the scenario 1.5 of the HazOp spreadsheet, where an opening higher than desired

is considered for the LV-465. However, in the classical HazOp analysis, a change in the level and pressure were considered for this particular scenario.

An analogous discussion can be made with regard to a decrease in feed flow. In this case, the sensitivity matrix also showed influence only in the liquid and gas outlet flows in the flash pot, with the liquid outlet being the most sensitive to this disturbance. This result is again complementary to the one demonstrated in scenario 1.2 of Table 2.3, where a "no flow" scenario, caused by a failure of the LV-465 is studied. This absence of flow by the LV-465 is equivalent to the reduction of the feeding rate studied in the sensitivity matrices.

As it is a more complete analysis of the whole system, the classic HazOp study shows all the protections, severity and frequency for the studied scenario, which is not addressed in the sensitivity matrices, which focus only on a cause and consequence relation. It is important to point out that even though it does not show 100% identical results to that of a classic HazOp for these scenarios of increase and decrease of S1F, the matrices obtained by the simulation are contained in these results and help to demonstrate how much some of the variables are affected by the perturbation in question, reducing the purely qualitative character of the analysis.

With regard to an increase in the feed pressure, the sensitivity results show an increase in all the gas and liquid outlets of the equipment, in addition to a practically negligible temperature increase. This increase in pressure was calculated as having the same sensitivity in all streams, which may deviate somewhat from what occurs in practice. This happens because the stationary simulation contains the pressure and pressure drops in valves already specified, and with a change in the inlet pressure, what the program does is only to recalculate these pressures based on the specified pressure drops. This helps to explain the identical value of sensitivity for all pressures. Although this value may vary in practice, the cause-consequence relationship shown by the stationary simulation was correct. In the classic HazOp spreadsheet, a decrease in inlet stream pressure was not explicitly included in the study, since it was considered that this deviation would be included in cause 1.1, no flow from the upstream node, which is perfectly acceptable from classic HazOp standpoint. An analogous reasoning can be applied for an increase in S1P feed pressure. An increase in feed temperature caused an unbalance in the outlet streams of the equipment, with an increase in gas flow and a decrease in liquid flow, which would be expected from a process point of view for this system. The sensitivity of the flow rates was significantly higher than the temperature sensitivity in this deviation. The classic HazOp spreadsheet did not take such a scenario into consideration, probably because the team responsible for the analysis did not give credit to

this scenario in question. Even the system having all the necessary protections for these deviations, here we can note a possible contribution of the simulation in obtaining results. Similar approach can be made for a low temperature.

A significant drawback of steady-state simulation is that deviations could be inserted only into the input streams of the overall envelope of the system. This occurs because all other streams are responses from the inlets of the system and cannot be modified. This ends up limiting the contribution of the analysis by stationary simulations, since deviations from the outlet streams cannot be studied.

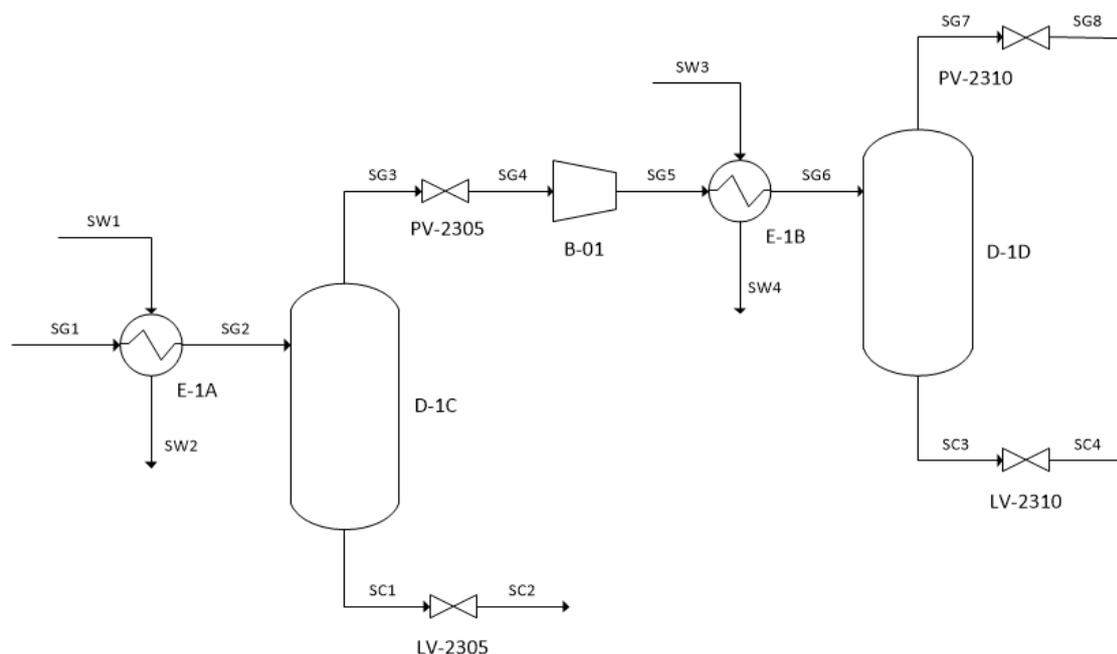
Another important aspect is that scenarios related to operational issues could be captured only by classic HazOp, not by the matrices. This could be evidenced from causes 1.8, 1.9, 1.10 and 1.11 of Table 2.3, where deviations resulting from actions of control logics and human action were studied. The following case presents a greater degree of complexity, where other aspects can be noticed.

3.3.2. Case Study 2 – Raw Gas Pumping System

This system was described in section 2.3.2, but for clarity some information will be presented here. In this system, a gaseous stream rich in CO₂ and water vapor is received from a source at low pressure, but at elevated temperature. This current passes through the shell-and-tube heat exchanger E-1A, where it is cooled with a stream of water. Such cooling will condense part of the water vapor contained in the stream, which will then be collected and separated from the gaseous stream in the separating vessel D-1C. The condensate will be withdrawn by the automatic valve LV-2305 and the gas stream will continue in the process through the PV-2305, passing through the centrifugal blower B-01, which will raise the pressure of this stream. With increasing pressure, there will also be an increase in temperature, and that heat will be removed in the E-1B heat exchanger, also with cooling water. This second cooling stage will cause another portion of the water vapor to condense and then to be withdrawn into the D-1D vessel, equally to the D-1C operation. The CO₂ enriched stream, yet with other non-condensable contaminants, will follow a gas pipeline to a purification and liquefaction plant.

Thus, the main purpose of this pumping system is to supply pressure and remove moisture from the raw gas and then feed this gas to the pipeline that will follow to a CO₂ production unit. Such a process can be seen in Figure 2.30 below, in a simplified manner, omitting controls and manual and safety valves, for ease of viewing.

Figure 2.30 – Raw gas pump system



Source: Author, 2018

A classical HazOp analysis was developed for this system, as presented in 2.3.2.

Regarding the stationary simulation, disturbances could be forced in the currents SG1 (raw gas supply), SW1 (cooling water supply for the E-1A heat exchanger) and SW3 (cooling water supply for the E-1B heat exchanger), which are all streams that reach the global envelope of the system and can have their flow (F), pressure (P) and temperature (T) modified. Following are the sensitivity matrices obtained for the raw gas pumping system (Table 3.6 and Table 3.7)

Table 3.6 – Sensitivity Matrix – Pumping system – Positive Disturbances

	SG1 T	SG1 P	SG1 F	SW1 T	SW1 P	SW1 F	SG2 T	SG2 P	SG2 F	SW2 T	SW2 P	SW2 F
SG1 T	1,00	0,00	0,00	0,00	0,00	0,00	0,10	0,00	0,00	0,11	0,00	0,00
SW1 T	0,00	0,00	0,00	1,00	0,00	0,00	0,96	0,00	0,00	0,90	0,00	0,00
SW3 T	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SG1 P	0,00	1,00	0,00	0,00	0,00	0,00	-0,32	1,00	0,00	-0,07	0,00	0,00
SW1 P	0,00	0,00	0,00	0,00	1,00	0,00	0,00	0,00	0,00	0,00	1,00	0,00
SW3 P	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SG1 F	0,00	0,00	1,00	0,00	0,00	0,00	4,77	0,00	1,00	1,07	0,00	0,00
SW1 F	0,00	0,00	0,00	0,00	0,00	1,00	-0,06	0,00	0,00	-0,11	0,00	1,00
SW3 F	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

	SG3 P	SG3 F	SG4 T	SG4 P	SG4 F	SG5 T	SG5 P	SG5 F	SW3 T	SW3 P	SW3 F	SG6 T
SG1 T	0,00	0,00	0,10	0,00	0,00	0,12	0,00	0,00	0,00	0,00	0,00	0,04
SW1 T	0,00	0,01	0,96	0,00	0,01	1,18	0,00	0,01	0,00	0,00	0,00	0,43
SW3 T	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	0,00	0,00	0,85
SG1 P	1,00	0,00	-0,32	1,00	0,00	-1,04	1,00	0,00	0,00	0,00	0,00	-0,21
SW1 P	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SW3 P	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	0,00	0,00
SG1 F	0,00	0,87	4,77	0,00	0,87	5,91	0,00	0,87	0,00	0,00	0,00	4,39
SW1 F	0,00	0,00	-0,06	0,00	0,00	-0,07	0,00	0,00	0,00	0,00	0,00	-0,03
SW3 F	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	-0,30

	SW4 F	SG7 T	SG7 P	SG7 F	SC3 T	SC3 P	SC3 F	SC2 T	SC2 P	SC2 F	SC4 T	SC4 P
SG1 T	0,00	0,04	0,00	0,00	0,04	0,00	0,00	0,10	0,00	0,00	0,04	0,00
SW1 T	0,00	0,43	0,00	0,00	0,43	0,00	0,01	0,96	0,00	-0,01	0,43	0,00
SW3 T	0,00	0,85	0,00	0,00	0,85	0,00	0,00	0,00	0,00	0,00	0,85	0,00
SG1 P	0,00	-0,21	1,00	0,00	-0,21	1,00	0,00	-0,32	1,00	0,00	-0,21	1,00
SW1 P	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SW3 P	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SG1 F	0,00	4,39	0,00	0,82	4,39	0,00	0,05	4,77	0,00	0,13	4,39	0,00
SW1 F	0,00	-0,03	0,00	0,00	-0,03	0,00	0,00	-0,06	0,00	0,00	-0,03	0,00
SW3 F	1,00	-0,30	0,00	0,00	-0,30	0,00	0,00	0,00	0,00	0,00	-0,30	0,00

Source: Author, 2018

Table 3.7 – Sensitivity Matrix – Pumping system – Negative Disturbances

	SG1 T	SG1 P	SG1 F	SW1 T	SW1 P	SW1 F	SG2 T	SG2 P	SG2 F	SW2 T	SW2 P	SW2 F
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SG1 T	-1,00	0,00	0,00	0,00	0,00	0,00	-1,31	0,00	0,00	-0,39	0,00	0,00
SW1 T	0,00	0,00	0,00	-1,00	0,00	0,00	-0,96	0,00	0,00	-0,90	0,00	0,00
SW3 T	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SG1 P	0,00	-1,00	0,00	0,00	0,00	0,00	0,18	-1,00	0,00	0,04	0,00	0,00
SW1 P	0,00	0,00	0,00	0,00	-1,00	0,00	0,00	0,00	0,00	0,00	-1,00	0,00
SW3 P	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SG1 F	0,00	0,00	-1,00	0,00	0,00	0,00	-4,80	0,00	-1,00	-1,09	0,00	0,00
SW1 F	0,00	0,00	0,00	0,00	0,00	-1,00	0,06	0,00	0,00	0,11	0,00	-1,00
SW3 F	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

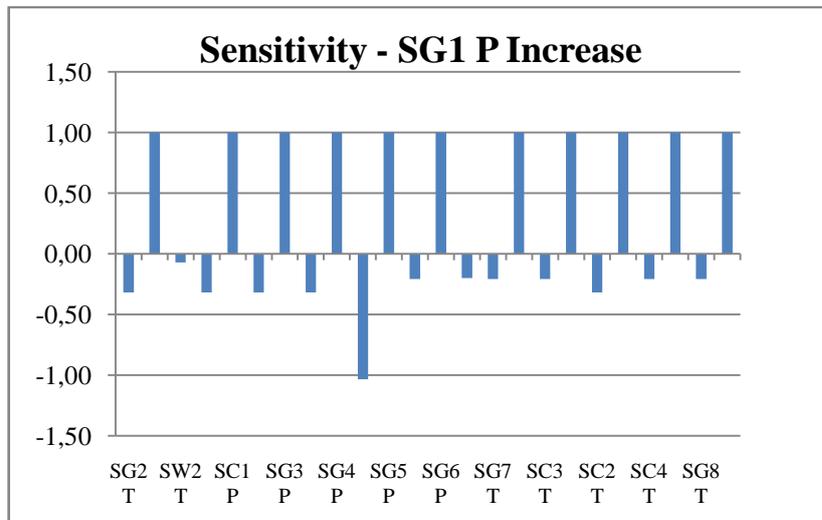
	SG3 P	SG3 F	SG4 T	SG4 P	SG4 F	SG5 T	SG5 P	SG5 F	SW3 T	SW3 P	SW3 F	SG6 T
SG1 T	0,00	-0,01	-1,31	0,00	-0,01	-1,62	0,00	-0,01	0,00	0,00	0,00	-0,53
SW1 T	0,00	-0,01	-0,96	0,00	-0,01	-1,18	0,00	-0,01	0,00	0,00	0,00	-0,41
SW3 T	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-1,00	0,00	0,00	-0,85
SG1 P	-1,00	0,00	0,18	-1,00	0,00	0,89	-1,00	0,00	0,00	0,00	0,00	0,16
SW1 P	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SW3 P	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-1,00	0,00	0,00
SG1 F	0,00	-0,87	-4,80	0,00	-0,87	-5,94	0,00	-0,87	0,00	0,00	0,00	-4,15
SW1 F	0,00	0,00	0,06	0,00	0,00	0,08	0,00	0,00	0,00	0,00	0,00	0,03
SW3 F	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,00	-1,00	0,31

	SW4 F	SG7 T	SG7 P	SG7 F	SC3 T	SC3 P	SC3 F	SC2 T	SC2 P	SC2 F	SC4 T	SC4 P
SG1 T	0,00	-0,53	0,00	0,00	-0,53	0,00	-0,01	-1,31	0,00	0,01	-0,53	0,00
SW1 T	0,00	-0,41	0,00	0,00	-0,41	0,00	-0,01	-0,96	0,00	0,01	-0,41	0,00
SW3 T	0,00	-0,85	0,00	0,00	-0,85	0,00	0,00	0,00	0,00	0,00	-0,85	0,00
SG1 P	0,00	0,16	-1,00	0,00	0,16	-1,00	0,00	0,18	-1,00	0,00	0,16	-1,00
SW1 P	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SW3 P	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SG1 F	0,00	-4,15	0,00	-0,82	-4,15	0,00	-0,05	-4,80	0,00	-0,13	-4,15	0,00
SW1 F	0,00	0,03	0,00	0,00	0,03	0,00	0,00	0,06	0,00	0,00	0,03	0,00
SW3 F	-1,00	0,31	0,00	0,00	0,31	0,00	0,00	0,00	0,00	0,00	0,31	0,00

Source: Author, 2018

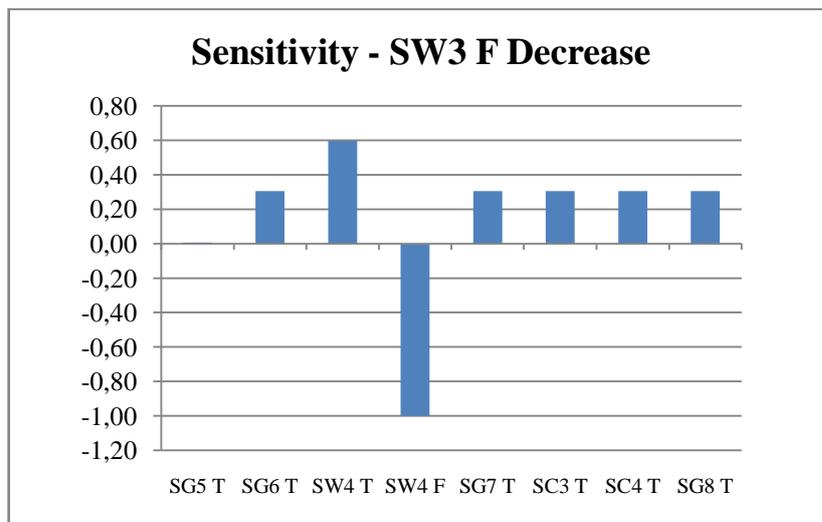
As the range of results is extensive, only a few results will be shown (in Figure 3.15 to Figure 3.20). In addition, the following bar charts show only variables that have relation to

Figure 3.17 – Sensitivity – SG1P Increase



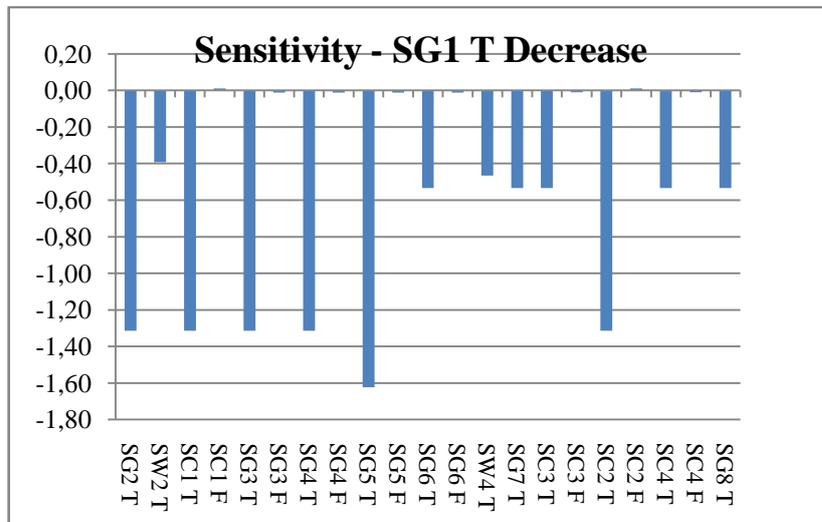
Source: Author, 2018

Figure 3.18 – Sensitivity – SW3F Decrease



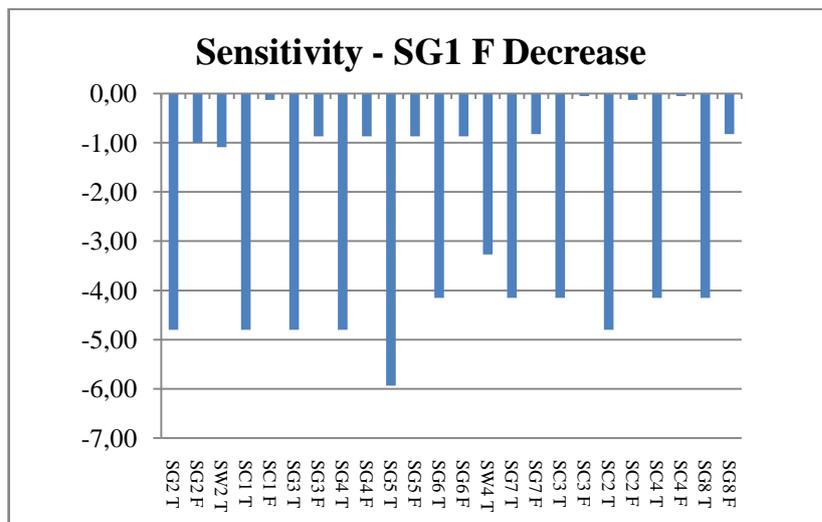
Source: Author, 2018

Figure 3.19 – Sensitivity – SG1 T decrease



Source: Author, 2018

Figure 3.20 – Sensitivity – SG1 F decrease

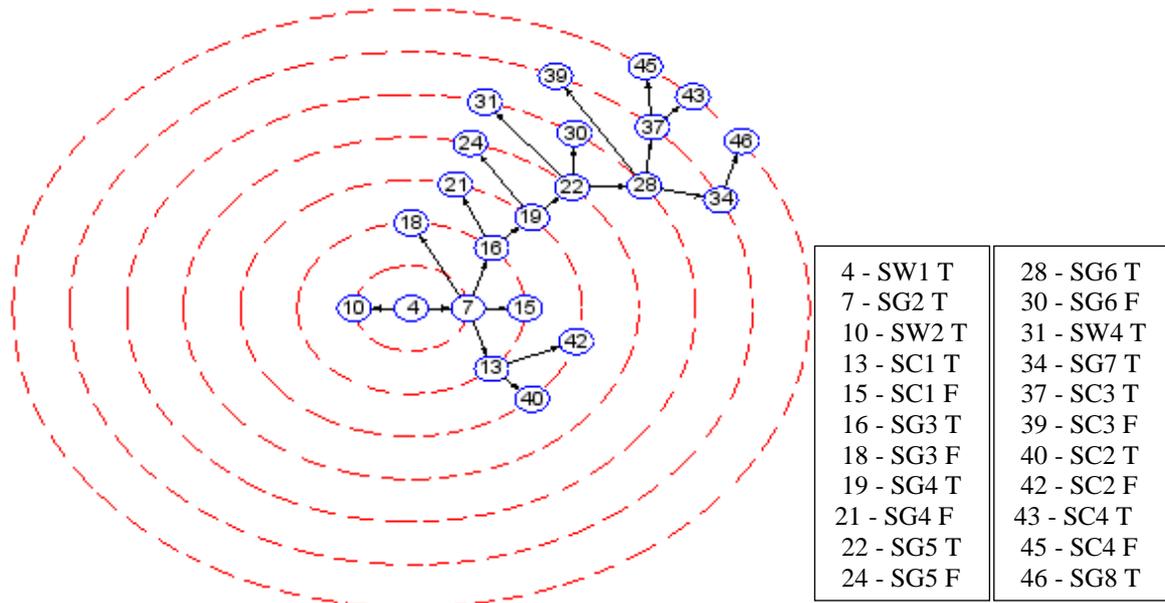


Source: Author, 2018

Such sensitivities can be used to reduce the tree of events from an original disturbance.

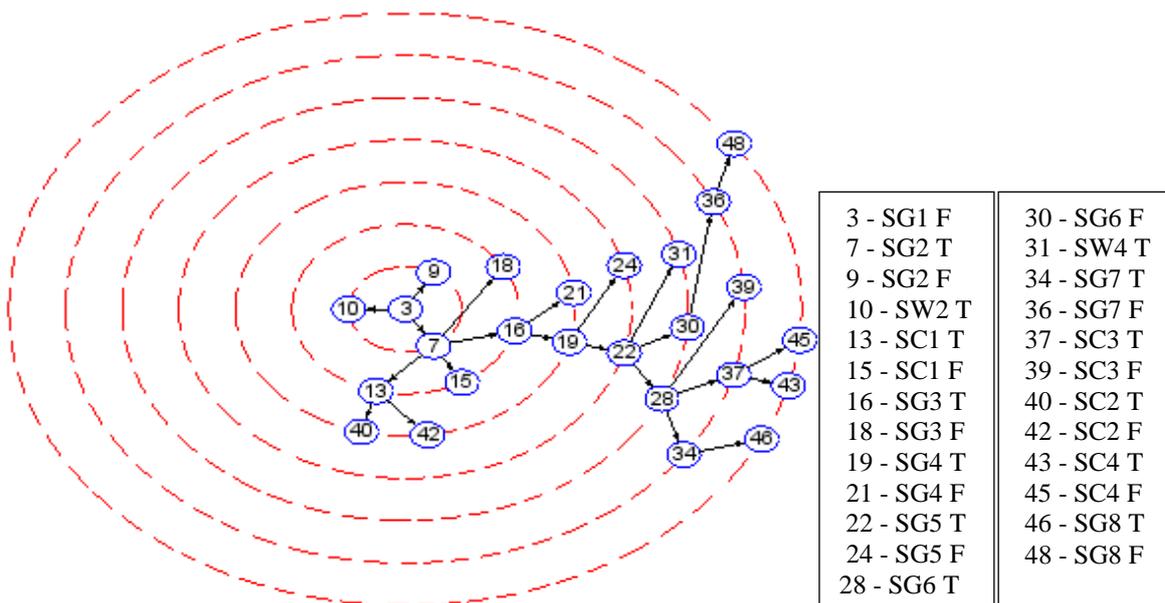
Next, we present some trees automatically generated from sensitivity analysis.

Figure 3.23 – One possible tree from sensitivity analysis SW1 T Increase – Pumping System



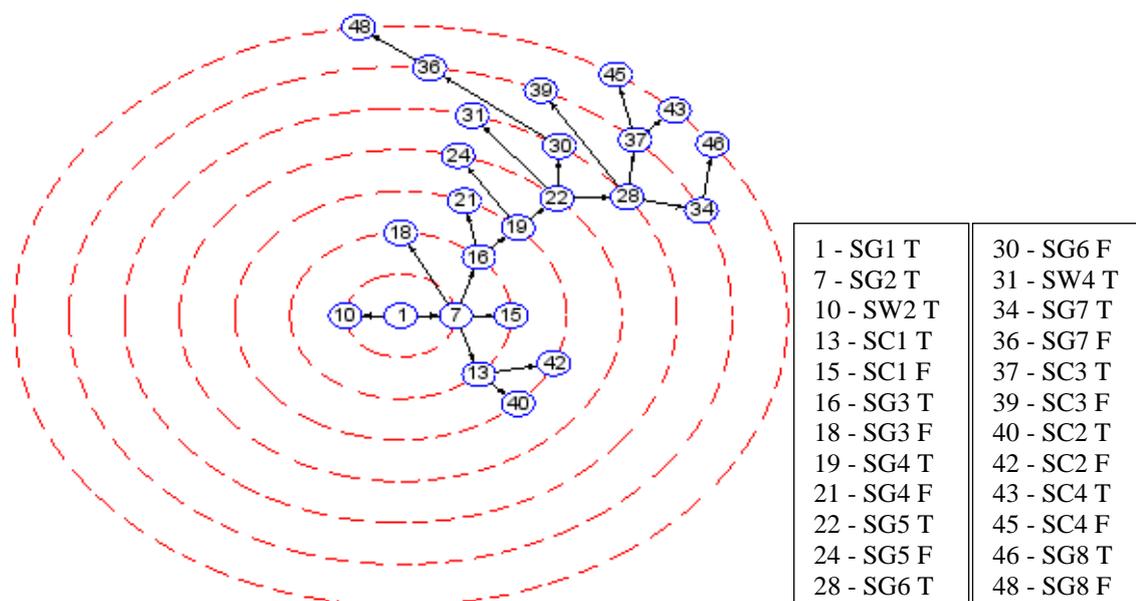
Source: Author, 2018

Figure 3.24 – One possible tree from sensitivity analysis SG1 F Decrease – Pumping System



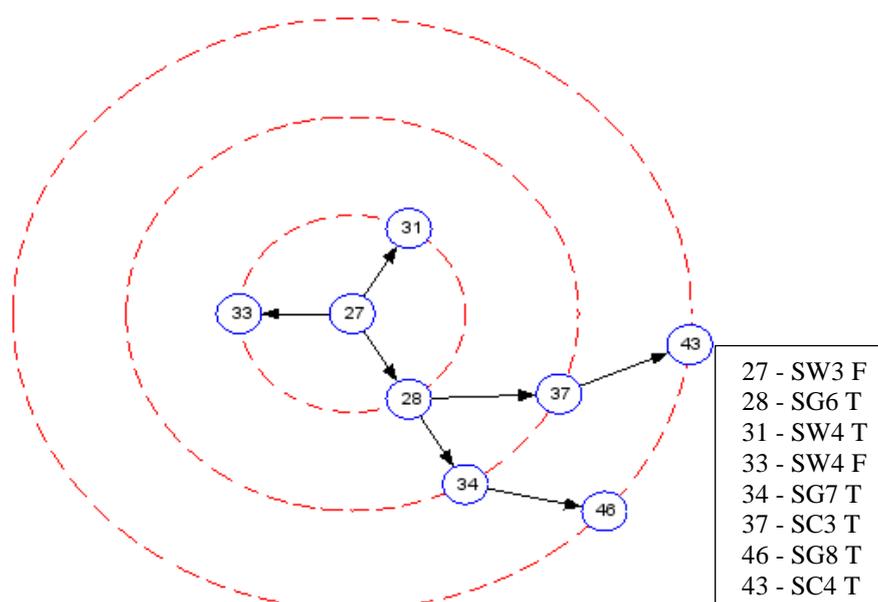
Source: Author, 2018

Figure 3.25 – One possible tree from sensitivity analysis SG1 T Decrease – Pumping System



Source: Author, 2018

Figure 3.26 – One possible tree from sensitivity analysis SW3 F Decrease – Pumping System



Source: Author, 2018

From the data obtained, some discussions and comparisons can be made:

It can be seen that a rise in temperature of the cooling water generated a change in all temperatures of the process gas streams after the E-1A heat exchanger and the outlet temperatures of the cooling water streams. In the original HazOp, a temperature increase was

also identified, however related only to an absence of cooling water flow and not to a temperature rise of the same, which is a possible scenario depending on the daytime temperature and atmospheric conditions. Here one can see a point where complementary analysis through stationary simulations can add information to a classical study.

An increase in SG1F caused an increase in the temperatures and flow rates of the streams in the process sequence. However, similarly to what happened in the nitrogen flash pot, this increase in flow of one of the process streams did not have any impact on the level of the separating vessels, which presents an inconsistency with reality and demonstrates a weakness of this approach. This high flux was not analyzed in the original HazOp study, because this hazard was probably not taken into account by the participating team. Even with this weakness when we approach the variable level, again this approach demonstrates that it can aid in the search for possible hazards in the process.

Regarding an increase in the inlet pressure in the system, the approach once again shows a sensitivity equal to 1 for all streams subsequent to SG1, because the program simply recalculates the pressures of a new steady state based on the estimated pressure drops on each equipment and valve. In the classic HazOp study, this pressure increase was identified in cause 1.5 at node 1. In addition, it was also identified in cause 2.9, now for node 2.

A decrease in the cooling water feed rate in the E-1B exchanger (stream SW3) also generated an increase in the stream temperatures at the exit of this exchanger and in the process sequence, going exactly to scenario 2.7 of the classic HazOp for the system. However, the approach provides a sensitivity analysis and shows that the most impacted variable is the temperature at the cooling water outlet of the heat exchanger in question.

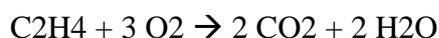
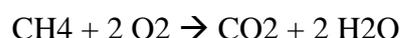
In relation to a decrease of SG1T, all the temperatures of the process streams downstream thereof also suffer a decrease. However, as expected, no impact is shown at the level of the vessels. For the classical HazOp study, no credit was given for a lower raw gas feed temperature. Finally, a decrease in SG1F will have the opposite effects to the increase in SG1F explained in this session.

It is important to point out that HazOp can identify deviations in the middle of the process, which cannot be forced in the stationary simulations, thus limiting its use. In addition, classic HazOps can deal with specific operational issues that are outside a process simulation (for example, vent valves that are unduly open, leading to a leak). In addition, it is also noticed that when the complexity of the system increases, the limitation of the use of the stationary simulation is more evident, because although there are more currents, we can only

change those that enter the global envelope of the process, which is treated as a single node, when the plant is simulated in its entirety.

3.3.3. Case Study 3 - CO₂ Purification and Liquefaction Plant

This system was presented in section 2.3.3, but some information will be repeated here. In this plant Figure 2.32, a gaseous stream enriched in CO₂ flows through a cooler in order to condensate part of the water in the stream. After that, the water will be collected in a collector vessel, with the gaseous stream flowing on the top. This gas is compressed and then mixed with a 99,9% gaseous oxygen stream. This mixture is fed to a catalytic oxidizer reactor (catox), which is filled with a catalyst which will promote the oxidation reaction of some hydrocarbons present in the stream. With this, more CO₂ will be formed, with water being the by-product. The main reactions considered are the following.

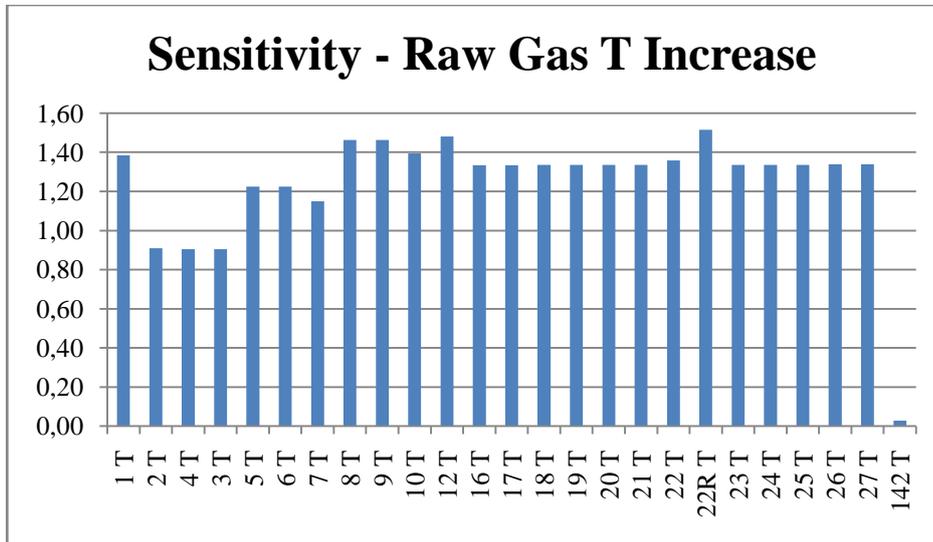


All the above reactions are exothermic, and then the outlet stream, now with a temperature above 400 ° C, is then used to preheat the charge of this reactor in the E-03, the cross heater. Even with this thermal exchange after the exit of the catox, a second stage of cooling is necessary, and it is done in the E-4 heat exchanger, the catox aftercooler. Similarly to the beginning of the process, some of the water present in the stream is condensed. and collected in a new collector vessel. Part of the gaseous stream leaving this last vessel is then divided: part is fed to the catox recycle blower, and another that will pass through another cooling battery.

The purpose of the recycle blower is to assist in the temperature adjustment of the catox, since its inlet stream has a lower temperature and will mix with the inlet stream of the catox, previous to the cross heater. The other stream, which passed through the cooling battery, is then sent to the distillation column D-14, where liquid CO₂ is obtained in the bottom, and gaseous CO₂, along with some contaminants, such as oxygen, methane, and water, is vented into the top. The liquid CO₂ is then cooled in the sub cooler to be stored in the ST-01 tank. Part of the bottom stream of the distillation column is vaporized and returns

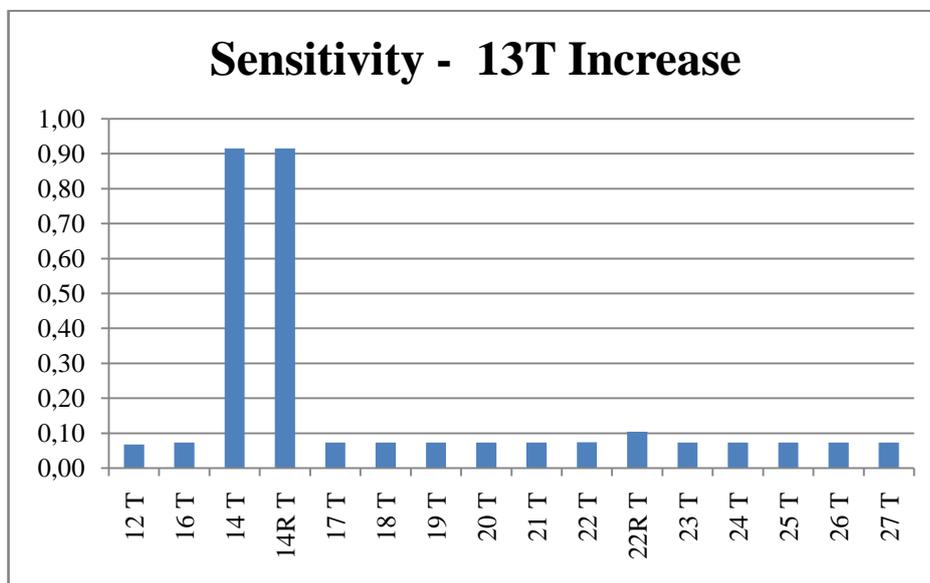
to the beginning of the process. Ammonia is coolant used in this process. The HazOp was already presented in 2.3.3. From Figure 3.27 to Figure 3.31, some sensitivity results are presented.

Figure 3.27 –Sensitivity for Raw Gas T Increase



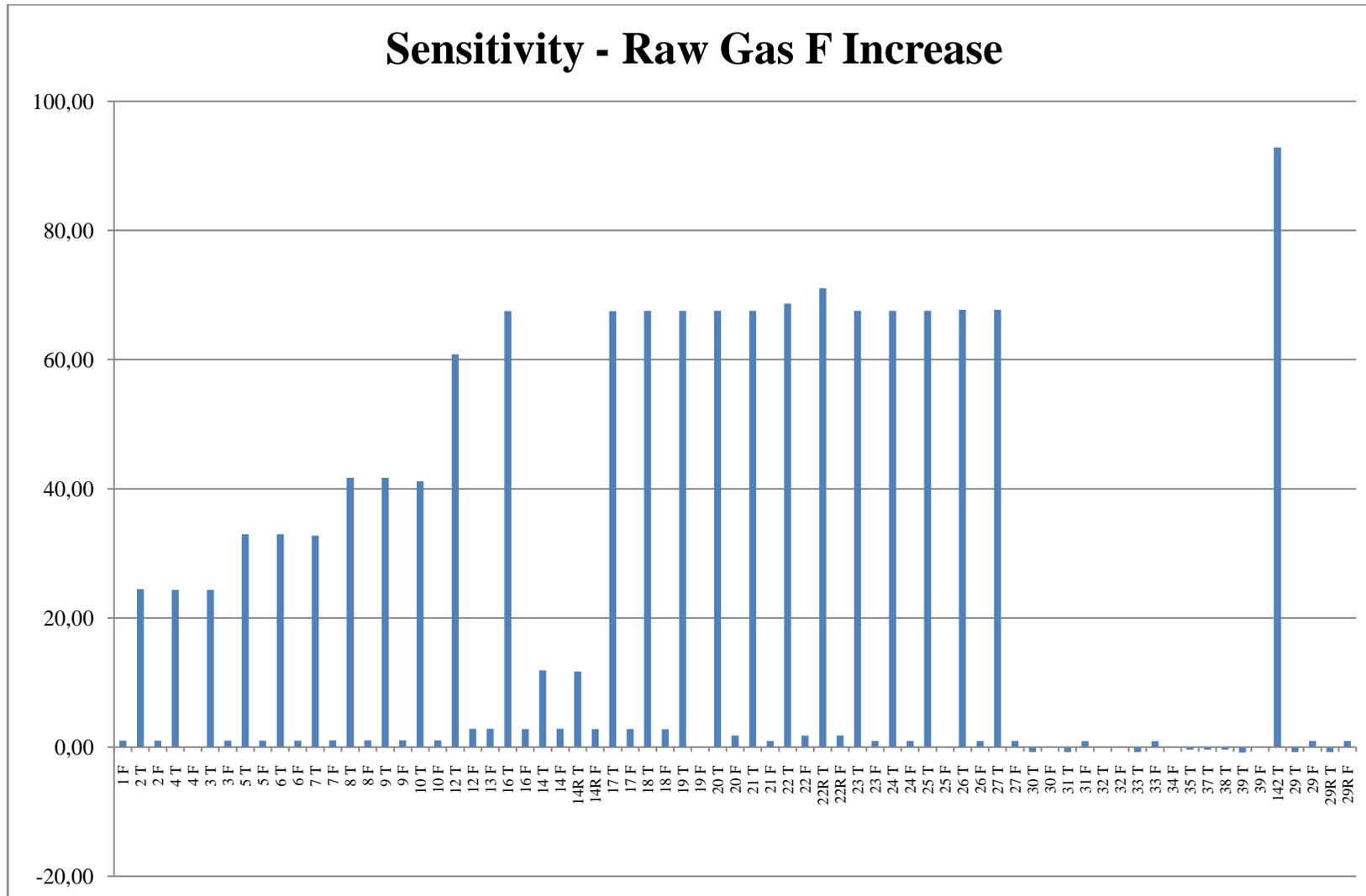
Source: Author, 2018

Figure 3.28 –Sensitivity for 13T Increase



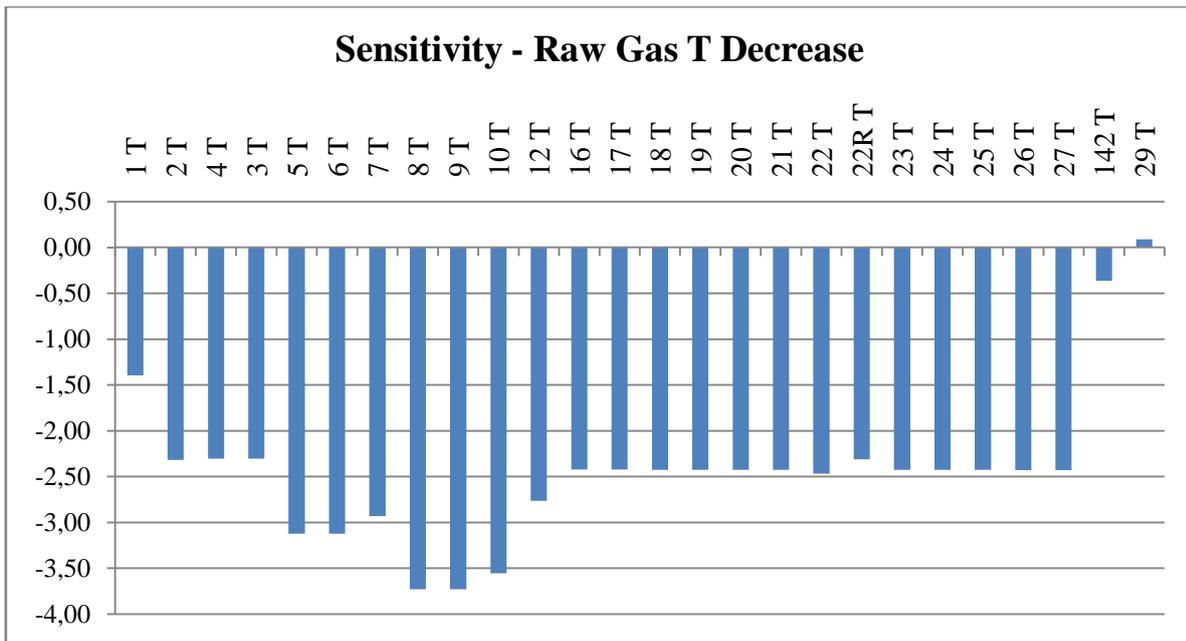
Source: Author, 2018

Figure 3.29 –Sensitivity for RGF Increase



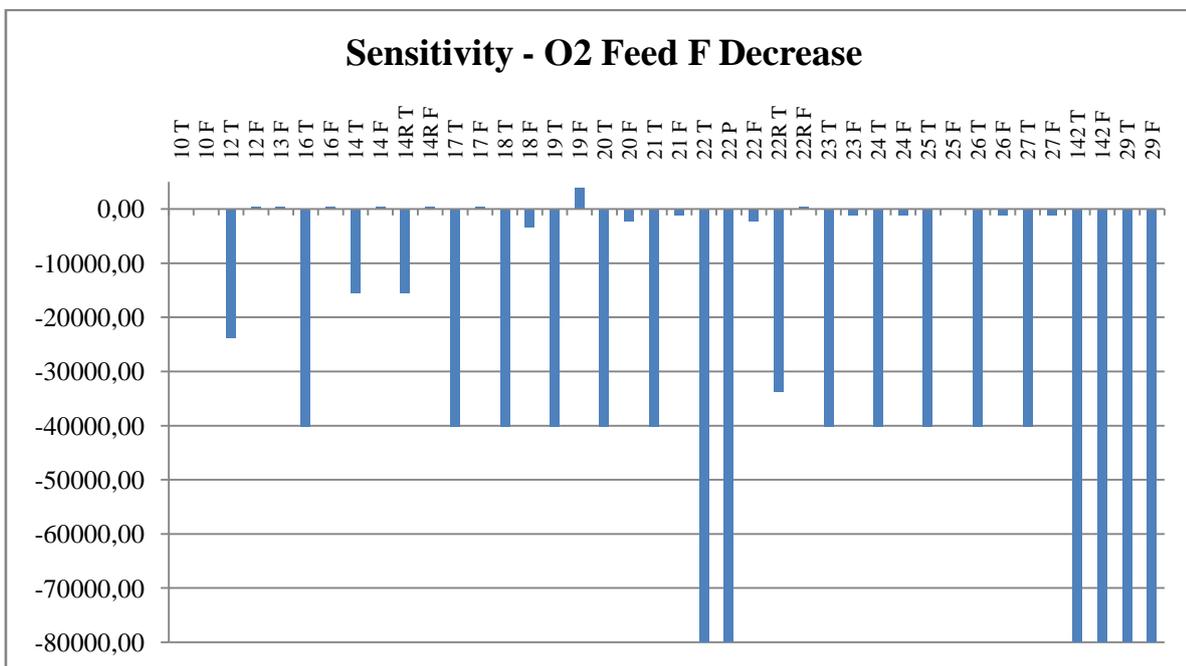
Source: Author, 2018

Figure 3.30 –Sensitivity for RGT Decrease



Source: Author, 2018

Figure 3.31 –Sensitivity for O2 Feed Decrease



Source: Author, 2018

Through this collection of results, some other analysis can be made.

It's possible to observe that with an increase in the raw gas temperature, the more pronounced response was an increase in the temperature in the middle portion of the process, beginning in the CO₂ compressor, going through the cross heater, the catox, aftercooler and recycle blower. However, after reaching the distillation column, no other change happened, indicating the equipment served as a damping for the propagation of the initial deviation. When comparing to the classical HazOp, this same scenario was covered in Cause 1.4 of Table 2.21. However, there is a difference between the both consequences found. The HazOp is not mentioning about the temperature increase as a result of the raw gas temperature, probably because the team did not consider that when recording the consequence. It shows again that the developed tool can be a valuable tool that can help project teams in identifying and being aware of process hazards.

When increasing the temperature of the stream at the outlet of the cross-heater E-03, the highest sensitivity was found in the temperature of the stream leaving the catox vessel. It is an expected result, once the chemical reaction conducted inside the vessel is exothermic and with the inlet stream with a higher temperature condition, the outlet will be more impacted. However, again, this effect lost its power after reaching the distillation column D-14. This same event was found in the HazOp study, on cause 2.6, showing an accordance of both approaches, for this particular scenario. Related to an increase in the Raw Gas F, a strong influence in the downstream flows and temperatures can be observed, again, in the middle section of the plant. It was not covered in the original HazOp, as probably the team deemed not feasible. For the decrease of Raw Gas T, an analogous analysis can be done as for the increase. When analyzing the results of the decrease of the O₂ feed flow, some considerations have to be made. In the process, it is known that a less flow of oxygen will affect the reaction in the Catox, once oxygen is one of the reagents. With less oxygen, some of the contaminants hydrocarbons will not be burned, the catox will cool down and contaminants will continue in the process. Qualitatively speaking, the results were in the direction expected. However, when assessing the sensitivity values, it is possible to say they are way above the expected, with values not physically possible to obtain in the real process. On fact that may have led to that is that the software calculations did not adapt well to this specific change, once it is a very complex simulation, with high level recycles and a distillation column. From this study case one can infer that it's possible to obtain reasonable results that can help in hazardous analysis. However, having a whole plant simulated in the same simulation environment may impair the results and reduce their reliability, once the software behavior can be affected by some of the

changes. A strategy to overcome this issue is to split the simulation of the whole process in different environments. With that, a new advantage is also acquired, which is the possibility of imputing deviations in other process streams in different portions of the process. The possibility of modifying only 4 process streams, even with helpful results, is a very limited approach. This reinforces the practice of splitting the system in nodes, as in real HazOps. However, it is totally attainable in simulations also.

3.4 Conclusions

Classical HazOp studies are entirely dependent on the people participating in the study, which can compromise the results obtained if the team does not have enough experience, commitment, time to conduct the study, etc. In addition, classic studies can become considerably expensive depending on the complexity of the process and the amount of people involved. Based on these facts, several attempts to make the HazOp study more practical, with more reliable results, are proposed. In this paper, a tool for sensitivity analysis based on steady-state process simulations was developed. Process simulations can be a useful tool in hazard analysis, since consequences for disturbances can be obtained within the process, based on physical-chemical relations drawn from appropriate process software, which reduces dependence on the HazOp team. In addition to the process simulation, the sensitivity analysis allows us to identify what variables higher influence each other. The tool applied to the case studies of this article allowed to obtain significant sensitivity results for deviations of flow and temperature. This sensitivity analysis approach showed potential in supporting HazOp teams to obtain more accurate results, once the human experience and knowledge is combined with machine knowledge. The use of event trees in HazOp analysis also showed a good potential to support classical studies, once incorrect chain of events can be easily identified and corrected properly.

CONCLUSÃO

A segurança de processos desempenha um papel extremamente importante na indústria, de maneira global. Empresas e associações normativas internacionais têm investido em estudos e pesquisas que garantam a segurança de processos e procedimentos existentes e novos. Seguindo nesta linha, a presente dissertação propôs duas metodologias com o objetivo de auxiliar em análises de HazOp, que é a técnica mais difundida e aplicada mundialmente. Ambas as metodologias propostas apresentaram pontos positivos e negativos. A abordagem que se utiliza de simulações estacionárias permite que processos sejam analisados, sob um ponto de vista fenomenológico, a partir de relações e conceitos de engenharia bem fundamentados, que fazem parte dos softwares de simulações disponíveis no mercado. Além disso, através da análise de sensibilidade, é possível observar quais são as variáveis mais impactadas para cada perturbação. Tal fato diminui a dependência humana no estudo, e ajuda a gerar resultados conceitualmente mais confiáveis. Com isso, constitui uma ferramenta com potencial para auxiliar em estudos de HazOp. Uma limitação importante é o fato de apenas algumas correntes de processo poderem ser perturbadas, devido à estrutura das simulações feitas. Esta particularidade pode limitar o escopo de cenários que podem ser vistos, o que por sua vez irá limitar a análise. Além disso, existem variáveis que não se alteram em uma simulação estacionária, tal como o nível, o que também confere uma limitação. Já a abordagem que realiza uma objetivação do estudo de HazOp, a partir de uma representação matricial, também mostrou resultados coerentes, que podem ajudar em estudos de HazOp. Como principal ponto positivo, destaca-se a possibilidade de gerar desvios em quaisquer partes dos processos, o que aumenta a gama de cenários identificados, e a geração em cadeia das influências, que podem ser visualizadas de forma clara em forma de árvore. Como ponto a ser melhorado, pode-se destacar o fato das matrizes estarem limitadas a desvios de fluxo, pressão e temperatura. No entanto, tal característica poderia ser aperfeiçoada em estudos futuros, com a inclusão de novas variáveis e relações. Um ponto comum aplicado à ambas as metodologias é o aspecto computacional, que permite que as mesmas sejam aplicadas a diferentes sistemas que os discutidos nesta dissertação, dependendo apenas de alguns *inputs* específicos para gerar a gama de resultados possível de ser obtida pelas técnicas. Além destes pontos relacionados às metodologias propostas, é importante destacar questões que apenas estudos de HazOp clássicos poderão capturar, como por exemplos questões estritamente

operacionais, que não são escopo de simulações de processo nem da representação matricial objetiva gerada em cada equipamento. Outro ponto positivo adicional é a maior flexibilidade de estudos clássicos, já que o brainstorming realizado permite que cenários não usuais sejam levantados, relacionados a diferentes variáveis que àquelas comentadas em simulações e matrizes. A criatividade inerente ao estudo de HazOp é uma de suas maiores forças, mas que também requer atenção, pois é definitivamente dependente de pessoas, com diferentes conhecimentos, diferentes experiências e especialidades, e também pode impactar negativamente os estudos.

O levantamento bibliométrico realizado nesta dissertação indica que a técnica de HazOp é a mais bem estabelecida, mas que existem novas possibilidades de forma a diminuir possíveis *gaps*, e aumentar sua confiabilidade. Estudos continuarão sendo feitos com esta intenção, indo de encontro à tendência mundial de implementar esforços na área de segurança de processo, garantindo assim um ambiente de trabalho seguro para as empresas, funcionários e meio-ambiente.

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