INTEGRATION OF HUMAN FACTORS ENGINEERING AT THE EARLY DESIGN OF HYDROCARBON AND CHEMICAL PROCESSING FACILITIES

A Thesis

by

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ABSTRACT

Human error is a major recurrent theme in industrial incidents in the Hydrocarbon Processing Industry and Chemical Processing Industry. However, advances in the science of Human Factors have shown that human error is not the root cause of such incidents but rather a mechanism of how these incidents transpire. Therefore, to manage human error, it is important to understand their mechanism and the conditions that give rise to them, that is, understand the human elements that can increase or decrease the likelihood of human error. Numerous activities are prescribed to manage human error. One group of activities occurs during the design and construction stages of capital or upgrade projects. While the remaining activities occur during startup and operations. This thesis describes both groups. However, the main focus is on the former, more specifically at the conceptual design stage where limited information is available. In this study, industry practices have been reviewed, and potential approaches to help designers make more informed decisions at the conceptual design stage are presented. The study reveals the challenging nature of early HFE integration and presents an initial effort to estimate Human Error Probabilities at such an early stage where limited plant data is available. The topics explored include the use of performance metrics to support HFE integration, use of Cognitive Work Analysis, use of process simulation, and the application of Bayesian Belief Networks.

DEDICATION

To my parents

Yahya Faisal and Raeda Faisal

To my siblings

Faris, Abdulaziz, Nayif and Nawaf

To my committee members

Dr. Camille Peres, Dr. Mahmoud El-Halwagi and Dr. Qingsheng Wang

ACKNOWLEDGEMENT

I would like to dedicate this research to my mother, who always believed in me and always kept me in her prayers and supplications. I also dedicate this research to my father, who taught me how to be patient and persistent to achieve my goals. They have always been proud of me. I owe them everything I accomplished. I cannot forget about my siblings, Faris, Abdulaziz, Nayfi, and Nawaf, who always looked up to me and stood by my side when things got tough. I extend my deep appreciation to my committee members for their continued support, motivation, and guidance. Special thanks to Dr. Peres for introducing me to the human factors community in Texas A&M. Throughout the study, Dr. Peres mentored me and gave excellent advice and suggestions. Finally, I thank Saudi Aramco, Loss Prevention Department management, for sponsoring me in this master's program, for giving me the opportunity to study abroad and enrich my knowledge.

NOMENCLATURE

ADS	Abstraction Decomposition Space
AIChE	American Institute for Chemical Engineers
BBN	Bayesian Belief Network
CCPS	Center for Chemical Process Safety
CWA	Cognitive Work Analysis
HOF	Human and Organizational Factors
HRA	Human Reliability Analysis
NPT	Nodal Probability Table
CPT	Conditional Probability Table
CDU	Crude Distillation Unit
HF	Human Factors
HFE	Human Factors Engineering
HEP	Human Error Probability
PSMS	Process Safety Management System
KPI	Key Performance Indicator
ROI	Return On Investment
WDA	Work Domain Analysis

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1. INTRODUCTION

Human error is a major theme in process safety incidents within Hydrocarbon Processing Industry (HPI) and Chemical Processing Industry (CPI). To share a few examples, in 2004, at Formosa Plastics in Illiopolis, Illinois, an explosion killed five workers and injured three others. The incident took place during the cleaning of one reactor vessel processing polyvinyl chloride (PVC), a highly explosive chemical, which was situated nearby an identical set of PVC reactors [1]. As part of the cleaning process, the outside operator was asked to empty the cleaning fluid from a Reactor by opening the bottom valve to drain. As the operator descended the stairs from the top floor of the Reactor Building to the ground floor, he turned right instead of left, which meant that he went to the wrong reactor. Unaware of his mistake, the operator opened the bottom valve of a reactor that was in service at the time, thereby releasing PVC to the atmosphere, which shortly ignited [1]. The incident investigation found numerous Human Factors (HF) deficiencies such as the inadequate labeling of the reactors, operators regularly bypassing an interlock put in place to prevent inadvertent releases of PVC, and lack of communication means between the outside operator and his supervisor [2]. Just one year later, an explosion took place in a Texas City refinery, which killed 15 workers and injured 180 others. The explosion occurred during the Isomerization unit startup, where a procedure deviation led to overfilling the Raffinate splitter tower, releasing flammables, and creating a vapor cloud that subsequently ignited and resulted in an explosion [3]. The incident investigation found numerous process safety deficiencies, some of which were related to HF. For example, the facility had defective and poorly designed Human-Machine Interfaces (HMIs). To elaborate, the field level indicator used to monitor the Raffinate splitter tower was uncalibrated and gave inaccurate readings when the level exceeded 9 feet; also, the high-high level alarms did not sound, thus giving confusing signals to the operators. Furthermore, the control room displays' design did not allow operators to view the flows in and out of the tower on a single screen. Instead, they were split into two different screens and did not show the total volume of liquid in the tower [4]. Together, the inaccurate level readings, malfunctioning alarms, and poorly configured display screens decreased the control room operator’s situation awareness at the perception level. Other issues were related to cultural and management deficiencies. Operators routinely deviated from procedures, and corporate downsizing efforts eliminated a critical operator position in the control room [2]. Formosa and Texas city refinery explosions are just two examples. There are many more incidents in the open literature where human factors issues played a big role [2], such as Flixborough in 1974 [5], Three Mile Island in 1979 [6], Piper Alpha in 1988 [7], and Buncefield in 2005 [8].

Indeed, trend analysis studies have consistently recognized a pattern of human performance issues in high-risk industries. A study done by the University of California at Berkley found that 80% of offshore oil and gas accidents in US territorial waters were attributed to human error [9]. Another study looked at more than 800 offshore incident reports in the U.S. Bureau of Safety and Environmental Enforcement (BSEE) database from 2003 to 2013. In this study, human error was identified as a contributory cause 50% of the time [10]. Human error is generally believed to have contributed to 80% of industrial accidents [2], with some studies going as far as saying that up to 99% of accidents begin with human error [11]. These figures draw a grim picture for the future; Behie, Halim [12] reviewed various published sources for accident data in HPI and CPI domains and concluded that the frequency of accidents remains unchanged in recent years. Among the reviewed sources was a publication prepared by Marsh, Mercer [13], which identified Human Factors Engineering (HFE) among the top four risk topics cited in investigation reports.

The science and application of HF can play a significant role in mitigating accident causation with profound implications in complex socio-technical systems such as HPIs and CPIs. Sanders and McCormick [14] defined HF as “the discovery and application of information about human behavior, abilities, limitations, and other characteristics to the design of tools, machines, systems, tasks, jobs, and environments for productive, safe, comfortable, and effective human use.” [14]. Essentially, HF professionals engage and leverage methods and processes that anticipate, mitigate, and manage human error in any given enterprise. Further, beyond reducing errors, these methods can increase workers' effectiveness and efficiency. HF methods and activities differ based on the lifecycle phase of the plant and governing organizational structure. Some of the HF activities occur during capital projects or upgrades of existing plants. On the other hand, different HF activities occur during the steady-state and transient operations of existing plants. The former set of activities relevant to the early design stages of industrial plants is commonly known as HFE, which is the focus of this thesis. Much like the concept of Inherently Safer Designs (ISDs) in process safety [15], HFE identifies opportunities to select the most suitable design options for new plants. Examples of these options include improved HMIs, control room design and layout, accessibility to critical valves, physical clearances for maintenance activities, equipment designs with compatible anthropometric dimensions, and optimal environmental conditions. The complexity, range of work activities, and multidisciplinary nature involved in realizing better human-error tolerant designs call for a holistic framework. This framework is known as HFE Integration, a subset of human-system integration [2] [16].

The HFE field saw great progress over the past 20 years. Numerous engineering standards and consensus codes were developed by International and regional organizations such as ISO, NORSOK, ABS, ASTM, and API [17]. These standards offer guidelines and prescribe design requirements for physical clearances, workstation design, valve handwheel design, and HMIs, etc. Other engineering guidelines are also available in published books [14] [18] [19] [20]. However, despite these advancements, there is little information in the literature about successful case studies of HFE integration in HPI and CPI companies. Among the reasons cited for this issue are lack of qualified and experienced HF professionals, lack of synergy between HFE research and practice, and lack of robust and validated HFE integration models and tools [21] [22].

There are two types of HFE assessments that can be done at the conceptual design stage, qualitative and quantitative assessments [2]. Qualitative assessments can be done by completing simple checklists in a team in what is referred to as HFE screening, conducting a high-level task analysis, or using hierarchical decomposition tools in cognitive engineering. Quantitative approaches can be via the use of HFE metrics and estimation of Human Error Probabilities through Human Reliability Analyses. Each one of these approaches has its strengths and limitations [2].

This thesis examines possible qualitative and quantitative solutions to integrate HFE at the conceptual design stage of HPI and CPI plants. After all, the conceptual design stage is the best stage to make significant design adjustments with minimal cost impact. As part of this effort, we look at the different techniques in which HF is quantified and evaluate the merits of each technique. The first method is the use of HF metrics or Key Performance Indicators (KPIs). KPIs are popular in the CPI and HPI domains, especially in health and safety. HPI and CPI companies collect injury and plant data to compute and report lagging (output-oriented) indicators such as injury rates or losses of primary containments. Similarly, leading (process-oriented) indicators are collected and reported, such as the timely completion of inspection activities or the number of safe operating limit excursions [23]. In the same manner, HF can be quantified as metrics and reported to measure the HF robustness and progress toward HF integration. The UK's Energy Institute (EI) developed guidelines for the identification and selection of HF indicators [24].

The second method explored is an approach to work analysis known as Work Domain Analysis (WDA). WDA is rooted in cognitive system engineering and is part of a broader concept known as Cognitive Work Analysis (CWA). WDA works similarly to Task Analysis (TA) by decomposing the system into its constituent functional objects. The only difference is that unlike TA, WDA is activity-independent, which means that it analyzes systems by considering the system functions, outcomes, constraints, and boundaries without any reference to activities or processes. A great analogy that explains this difference states that WDA is like a map while TA is the navigational directions on that map [25]. Most scholars interested in WDA use Rasmussen's Abstraction Decomposition Space (ADS) to determine the system's means-end and part-whole relationships. ADS breaks down the general work domain in which tasks are performed into a hierarchal structure without listing the actual tasks. The idea is that the work domain encompasses components that are fixed and not as dynamic as tasks. Another analogy to the work domain would be the kitchen design, equipment, and tools, whereas the tasks would be the actual cooking recipe and sequences. In this paper, we perform a WDA ADS on a Crude Distillation Unit (CDU) case study followed by Work Organization Analysis (WOA) and Cognitive Transformation Analysis (CTA) [25]. From these analyses, we demonstrate how early HF design principles for HMI can be determined. The third method uses the ADS graphical formalism determined in the second method and applies numerical calculations to obtain a Human Error Probability (HEP) estimate, which would help analysts make sense of their systems at the conceptual design stage. It is then possible to identify the critical system functions, tools, and boundaries that will later influence the tasks and human-system interactions.

In the fourth method, we attempt to model the CDU case study in Aspen HYSYS, a process simulation software. Then we examine the possibility of making HFE related adjustments to the process. Aspen HYSYS has been used extensively for applications of Inherently Safer Assessment Tools (ISATs), which are quite similar in concept to HFE integration [26]. A common approach to applying the principles of inherently safer designs known as minimization, substitution, moderation, and simplification [15]. Park, Xu [26] identified a number of ISAT that can be used among them is Fire and Explosion Damage Index (FEDI) [27]. Guillen-Cuevas, Ortiz-Espinoza [28] modeled an ethylene-to-butadiene process plant in Aspen HYSYS and calculated the FEDI index and Return On Investment (ROI) associated with different operating temperature setpoints in the Dimerization Reactor. The result was a chart reflecting the favorable operating temperature limits that will maximize safety while keeping the process profitable as much as possible. The same concept is considered for HFE.

The fifth method uses Bayesian Belief Network (BBN) [29] to model a simple framework for human reliability. The BBN models a simple framework that allows the analyst to enter incident data and subject matter judgment on several dimensions related to human factors. The product is predicted HEP values and insights about the need to carry out additional HFE studies and design activities.

Throughout this thesis, I will be using the colloquial term ‘Human Factors deficiencies’ to refer to gaps in the integration of Human Factors in HPI and CPI plants. However, I caution the reader that this term is not fully accurate, as it implies that Human Factors are a list of factors or a bounded topic similar to process safety which is a misconception because, in fact, Human Factors is a full-fledged discipline like chemical engineering. It would be quite strange to read the term ‘chemical engineering deficiencies’ when someone refers to a problem with the design of a chemical reaction or process. Hence for the lack of a better term and because of its widespread use in literary publications, I will use the term Human Factors deficiencies or HF deficiencies. For design deficiencies that would result in degraded human performance, I will use the term HFE deficiencies.

1.1 Contracting Strategy

Upon reviewing several approaches to HFE integrations, it became clear that most scholars advocate for the traditional system engineering (waterfall) approach to incorporating HFE [17] [10] [30] [31] [21]. This staged approach works by specifying key activities and expected deliverables at different stages of the project. Unsurprisingly, this approach is tailored to fit logically in an existing contracting strategy that HPI and CPI companies adopt to manage capital projects and upgrades [17]. This contract strategy is known as Engineering, Procurement, and Construction (EPC) contract form [32].

A critical consideration in building new chemical, petrochemical, oil, and gas plants is the selection of the appropriate contracting form. The choice of the right contract depends on the size of the project, location, risk allocation, division of responsibilities, interfaces, market situation, and project time constraints [33]. There are many types of contracting forms available at the disposal of prospective facility owners; two examples of these contracts are the owner-managed contract and EPC EPC Lump Sum Turnkey (LSTK). The latter is the most commonly used form by HPI and CPI companies.

In the LSTK Contract, a primary or general contractor assumes the full responsibility to deliver a completed facility to the owner (i.e., turn the key to the owner to start the plant). In this contract form, the general contractor takes care of the coordination between the different subcontractors and makes sure the facility is completed within the agreed time frame. The risk is transferred from the owner to the contractor. This contract form is the most popular form in chemical, petrochemical, oil, and gas major projects (see Figure 1) [32].

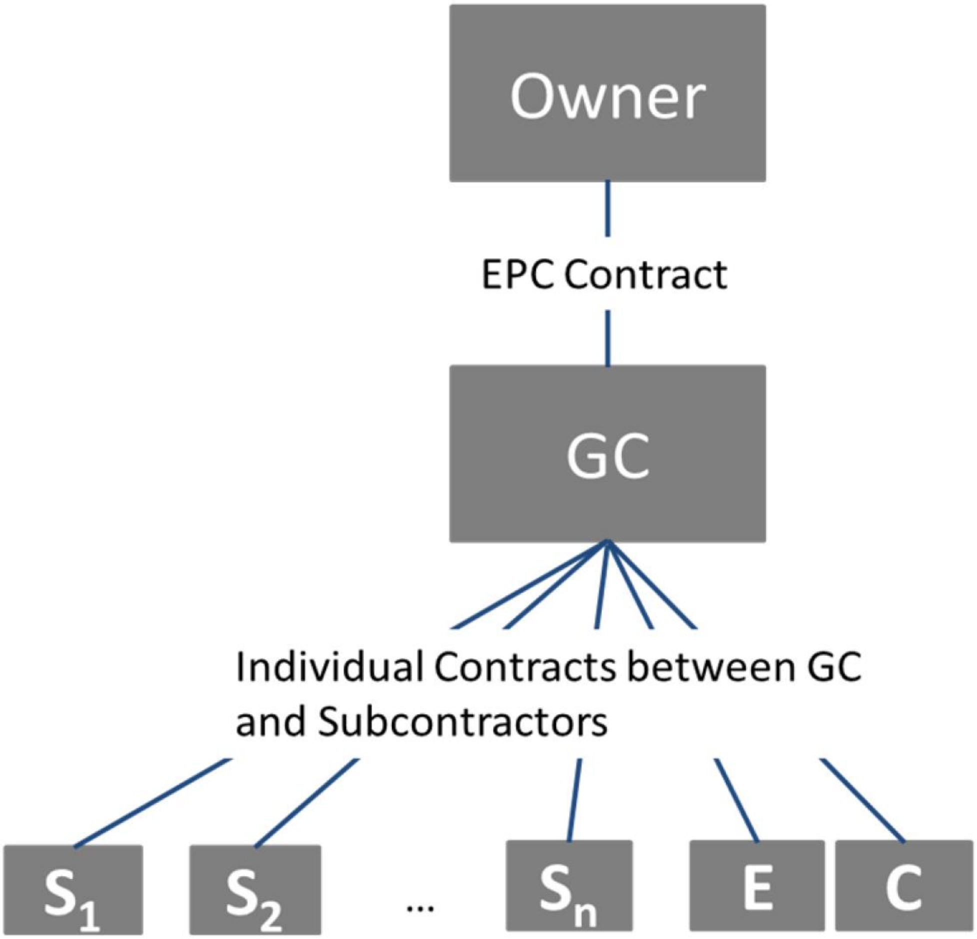

Figure 1: EPC LSTK Contract[1] [32]

Like other contract forms, this contracting style splits the work among different engineering design firms, construction companies, equipment vendors, and suppliers. It is not difficult to foresee that large capital projects (i.e., megaprojects) will involve a

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[1] Reprinted from "Evaluating main order contract forms for Major Industrial Plant Projects (MIPP)" by Anita Erbe, 2013, Freiberger Arbeitspapiere, 33, Copyright 2013 by Anita Erbe

large contract workforce from different companies hailing from different countries. To put things into perspective, one Spanish engineering firm (S_1) could be responsible for designing the sulfur recovery unit in a refinery, but the construction of this unit could be done by a Chinese construction company (C). Language barriers, cultural barriers, miscoordinations, and other communication challenges are inherent during the critical phases of engineering, procurement, and construction. Therefore, there are many opportunities for design and construction inefficiencies, which are likely to result in detrimental design and construction errors. This entire complex system is a temporary socio-technical system, and errors occurring at this stage are termed latent failures because they may not materialize until the project is completed and the plant is fully operational. Hence, HFE Integration at the earliest stages is key to manage inherent project inefficiencies, identify latent design failures, and correct them quickly and cost-effectively before it is too late or before changes become too impractical [34].

1.2 Project Lifecycle

Designing and building plants in the process industry is an incredibly complex endeavor. For many of these projects, the scale and magnitude of work activities are overwhelming for energy companies. Multiple design consulting firms across the world can get involved in the design of one single project. Thousands of employees and contract workers can be present at the site and work side by side during construction.

In many cases, contract workers can come from different companies with different backgrounds imposing cultural and language barriers. These factors complicate the resulting socio-technical system and can expose the project to many inefficiencies; thus, it is necessary to have effective coordination, oversight, and organizational governance. The manufacturing industry (including chemical, petrochemical, oil, and gas), internalized these points and adopted a facilitative approach to engineering design development and execution. Major engineering activities are clustered into phases that will address significant engineering objectives, such as doing the feasibility study to determine if the project is worthwhile, purchasing the equipment from vendors, and finally building the plant. These objectives are addressed in the following stages: feasibility, conceptual design, preliminary design (sometimes referred to as front-end loading or basic engineering), detailed design, construction, commissioning, startup, operations, and decommissioning [35]. The average time for project development is 1 to 2 years. In comparison, project execution can run from 2 to 5 years, while operation can last as long as 60 years. It is noted that some portions of project development can run in parallel with project execution [32].

1.3 Human Factors Principles

Multiple frameworks exist to represent HFs. One such framework developed by the UK Health and Safety Executive (HSE) posits that there are three main categories that influence workers' behavior, and consequently, their propensity for error [36]. These categories are job factors (focused on the task such as task complexity and procedures), and organizational factors (focused on issues such as leadership, organizational structure, and safety culture), and finally, individual factors (focused on workers skills, competence, personality) [36]. Another model configuration breaks HFs into categories of work tasks, organizational context, environmental context, work tools, work equipment, workspace, and work area [2]. A different approach more in line with cognitive science views HFs as an interactive behavior triad consisting of task, environment, and embodied cognition, where embodied cognition is defined as the capabilities and limitations of the human perceptual, cognitive, and motor system [37]. All the mentioned models consist of more or less the same HFs elements; however, one important aspect of understanding HF in HPI and CPI is by putting oneself in the shoes of the worker. This allows us to identify preconditions that give rise to human error. These preconditions are known as Performance Shaping Factors (PSFs). PSFs are contextual factors that are commonly used in Human Reliability Analysis (HRA) techniques such as SPAR-H, HEART, THERP [38], etc. Their function is to adjust Human Error Probabilities (HEP) by applying context-specific multipliers [38]. They also provide a specific picture of the main parameters that can give rise to human error. Understanding human error is one of the activities involved in HRA. Numerous techniques are available for HRAs with great room for customization. HRA techniques can be categorized as first-generation, second-generation, and third-generation methods. One first-generation method that uses PSFs is the Petro SPAR-H.

The Petro SPAR-H technique, which is a modified version of SPAR-H, is tailored for the offshore oil industry, identifies 9 PSFs (see Figure 2).

Figure 2: PetroSPAR-H PSFs [39]

- **Time:** is the available time the worker has to respond to a particular emergency or system demand
- **Threat stress:** the amount of stress experienced during operations
- **Task Complexity:** the level of task difficulty in terms of the multiplicity of goals, number of information cues, step size, connection, dynamic nature, and the order or logical structure
- **Experience or training:** The operator familiarity with the task acquired from exposure, on-job training, and other training methods
- **Procedure:** availability and quality of procedures
- **Human Machine Interface (HMI):** The design of displays and controls and adoption of human factors design principles

- **Attitude towards safety, work, and management support:** how the organization promotes and sustains a sound safety culture. This will frame individuals' attitudes and influence their behavior in their day to day activities.
- **Teamwork:** Arguably, another component of safety culture. Several factors influence teamwork, such as team direction, coordination, peer checking, anticipating needs, adaptability, task involvement and consultation, mutual trust, and sharing of information [40].
- **Physical Working Environment:** Working and Environmental conditions such as accessibility, layout, temperature, noise, and vibration.

1.4 Integration of Human Factors

The discussion of human factors here is within the context of chemical, petrochemical, and oil and gas plants. Naturally, for this discussion to be meaningful to companies operating in these domains, it must take into account their operating frameworks, existing management systems, and business processes. Several business frameworks may exist to manage the multitude of staff and line functions. Names or titles of these business frameworks can differ from company to company. Still, their underlying principles will be primarily the same. To name a few of the functions governed under these frameworks and management systems are project management, environmental compliance, sustainability, safety, security, human resources, project management, etc. Some companies have chosen to use an overarching framework to govern all these seemingly separate yet highly dependent functions, such as Exxon Mobil's Operational Excellence (OE) Framework. Incorporating HFs into an organization would mean that they have to be carefully injected into these business functions. Failure to do so may result in huge costs, overwhelming the staff with redundant activities, and not achieving the desired improvements in human performance.

It is important to distinguish between two kinds of HF integration activities, one which occurs in the design and construction phase (Human Factors Engineering) and one which occurs during the operational phase of the plant. The former requires an integration plan, close coordination with the project team, designers, vendors, and a multidisciplinary engineering team, which includes the safety engineers and the human factors analyst. The latter rests with the plant owner and relies heavily on management systems and processes. Since human performance can be subject to deterioration at any time during the plant's lifecycle, both kinds of HF integration efforts are required.

Recognizing that HF integration efforts are important, the natural path forward is identifying which HF issues that require attention. The UK HSE identified the top 10 human factors issues that every plant should consider affecting the entire lifecycle of the plant. These issues are risk assessment, incident investigation, design, procedures, organizational culture, organizational change, staffing, training and competence, safety-critical communication, fatigue, and shift work [41].

1.4.1 Integration Into PSMS

Safety Management System (SMS) is one of the essential frameworks for companies operating in high-risk industries. The Process Safety Management System (PSMS) is a specialized version of the SMS used in the chemical, petrochemical, and oil and gas plants, which is customized to emphasize the unique process safety hazards in these plants. The SMS or PSMS derives some of their principles from another legacy management system known as the Total Quality Management (TQM) system [42] [43]. Multiple studies were conducted to evaluate how well HFs are covered in companies' PSMS. In one particular study, several PSM frameworks, including OSHA PSM [44], Energy Institute PSM [45], CCPS RBPS [46], Responsible Care [47], API 754 recommended practice [48] were reviewed against the Human Factors Analysis and Classification (HFAC) scheme [49]. This study showed that while there are many available PSM frameworks and guidelines, none of them provide comprehensive coverage of HFs. For example, the OSHA PSM framework lacked coverage of perceptual errors, willful violations, physical environment, supervisory violations, operator conditions, crew resources, and planned inappropriate operations [50]. This is a bit surprising since many of the HF topics (risk assessment, incident investigation, procedures, training and competence, etc.) are clearly stated as process safety elements in almost all prominent PSM frameworks. For example, the work in [50] shows that OSHA PSM covers incident investigation, operating manuals and procedures, and training competence and performance. Interestingly, the title of the elements may suggest that human performance issues are already addressed and there no need to worry about HF integration. However, a closer review of how these elements are designed and implemented, would reveal gaps in managing human performance, which is a classic example of the popular idiom “the devil is in the detail”.

To rectify this issue, research done by [51] recommends a design from first principles approach, whereby management processes are constructed in the following steps:

1. **Determine process outputs**: the ultimate result of interest related to human performance. As an example in the incident investigation process, the process

output could be phrased as capturing lessons and preventing re-occurrence of undesired events, including human failures

2. **Identify stakeholders**: users and those who will benefit from the process outputs, e.g., management, operators, the public, and nearby community
3. **Determine stakeholder requirements**: requirements can either be stated (prescriptive) or implied (performance-based); this step must incorporate both. An example of stated requirements would be the frequency of gas testing by a qualified tester while working in a confined space; on the other hand, an implied requirement can be the authorization of a change subject to the Management of Change (MOC) process. The former is clear as to who, what, and when it's done, whereas the latter is left to the organization to decided how to answer these questions. Implied requirements can come from regulations, codes, and industry guidelines. It is important to identify those requirements related to human performance, such as generic heuristics or rules of thumb, in terms of usability and operability. These heuristics would need to be stated in prescriptive terms to allow achieving the process output. For example, one HF heuristic in an operating procedure is 'readability.' For this heuristic to be meaningful, the requirement will need to be made relevant to the context of use by stating '*procedure steps where order matters shall be numbered consistently and consecutively to avoid confusion*' [52]. Therefore the PSMS process designer must be aware of existing guidelines for HF principles to be able to generate stakeholder requirements.

4. **Convert stakeholder requirements into specifications:** specifications are organized into documented processes with clear delineation of work task execution steps (as in a procedure), qualification expectations, use of job-aids such as checklists and decision flow charts, roles and responsibilities, approval authority, etc.
5. **Identify process steps:** cyclical steps required to generate the process output are specified.
6. **Choose performance targets/criteria:** This includes certification and performance requirements, which may be capture as Key Performance Indicators (KPIs) targets. The identification and selection of HF performance indicators are covered in a later section. Refer to **Error! Reference source not found.**.
7. **Determine process capability:** Identify the resources and tools necessary to achieve the process output
8. **Evaluate results:** includes periodic verification by staff and management, monitoring of lagging and leading KPIs
9. **Improve results:** stating how identified deficiencies will be corrected, reviewed, and resolved

HFs are not integrated into PSMS processes only since these processes are seldom operationalized in isolation but rather always supported by other company documents such as vision, mission, value statements, policies, plans, procedures, products, programs, and performance metrics. Hence to successfully integrate HF into PSMS, it would be necessary for the integration efforts to extend to all these interrelated documents resting within the organization [51].

In addition to making sure that PSMS processes are designed with HFs in mind, it is also important to identify any missing HFs processes that require the same treatment mentioned before. A study done by [11] reviewed how well OSHA PSM covered broad human factors elements and found that it was missing elements related to fitness for duty, attention and motivation, staffing issues, human system interface design, task design, and communication between workers. Companies adopting off-the-shelf PSMS frameworks should exercise due caution by understanding how well these models incorporate HFs and compliment them as needed.

1.4.2 Integration Into design and construction

So far, the discussion was centered on how HFs can be integrated into an organization’s PSMS to cope with HF issues that may arise during day-to-day operations. Equally important is to present the staff and line personnel with a facility that has been designed specifically and carefully to cater to their needs, maximize plant usability, performance, and safety. During the early design stage of a plant, many opportunities exist, at a low cost, to significantly improve human performance and minimize errors. As the design progresses, these opportunities become limited and more costly. Once the facility is built and operated, the costs can become extremely prohibitive, leaving plant personnel with a myriad of human issues that they have to deal with using their judgment, tools, and resources. Figure 3 shows how, in the absence of an HFE approach to control room design, operators were forced to improvise solutions to HF issues. In this case, operators had to attach an arrow label to clarify the link between relevant control modules. These manual fixes can become cluttered, deteriorate with time, and may inadvertently degrade human performance rather than improve it [53].

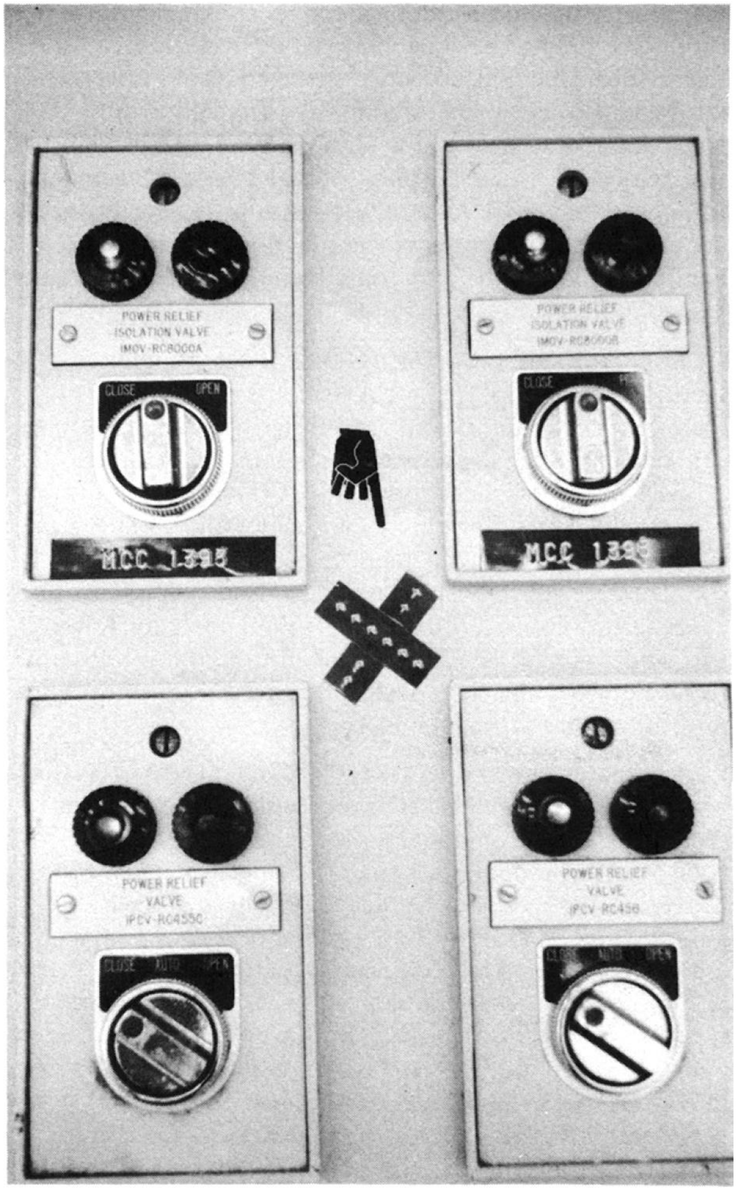

Figure 3: Operators' attempt to clarify the control modules' relationship[2] [53]

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[2] Reprinted from "Remedial Human Factors Engineering - Part 1" by J.L.Seminara and D.L.Smith, 1983, Applied Ergonomics, 12, Copyright 1983 by J.L.Seminara and D.L.Smith

There are various benefits to HFE integration at the early stages of plant design; these benefits are in the form of personnel benefits, equipment benefits, and other intangible benefits [54]:

1. Personnel benefits include:
    - Increased worker productivity
    - Reduced error rates
    - Reduced accident and injury illnesses,
    - Reduced time for training and maintenance
    - Reduced skill requirement
    - Reduced absenteeism and turnover
2. Equipment benefits include:
    - Reduced leftover scrap material during construction
    - Equipment saving as a result of limiting the number of components and enhanced employee care
    - Reduced production parts and material as a result of simplifying their design
    - Reduced stocking and storage of parts
    - Reduced need for maintenance tools and materials
    - Reduced costs by avoiding future expensive changes and re-work [17]
3. Intangible benefits include:
    - Increased employee commitment
    - Improved corporate image

Despite these benefits, it is noticed that HF integration has not been consistently adopted in the chemical, petrochemical, oil, and gas industry. The review in [22] cites the following reasons:

- **Lack of awareness:** discipline engineers see equipment when they think of a process and neglect the role people play
- **HFE seems confusing, and not many people understand it:** Lack of structured definitive analysis approaches of comprehensive human factors integration models. It is difficult for engineers to know where to start and when they are finished
- Engineers in the process industries are unaware of the benefits of incorporating HFs
- Fear of the effort involved with the workforce already stretched, fear from having a personality or individual performance evaluations
- Fear that similar to Process Hazard Analyses (PHAs), human factors studies may result in a high number of recommendations that are difficult to manage
- For non-hardware HFs issues such as those concerned with organizational or socio-technical issues (addressed in HF integration in PSMS), solutions may be difficult to identify
- Lack of qualified HF analyst/specialists, especially those with expertise in chemical, petrochemical, and oil and gas
- The knowledge gap between research and practice, where professionals are not aware of advances in research and researchers are not informed of the

knowledge body gained from practice, or integration challenges that HPI and CPI professionals face in their organization and facilities [21].

Even when the benefits are recognized, decision-makers in big projects will scrutinize the cost aspect of HFE integration. Typical costs of HFE integration include payroll for internal expertise, cost of hiring outside personnel if no internal HF capabilities are available (such as using a consultant), potential employee downtime of HF activities render certain equipment idle, cost of procuring equipment and materials, reduced sales and productivity as a result of process shutdowns, and other overhead costs (e.g., utilities, administration) [54]. Nevertheless, a closer look at these costs shows that they are minimal compared to the project's capital cost. Additionally, some of these cost items occur regardless if HFE integration is adopted or not (e.g., reduced productivity, and idle operations are natural consequences of upgrade projects following a plant shutdown)

Several examples exist in the literature of HFE integration success stories, to share a few:

- A $400 million petrochemical project noted that 0.25% savings of capital investment, 1% savings in engineering hours, and 3 – 6% savings in lifecycle costs [55].
- For many offshore platform projects, HFE integration costs never exceeded %0.12 of the acquisition cost of the platform. In one particular offshore project, changes made to the design of a riser tensioner system reduced the system's construction cost by $242,000 [9].

- The Sable Offshore Energy project located in Nova Scotia offshore included the construction of onshore facilities, offshore facilities, offshore wells, and offshore pipelines with a total capital cost of $1.35 billion. The cost of HFE integration was not more than %0.07 of the total project cost [56].
- In the aviation industry, a project for Air Force C-141 aircraft system development program observed HFE integration costs of no more than $500,000 and then realized initial cost savings of $5 million [54].

1.4.2.1 HFE Lifecycle Integration

Organizing and adequately coordinating HFE activities in complex energy projects is necessary to support effective integration throughout the project lifecycle. Key factors for a successful HFE integration include leadership commitment, appropriate HF staff competency, use of a detailed integration plan, use of performance indicators to monitor progress, treating HF issues with equal rigor and urgency as other operational issues, the involvement of a multidisciplinary team, and use of a robust design review process [17]. Not every project will require the same level of HFE integration effort. Scope size will ultimately influence the level of HF competency needed and the use of detailed integration plans. Table 1 shows common and recommended HFE activities undertaken as part of HFE integration against different project phases. It is common practice for companies to break down some of the project phases into 30%, 60%, and 90% cycles. In each of these cycles, the multidisciplinary team, including the HF analyst, will be involved in performing design review and validation activities in various forms such as drawings reviews, 3D model reviews, demos, and prototype exercises.

Table 1: HF deliverables throughout the project lifecycle [17] [57] [31] [58]

HFE Activity	Project Phases							
	Feasibility	CD[3]	PD/FEED[3]	DD[3]	Construction	Commissioning And Startup	Operations	Decommissioning
Produce Target Audience Description (TAD)[3]	●	●	●					
Outline Usability Scenarios[4]	●	●	●					
HFE Screening		●						
Decide on HF Integration Strategy		●						
Develop HF Integration Plan (HFIP)		●						
Assign HFE roles and Responsibilities		●						
Setup HF Integration Register (HFIR)		●						
Review standards			●					
Develop HFE design specifications			●					
Conduct HFE awareness training			●		●	●		
Complete HFE design Analyses (see **Error! Reference source not found.**)			●	●				
Perform HFE design review and validations			●	●	●	●		
Provide HFE Input to Hazard Identification and Risk Analysis activities (see **Error! Reference source not found.**)			●	●				
Track and Resolve HFE issues			●	●				
Conduct HFE closeout report				●				

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[3] Information about the characteristics of the personnel who will operate, and maintain equipment such as anthropometric, biomechanical limitations, skills and abilities

[4] Scenarios where the systems/equipment is used, context of use i.e. defining the user context which will feed later in task requirements analysis

[3] CD: Conceptual Design, PD: Preliminary Design, FEED: Front End Engineering Design, DD: Detail Design

Table 1: HF deliverables throughout the project lifecycle [17] [57] [31] [58]

HFE Activity	Project Phases							
	Feasibility	CD^3	PD/FEED^3	DD^3	Construction	Commissioning And Startup	Operations	Decommissioning
Develop HFE Plan for Construction				•				
Perform Pre-Startup Safety Reviews (PSSRs)					•	•		
Capture HFE lessons learned					•	•		
Conduct Follow-up evaluation							•	
Prepare Procedures and manuals				•	•			
Conduct Workload assessment and staffing levels			•					
Produce training specification/design training courses				•				
Develop PSM policies, processes, programs, and work procedures development				•	•			

Table 2: Example of design analyses, and HIRA activities [17] [57] [31] [58]

HFE design Analyses	HFE Input to Hazard Identification and Risk Analysis (HIRA) activities
• Task Requirements Analysis (TRA) • Valve Criticality Analysis (VCA) • Vendor Package Screening and Review • Control Room Analysis and Review • Alarm System Analysis and Review • Plant Layout Design and Review • Material Handling Study • Crane Operations • Functional Requirements and Allocation • Lifeboat selection and placement (offshore facilities)	• Process Hazard Analysis (PHA) such as Human HAZOP, HAZID, Bow-tie analysis • Safety-Critical Task Analysis (SCTA) • Human Reliability Analysis (HRA)

1.5 Quantification of Human Factors

The quantification of design concepts at the conceptual design stage to aid designers and decision-makers in selecting the optimal plant configuration, chemical process route, and structure is not a new idea. Researchers have explored this idea for Inherently Safer Designs (ISD). A design concept which advocates for reducing the inherent hazards rather than managing risk through ad-on safety features. ISD is achieved by applying four guide words or design principles: minimization, substitution, moderation, and simplification during design synthesis, integration, and while examining different process routes, streams, and steps. These four ISD principles may be applied through Inherent Safety Assessment Tools (ISATs). ISATs employ analytical methods such as indexing, consequence-based, graphical, numerical, computer-aided, optimization, and experimental. Indexing methods being the most popular. A review done by [26] analyzed many different ISAT indices that can be potentially incorporated at the conceptual design stage. The study identified that ISATs indices could be hazard-based, risk-based, or cost optimization-based. The hazard-based ISATs (H-ISAT) indices compare the inherent hazard levels among different design solutions. H-ISAT aggregates chemical and process design indicators that are available at the conceptual design stage. Chemical indicators refer to those parameters that can indicate the hazard level represented by the chemical material properties (e.g., flammability, explosivity, etc.), while process indicators refer to those parameters that can indicate the hazard level represented by the operating conditions (e.g., pressure, temperature, etc.). Examples of H-ISATs include the Prototype Index for Inherent Safety (PIIS), which aggregates flammability, explosiveness, toxicity, temperature, pressure, inventory, and yield. A similar approach can be adopted for human factors quantification where fundamental human factors units are identified and aggregated in a manner that allows the designer to explore the merits of different design options.

1.5.1 Human Error Probabilities (HEPs)

The UK HSE defines human error as "an action or decision which was not intended, which involved a deviation from an accepted standard, and which led to an undesirable outcome." This definition does not include violations (non-compliances), which are defined as "deliberate deviations from a rule or procedure," violations are carried out without malicious intent and are different from acts of sabotage [36]. Several classification schemes exist to categorize human error and help analysts contextualize them and produce appropriate control measures; three schemes are presented here. The first scheme is based on the time of error occurrence:

- **Category A**: errors occurring before the accident, which can lead to system degradation and unavailability, e.g., taking an emergency shutdown device out of service. These errors can sometimes be referred to as latent errors
- **Category B**: errors that can cause the initiating event of the accident, e.g., closing the wrong valve resulting in overpressure of the trapped space
- **Category C**: errors that occur after the occurrence of an accident sequence, e.g., failure to respond to an accident within the available time window or errors that escalate consequences of the accident

It is important to recognize that not all errors occur at the front line employee level; in other references, another category of errors is identified, which is **organizational**

decisions. These decisions are concerned with those related to how tasks are managed, and they can come from leadership positions at different levels in an organization [59].

The second scheme is based on the output of human error [60]

- **Errors of omission:** failure to act
  - Omit entire task
  - Omit a step in tasks
- **Errors of commission:** performing the wrong action
  - Selection errors
    - Select wrong control
    - Misposition of controls
    - Issue wrong command on information
  - Errors of the sequence
  - Timing errors
    - Too early (may not produce the desired outcome or worsens the situation)
    - Too late
  - Qualitative errors
    - Too little (insert too little water)
    - Too much (insert too much water)

The third and perhaps the most popular scheme is based on the cause of the error; this scheme is also referred to as the Skill, Rule, Knowledge (SRK) model. Multiple variations exist for this scheme; however, they more or less mention the same points. The scheme is shown in Figure 4 below.

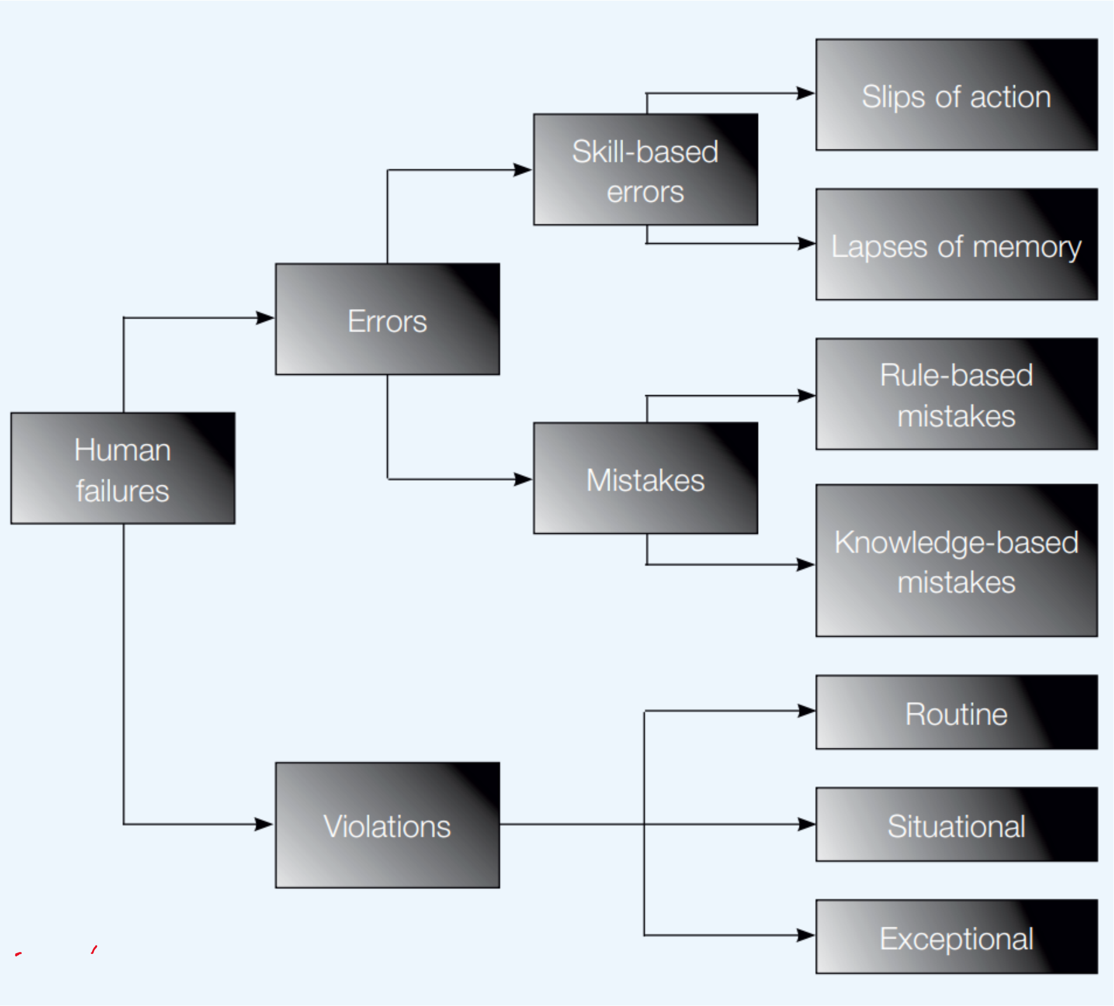

Figure 4: SRK Error Classification Scheme[5] [36]

Analyzing human error is one of the activities involved in a larger effort to quantify human errors, which is called Human Reliability Assessment (HRA). Numerous techniques are available for HRAs with great room for customization and innovation, but they typically involve the same broad steps, which are as follows [38]:

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[5] Reprinted from *reducing error and influencing behaviour,* by Health and Safety Executive, 1998, The Stationary Office, United Knigdom. Copyright 1999 by Health and Safety Executive

1. **Preparation and problem definition**: this stage documents the reasons for performing HRA, stating the undesired outcome of concern, clarifying how the results for HRA will be used, and identifying the required input data such as incident reports, plant drawings (e.g., P&IDs), procedures, etc.
2. **Task analysis (TA):** understanding the tasks is at the core of HRA; without TA, almost all of the subsequent HRA would not be completed. There are many techniques for conducting TA, with Hierarchal Task Analysis (HTA) being a popular one. It is important for TA to capture the real tasks being executed in the field. To ensure an accurate representation of the tasks, HRA analysts will need to review procedures, interview Subject Matter Experts (SMEs), and conduct field walkthroughs at the task site.
3. **Human failure identification:** an accurate representation and breakdown of the tasks allow the analyst to understand how basic actions can fail. Failure identification is carried out by the application of deviation guidewords to basic actions; it is important to note that only observable human failures are recorded at this stage of HRA analysis, e.g., failure to close a valve. There is a tendency to overspecify human failures at this stage; hence the analyst must be careful to include only those failures known to result in the consequences of concern are considered for subsequent steps (as identified in the first stage of HRA). Failure identification is typically accomplished via a team workshop, and in this manner, opportunities for valuable information exist, such as identifying potential recovery mechanisms and causes for observable failures. It is worthwhile to capture and document such information as it will prove valuable for subsequent stages of the analysis.

4. **Human failure modeling:** The identified failure can now be integrated with broader risk assessment (i.e., if this HRA was part of a QRA); alternatively, the modeling can be done as a standalone activity. Tools such as event trees can be used to define the mechanism of failure; these should recognize issues such as time for operator recognition and recovery of the failed event. Caution should be exercised when dealing with safeguards that are not independent of each other. For example, when two operators check to verify each other's work, an error committed by one operator can still be missed by the other operator [39]. Other activities of this nature are referred to as human performance tools (e.g., supervisory checks or peer checks)[61].
5. **Human failure quantification:** Several HRA techniques or tools can be used to aid in the quantification. For each identified failure from step 3, a Human Error Probabilities (HEP) is specified (measured as the number of errors that occurred divided by the number of opportunities for error). The values are then aggregated through the developed model (e.g., event tree calculations). It is important to recognize the applicability of the HEPs to the context. PSFs are used for some HRA tools to scale the values for HEPs and make them more appropriate to the context.
6. **Impact assessment:** Calculation of HEPs allows the analyst to use these values for risk assessment purposes; for example, by knowing the HEP for a task and the frequency of the operator exposure to the task, the analyst can compute the overall probability of the event scenario. These values can be compared with acceptable limits set by the organization and determine whether or not failure reduction is warranted.
7. **Failure reduction:** identified failure may be reduced in four ways:

- Removing the hazards: this an inherently safer design practice because what you don’t have can't leak. It is noted that this approach may not be feasible at times.
- Eliminating the possibility of failure occurrence, e.g., via interlocks.
- Increasing the possibility of failure recovery, this may be achieved through use of human performance tools such as independent checks.
- Optimizing the identified PSFs that influence the HEPs.

8. **Review:** as with any risk assessment or hazard elimination process, a continuous review is important to make sure that the desired effects materialize and to ensure that any changes to the underlying assumptions of the HRA are properly managed.

HRA techniques can be categorized as first-generation, second-generation, and third-generation methods. First-generation methods use expert judgment to modify HEPs; they also focus on the skill and rule-based level of human interaction and are behavior-based. 2nd generation methods are conceptual-based, which extend their analyses to cover issues related to cognition, such as decision making and problem-solving. Moreover, third-generation utilizes industry-specific data [62]. Table 3 presents examples of HRA techniques.

Table 3: Examples of HRA methods [62]

Generation	HRA Method
First-Generation	Technique for Human Error Rate Prediction (THERP)
	Accident Sequence Evaluation Program (ASEP)
	Human Error Assessment and Reduction Technique (HEART)
	Simplified Plant Analysis Risk Human Reliability Assessment (SPAR-H)
	Human Reliability Management System (HRMS)
	Justification of Human Error data Information (JHEDI)
	INTENT
Second-Generation	Technique for Human Event Analysis (ATHEANA)
	Cognitive Reliability and Error Analysis Method (CREAM)
	Connectionism Assessment of Human Reliability (CAHR)
	Commission Errors Search and Assessment (CESA)
	Conclusions from occurrences by descriptions of actions (CODA)
	Method d'Evaluation de la Realisation des Missions Operateur pour la Surete (MERMOS)
Third-Generation	Nuclear Action Reliability Assessment (NARA)

1.5.1.1 HEART Case Study

The HEART methodology is one of the first generation methods; it was developed by J.C William in 1985 [63]. In this method, the user matches tasks from a list of 9 predefined generic task categories; each category is based on the nature of the task and has an assigned nominal human unreliability. Once nominal human unreliability values are identified, the analyst is advised to select context modifiers or PSF multipliers from a list of 38 PSFs. For each PSF, a quantity called the Proportion of Effect (APOA) is then identified. APOA is a subjective value that ranges from 0 to 1, and it corresponds to how strongly a given PSF will influence the success of task performance, i.e., the importance of a PSF among other PSFs based on the analyzed context. The heart method has undergone several developments and revisions since its inception in light of new research in human factors. For example, the generic human unreliability values were revised in 2016, and two new PSFs were added, bringing the total number of predefined PSFs to 40. The assessed impact is then calculated, and HEPs are determined [63]. An isolation task case study is presented in the next section, and the HRA steps from 1 to 5 will be addressed to illustrate how HEART can be applied.

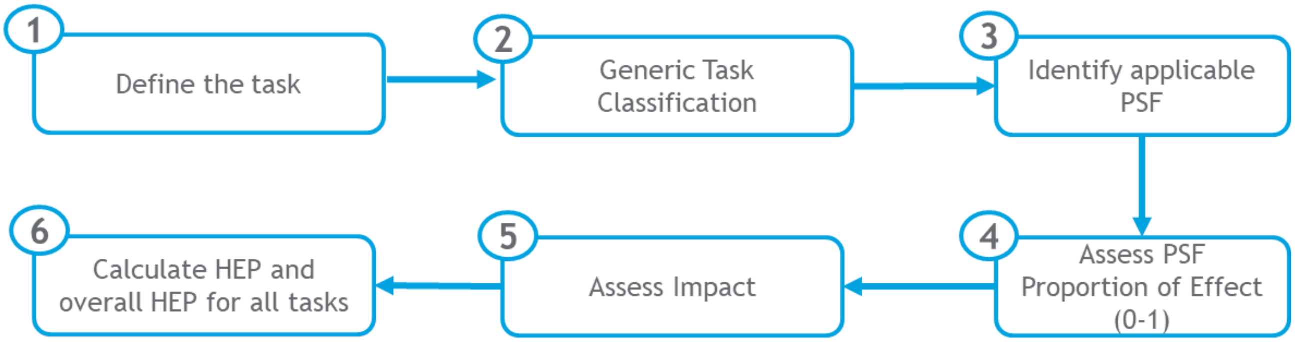

Figure 5: Flowchart of HEART methodology [63]

$$Assessed\ Level\ of\ Impact\ = \big((PSF\ Multiplier\ - 1)\ \mathrm{APOA}\big) + 1 \qquad \text{Eq. (1)}$$

$$HEP_{Task} = Nominal\ Human\ Unreliability \prod_{PSF=1}^{n} Assessed\ level\ of\ Impact_{PSF} \qquad \text{Eq. (2)}$$

$$HEP_{Overall} = \sum_{Task=1}^{n} HEP_{Task} \qquad \text{Eq. (3)}$$

Step 1: Preparation and problem definition

Following the HRA methodology, the HRA team should begin by understanding the scope of the problem. In this case, the job is to replace a faulty valve (Valve B) in a pipeline section inside a petroleum refinery. Valves A and B are isolation valves; the vent and drain valves are used to empty the content of the piping section before isolation. The hydrocarbon flow is assumed to be influenced by Pump A, and there are two pressure gauges available to indicate pressure levels upstream and downstream Valve B. In this analysis, we will assume that lockout tag out (LOTO) procedures are not applied.

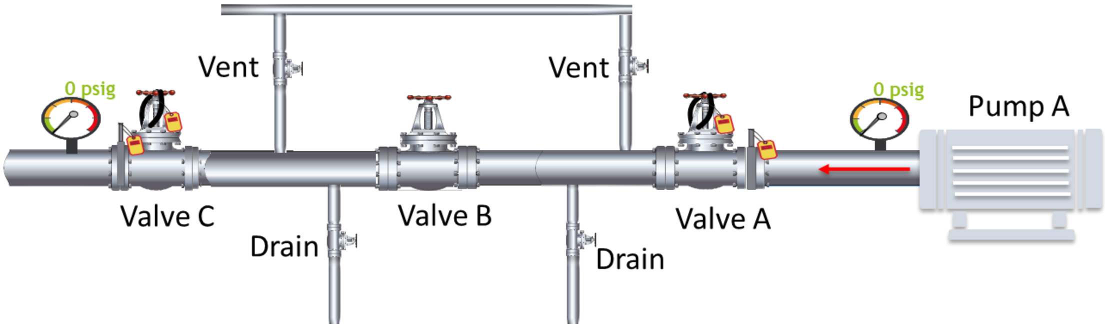

Figure 6: Sketch of a Pipeline Section

Step 2: Task analysis (TA)

Several TA techniques exist; in this case study, a Hierarchical Task Analysis (HTA) is used to decompose the tasks (see Figure 7). Following the methodology identified earlier, we begin by understanding the scope of the problem.

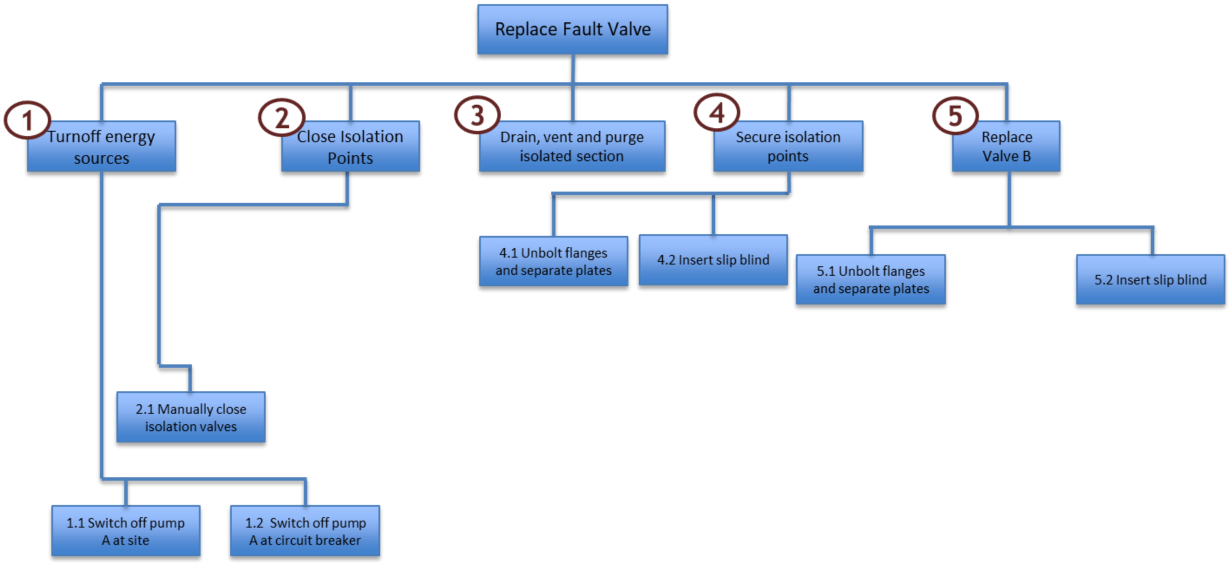

Figure 7: HTA of Valve Isolation Task

Step 3: Human failure identification

In HEART methodology, human failure is identified by matching each task with Generic Task Types (GTTs) (see In this study, we highlighted that HF is a contributory cause to most accidents and that it is influenced by work tasks, organizational context, environmental context, work tools and work equipment, workspace, and work area. Moreover, the field s concerned with addressing these influencers is HF Integration, in which HF can be integrated at the design stage (commonly referred to HFE integration) or at the operational stage. When discussing the operational stage integration, the integration model must align with the organization's management systems, most preferably its PSMS, and should be embedded at all levels of the PSMS document hierarchy. At the design stage, most HPI and CPI companies follow the Waterfall System Development Lifecycle (SDLC) approach to system design; hence the integration strategy should be aligned with this approach. At the conceptual design stage, there is limited information available; however, there is still an opportunity to make decisions that can improve human performance. Such decisions include the identification of the user requirements, functional requirements, preliminary allocation of these functions, and project management requirements. We presented five approaches to HFE integration at the conceptual design stage. In the first approach, we highlighted that HF KPIs could be used for operational stage and design stage integration; however, there are challenges to their incorporation at the conceptual design stage where most of the KPIs are valid at the operational stage, and the ones that are valid at the design stage require information that is only available in later design stages. Furthermore, the KPIs rely on HPI and CPI companies' past experiences in HFE, not to mention the lack of a validated HFE integration model to give companies more confidence in following a specific HFE integration approach. In the 2nd approach, we showed how CWA could be used to help define HMI functional requirements and decision support principles at the conceptual stage. However, this requires input from operational personnel and people familiar with CWA. In the 3rd approach, we showed a simple numerical analysis tool based on WDA results to help estimate HEP for the physical functions of the plant. This approach has its limitation due to the inability to aggregate physical function probabilities to high-level probabilities. In the 4th approach, we showed how inherently safer design can be successfully integrated into the conceptual design and how this may not be applicable to HFE due to the limitation of process modeling software in addressing human performance requirements. Finally, in the 5th approach, we built a BBN to help the project team decide the level of resources needed for HFE Integration. This was demonstrated by incorporating incident data and HFE screening rating of several facets of HFE. This research highlights the difficulty associated with currently available models of HFE integration and how more refinement and guidance is need for HFE Integration at the conceptual design stage. Table 9.) These GTTs have assigned nominal human unreliability values. Table 4 lists the selected GTTS and Nominal Human Unreliabilities for this case study.

Table 4: Valve isolation task selected GTTs and Nominal Human Unreliability

#	Task	#	Task Steps (Sub-Tasks)	Generic Task Type (GTT)	Nominal Human Unreliability
1	Turn off all energy sources	1.1	The operator isolates energy sources by switching off Pump A	G	0.002
		1.2	The operator switches off Pump A at the circuit breaker in the designated electric substation	G	0.002
2	Close isolation points	2	Manually close Valve A and Valve C by operating valve handwheel	G	0.002
3	Drain, vent, and purge isolated section	3	Operator drains, vents, and purges content of piping	F	0.001
4	Secure Isolation Points by positive isolation	4.1	Operator unbolt flange and separate faces of Valves A and C	D	0.06
		4.2	The operator installs a slip blind	E	0.02

Table 4: Valve isolation task selected GTTs and Nominal Human Unreliability

#	Task	#	Task Steps (Sub-Tasks)	Generic Task Type (GTT)	Nominal Human Unreliability
			at Valve C and Valve A		
5	Replace Valve B	5.1	Maintenance technician removes old valve	F	0.001
		5.2	Maintenance technician installs new valve	F	0.001

Step 4: Human failure modeling

An Event Tree Analysis (ETA) was chosen to model the activity flow of the isolation task. For simplicity, failure to perform any of the subtasks leads to a task failure. The ETA is presented in Figure 8. Failure events are designated by capital letters, while successes are designated by lower case letters.

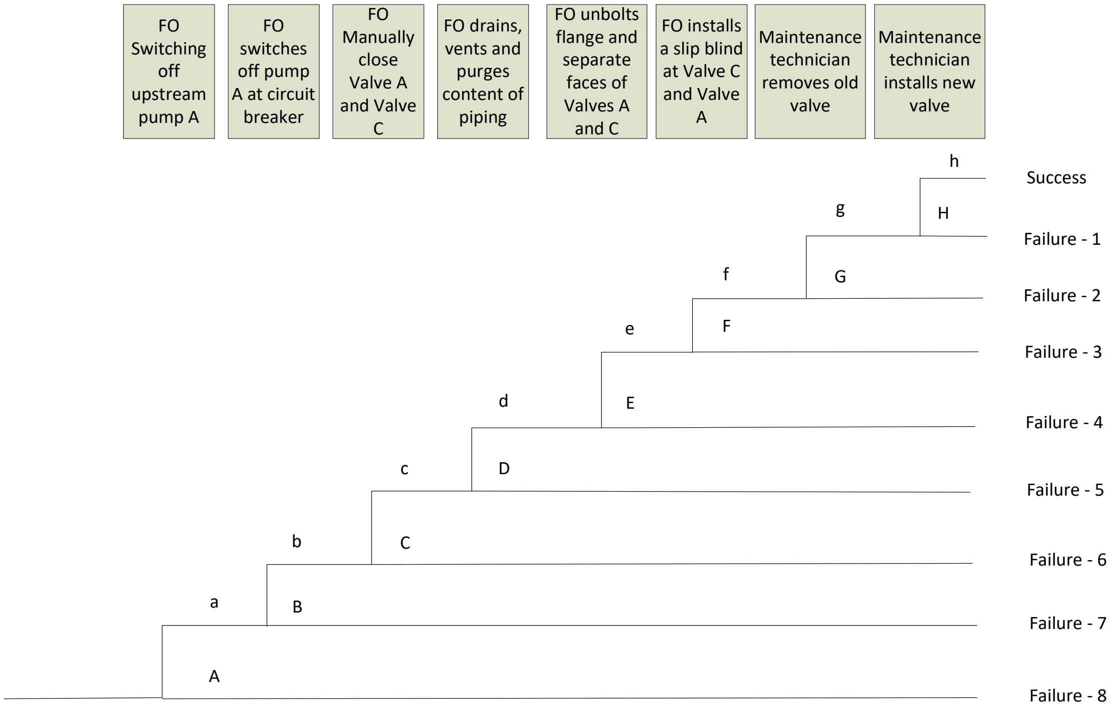

Figure 8: Event Tree Analysis of the valve Isolation Task

Step 5: Human failure quantification

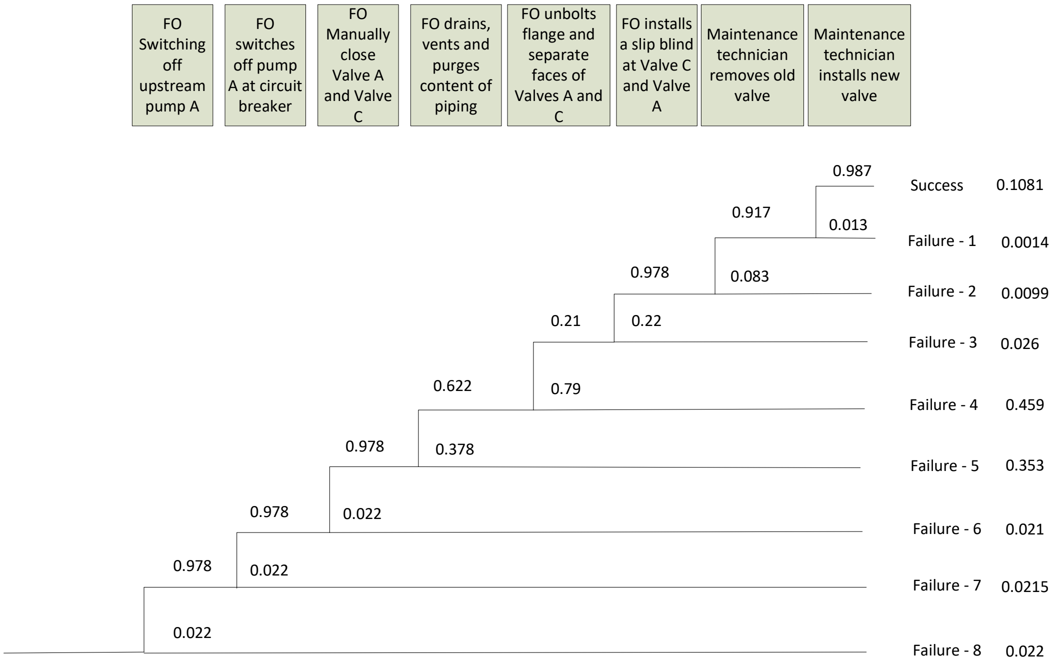

Figure 9: Event Tree Analysis of the valve isolation task with assigned HEPs

Based on the calculations made in Figure 9, the overall HEP is computed as 0.251.

1.6 Gaps

The HFE activities mentioned in Table 1 have many overlaps with each other hence a summary is presented below showing the major activities at the conceptual design stage under five major themes:

- **User needs and characteristics**: a review of user demographic, anthropometric, and biomechanical data, identification of environmental demands on workers, requirements for knowledge, skills, and abilities, development and recording of usability scenarios
- **Identifying potential risks from predecessor plants or previous projects:** a review of incident data related to the project scope, interview with users involved in similar or predecessor plants, review other observation data such as near misses and fault reports
- **Potential issues with novel designs:** if the project involves a novel design with no available published information, the HFE working group may decide to conduct a specific HFE screening to review aspects of the design where potential human performance issues may occur
- **Early functional requirements or design principles:** a good understanding of cognitive processes and cognitive states can help identify functional requirements that would benefit from further analyses and user testing in later design stages

- **Project planning, organization, and management**: this may be the biggest chunk of activities performed in the conceptual design stage, especially for megaprojects. The activities are mainly related to identifying the relevant HFE standards, formalizing the HFE integration plan, establishing the HFE working team and chairpersons, and establishing the HFE issues record-keeping register Figure 10 shows how these major themes interact with each other.

  It is noted that, with the exception of the last activity, these activities rely heavily on incident data, input from subject matter experts, and understanding of the expected users. There is little information in the literature about tools and techniques to leverage these conceptual design activities. Hence this research will consider potential ways to make better use of such activities

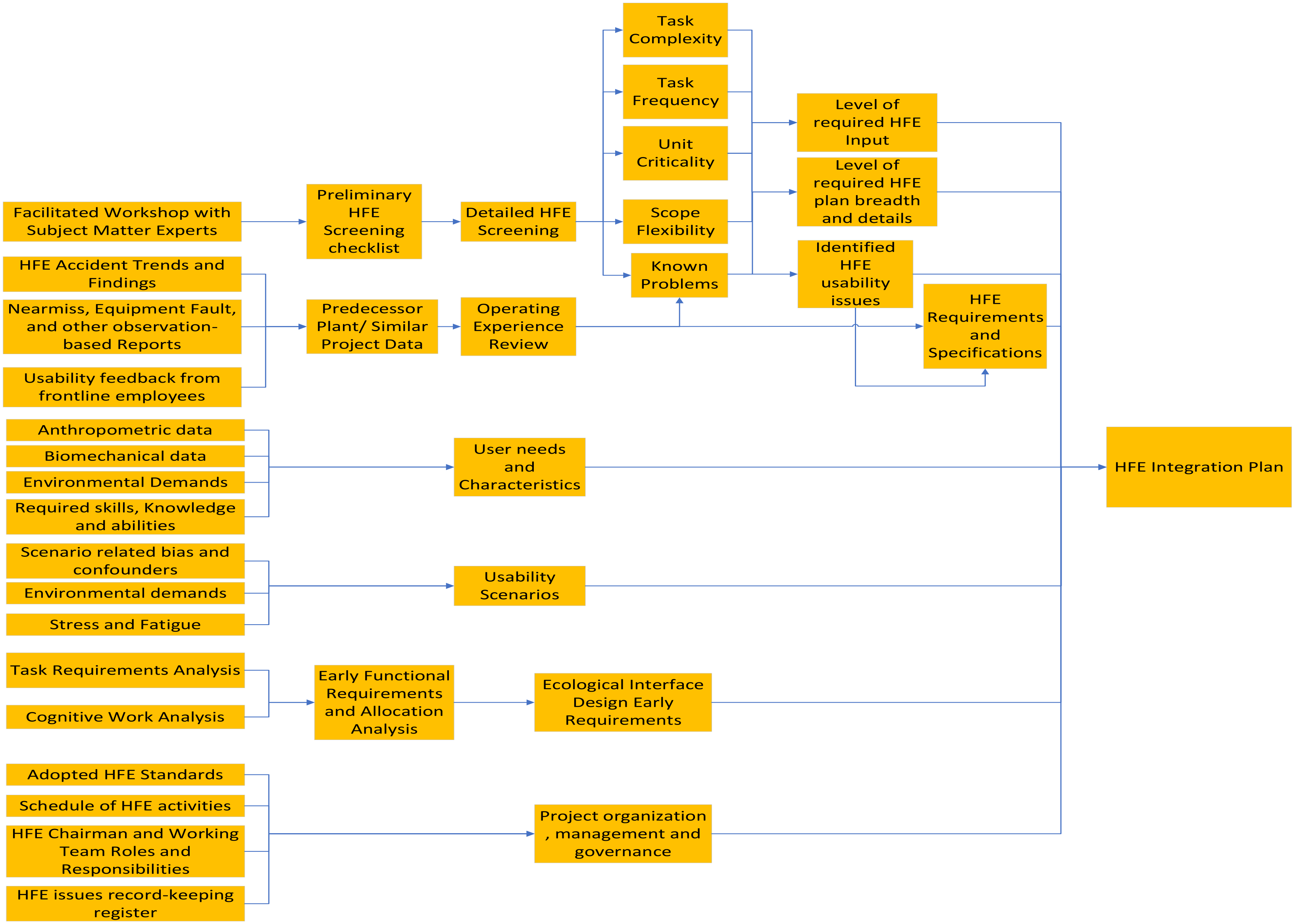

Figure 10: Flowchart of HFE Activities at the Conceptual Design Stage

This thesis is an initial effort to bridge the gap in the missing tools and methods to operationalize HFE activities at the conceptual design.

2. METHODOLOGY

An internet-based search was conducted to review and contrast concepts in Human System Integration, look into potential tools used in assessing human factors, with a particular focus is given to those that are applicable to the early design of chemical plants. A case study of crude distillation unit is evaluated to examine how HFE can be integrated at the conceptual design of HPI and CPI plants. Five approaches are considered: the first is the identification of industry key performance indicators as a means to measure progress to HFE integration. The second is the application of WDA, WOA, and CTA to a refinery's CDU case study with the objective of determining early HMI requirements. The third approach uses the results from WDA and applies numerical calculations to estimate HEP values. The fourth approach is to review the feasibility of process simulation software Aspen HYSYS to model HFE integration for a CDU case study. The fifth and final approach is using Bayesian Belief Networks (BBN) to calculate Human Error Probabilities (HEPs) for a CDU case study.

2.1 Distillation Column Case Study

A simplified crude distillation unit is analyzed in approaches 2, 3, 4, and 5. The crude distillation unit is the first unit that crude oil enters in a refinery. In a crude distillation column, crude oil is distilled into refined products to be sold or to be further processed by downstream equipment into other useful products [64].

There are several hazards involved in the distillation unit; perhaps some of the most prominent ones are the high processing temperatures, which range between 360^{o}

to 434º C (680º – 813º F), which is above the flashpoints of the light hydrocarbon fractions (Gasoline and Naptha) and above the autoignition temperatures for some of the light and heavy fractions (kerosene, gas oil) making it very likely for fires and explosions to take place if these products leak. Furthermore, crude oil feed can contain trace amounts of H_2S, a highly toxic chemical, if inhaled at small concentrations. Another hazard is the high possibility of leaks from vulnerable equipment like valves and flanges in addition to pipe sections that are susceptible to corrosion attacks. Human error is one of the major contributory causes to incidents in crude distillation in particular and refineries in general. A survey was done by British Petroleum (BP) looked at 100 incidents that occurred at crude distillation units was the most frequently reported contributory cause [65]

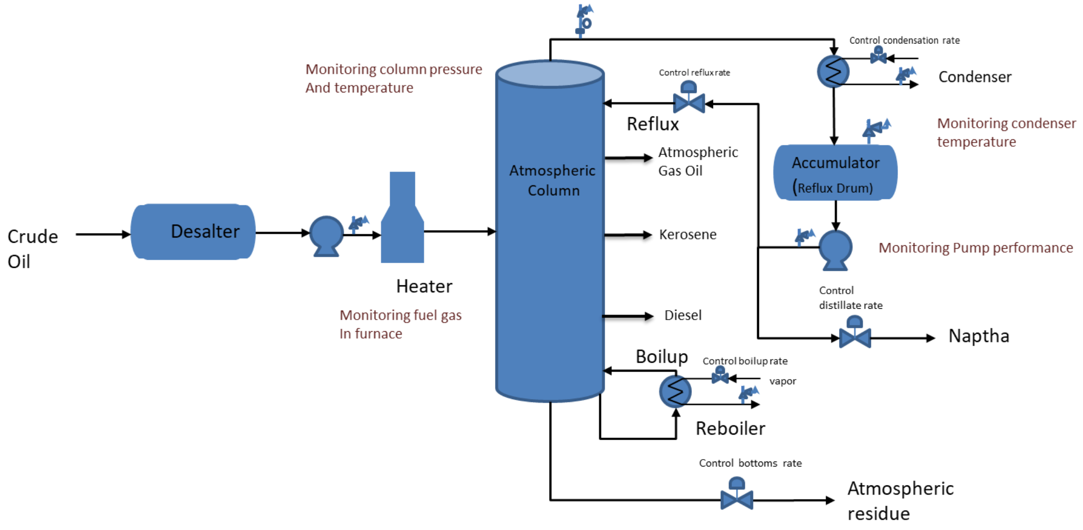

Figure 11: Base Case Atmospheric Distillation Column

A schematic of a base case Atmospheric Distillation Column (ADC) is presented in Figure 11. The ADC consist of the fractionation column, reflux drum, condenser, flow pumps, and heater. For simplicity, the case is limited to upper distillates and lower bottoms with no sidecut products. This case study will be used to demonstrate approaches 2, 3, 4, and 5 in the subsequent sections of this thesis.

2.2 Approach 1: HF Key Performance Indicators

Performance Indicators (PI) or Key Performance Indicators (KPIs) are widely used to help organizations monitor and improve their businesses. There are two types of PIs, lagging (outcome-oriented) metrics and leading (input or process-oriented) metrics [48]. When the organization chooses a PI to monitor, the indicator can be referred to as a KPI. In the safety field, particularly within the context of the chemical, petrochemical, and oil and gas industry, the focus has been on lagging indicators such as fatalities and injury statistics. However, after the Texas City Refinery explosion in 2005, which killed 15 and injured 180 workers, the industry shifted to a more risk-based approach to safety by giving more attention to leading indicators [46]. Several consensus standards and guidelines were developed to help companies identify, select, and use a mixture of lagging and leading process safety indicators. Guidelines developed by the Center for Chemical Process Safety (CCPS) lists lagging and leading PIs for every PSM element [66]. The American Petroleum Institute, through its API-754 recommended practice, categorizes process safety PIs into four tiers. Tier 1 and Tier 2 are lagging PIs concerning Losses of Primary Containment (LOPCs), classified based on threshold values, with defined formulas. Conversely, Tier 3 and Tier 4 are leading PIs. Tier 3 PIs represent challenges or demands on systems barriers, including nearmisses and minor LOPCs. Tier 4 PIs represent the performance of individual components of the system barriers [48]. These two guidelines, however, do not provide a logical approach for selecting the appropriate PIs and leaves it to the concerned organization to judge which indicators should be used. The UK Health and Safety Executive developed the guideline HSG 254, which provides a hazard-based method to select the PIs. The Energy Institute adopted the approach outlined in HSG 254 in the development of HF PIs. The steps involved in developing HF PIs are as follows [67]:

1. **Identify the main process safety hazard scenarios:** this will include the unit or plant, understanding what can go wrong, and the immediate causes of the hazard scenario. Example scenarios include fires, explosions, loss of liquid into tank dikes. Examples of immediate causes can be corrosion, overpressurization, etc.
2. **Identify the relevant Risk Control System (RCS) to prevent major accidents:** RCS can be layers of protection or safety barriers. Examples of RCS can be inspection and maintenance, procedures, instrumentations, and alarms.
3. **State the desired safety outcome or purpose of each identified RCS:** the safety outcomes represent what success looks like for the RCS, such as the major consequences to be averted or the reasons why the RCS is in place, for example, a desired safety outcome for a procedure RCS would be that tasks are executed safely in line with the original design intent of the procedure
4. **Set a lagging indicator for the identified outcomes.**
5. **State the critical elements of the identified RCS:** critical elements are the essential components for each RCS that are responsible for controlling the risk.

These may be activities that must be undertaken frequently to ensure the effectiveness of the RCS or the aspects of RCS, which are subject to deterioration with time.

6. **Set leading indicators for the identified critical elements of the RCS.**

   Figure 12 shows the different RCS involved in Human Factors, which represent the main overarching elements for HFs in PSM, and Table 5 presents a selected number of PIs for each RCS. When HF KPIs are selected, they should be embedded within the organizations PSMS as outlined in an earlier section of this research (refer to 1.4.1 Integration Into **PSMS**)

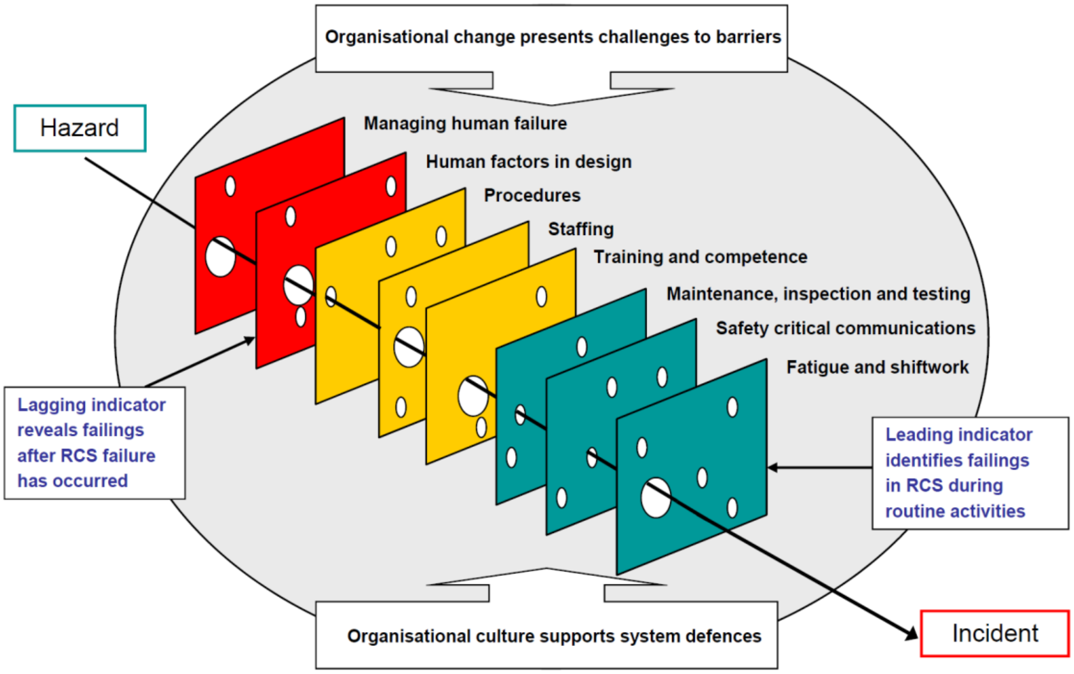

Figure 12: Reasons' Swiss Cheese Accident Trajectory Model[6] [24]

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[6] Reprinted from *Human Factors Performance Indicators for the Energy and Related Industries,* by The Energy Institute, 2010, by The Energy Institute, United Knigdom. Copyright 2010 by The Energy Institute

Table 5: Selected HF PIs for each RCS [24]

RCS	HF Lagging PI	HF Leading PI
Managing Human Failure	Quantity or percentage of investigated accidents in which human failure was identified as a causal factor	Quantity or percentage of HAZOPs that evaluated human failure
Human Factors in Design	Quantity or percentage of incidents where human failure was attributable to poor design	- The compliance rate with Human Factors Integration Plan (HFIP) - HF issues raised during design reviews - Operator views or rating of equipment usability - Design reviews completed with the participation of HF specialists - Percentage of equipment found non-compliant with HF standards after construction - The compliance rate with workplace HF environmental issues (e.g., lighting, noise, and temperature)
Procedures	Quantity or percentage of non-compliance/violations in following a procedure (equipment manuals or permit to work forms)	- Timely completion of scheduled procedure reviews - Procedures found to be meeting quality criteria (i.e., writers guide) in procedure walkthroughs
Staffing	Quantity or percentage of incidents where staff shortages/workload was identified as a root cause	Completion of staff workload assessment

Table 5: Selected HF PIs for each RCS [24]

RCS	HF Lagging PI	HF Leading PI
Training and Competence	Quantity or percentage of incidents where lack of competence was identified as a root cause	- Timely completion of scheduled training - Percentage of safety-critical staff assessed to be competent in their role
Maintenance, Inspection, and testing	Quantity or percentage of incidents in which failure in maintenance, inspection, and testing was identified as a root cause	Percentage of the maintenance backlog
Safety-critical communication	Quantity or percentage of incidents where a failure of safety-critical communication was identified as a root cause	The compliance rate with communication protocols based on spot checks
Fatigue and shiftwork	Quantity or percentage of incidents where fatigue issues or shift scheduling was identified as a causal factor	- The average number of hours worked per employee - Number or percentage of non-compliance with shift patterns
Organizational Change	Quantity or percentage of incidents where failures in the Management Of Organizational Change (MOOC) process was to be a root cause	Quantity or percentage of Organizational Changes assessed as part of MOOC
Organizational Culture	Number or percentage of reported nearmisses	- Number or percentage of leadership plant walkthroughs - Results from safety climate surveys

2.3 Approach 2: Work Domain Analysis

Human performance can be analyzed qualitatively through work analysis, which can be in one of two ways: task analysis or Work Domain Analysis (WDA). Tasks analysis describes the operator actions that need to be taken to achieve system goals, while WDA describes the system functional structures and constraints independently of tasks or events. A straightforward way to distinguish between the two is to think of task analysis as navigating through a map of a city to reach a destination, while WDA is the map itself with all locations and districts labeled. The latter approach is favored for safety-critical systems because it emphasizes the invariable features of a given system. WDA provides more flexibility in managing abnormal or unanticipated events that have given rise to major industrial catastrophes throughout history, such as the Texas city refinery explosion or Bhopal MIC gas release into the surrounding community. The most common method for performing WDA is via the Rasmussen Abstract Decomposition Space (ADS) or sometimes called the Abstraction Hierarchy. ADS is a two-dimensional matrix that describes the structural means-ends and part-whole relationships. The means-end functional relationship links the conceptual model of a system to its physical components by decomposing the socio-technical system structure into five levels known as domain purpose, domain values and priorities, domain functions, physical functions, and physical objects. Each one of these levels is explained in Table 6. ADS is quite useful in designing human-machine interfaces by identifying critical information that needs to be monitored and controlled. The human-centered design of Interfaces using the ADS approach is referred to as Ecological Interface Design (EID) [68].

Table 6: Abstraction Hierarchy Components [25]

Abstraction Hierarchy	
Domain purpose	The main purpose that the work domain (environment or socio-technical system) is designed to satisfy, e.g., build furniture, theatrical entertainment
Domain Values and Priorities	Principles, standards, or qualities to be maintained, e.g., aesthetic, stability, engagement
Domain Functions	General operational functions sufficient to execute the work that will satisfy the domain, device-independent and purpose-related, constrained by the Domain Values and Priorities, e.g., fabrication, planning, communication
Physical Functions	Functions realized by activation or use of technical devices or physical subsystems (physical elements of the system), e.g., lightning, cutting
Physical Objects	Physical devices and subsystems Identified by their names, appearances, and locations, e.g., saw, tape, plane

The ADS for the ADC is presented in Figure 13. The ultimate purpose of an ADC is to distill crude oil into useful products. The guiding principles for this purpose are process stability, meeting specifications, maintaining asset integrity, efficient operations, and safe operations. Process stability addresses situations that give rise to column flooding, entrainment, and weeping while at the same time managing environmental disturbances and changing operational requirements. Safe operations is closely related to process stability, with a focus on ensuring that process parameters do not result in overpressure scenarios. To maintain operations stability, certain functions must be observed, such as adequate heat supply and removal, maintain and maximize vapor-liquid contact to achieve product separation, maintain adequate vapor pressure in the column, as well as liquid velocity and product extraction to downstream equipment. At the physical level, domain functions are achieved by process control loops for temperature, pressure, level and flow. Process control loops make changes at individual equipment like the condenser, inlet furnace, reboiler, reflux drum, and column.

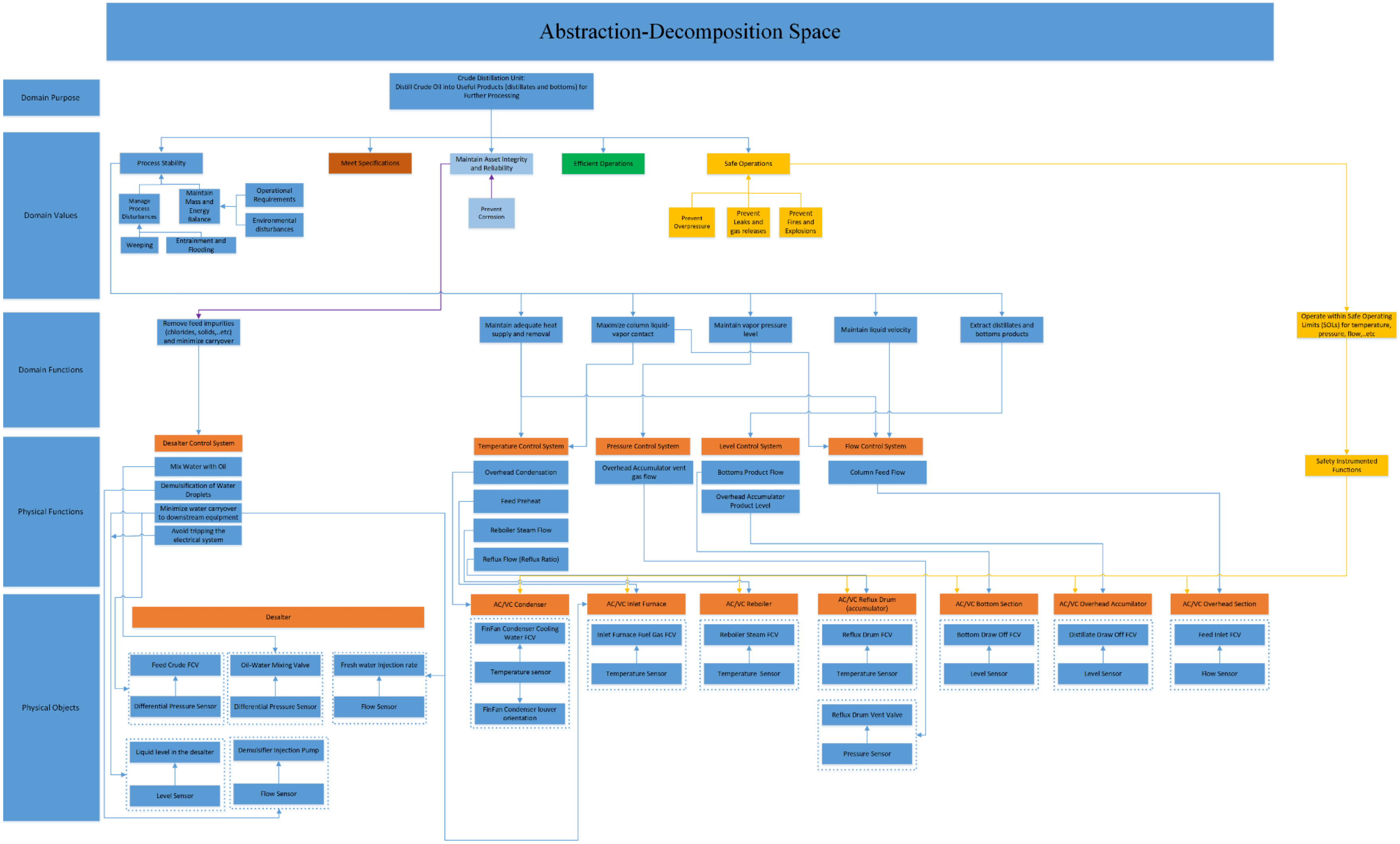


Figure 13: ADS for an Atmospheric Distillation Column

Process control loops make changes at individual equipment like the condenser, inlet furnace, reboiler, reflux drum, and column.

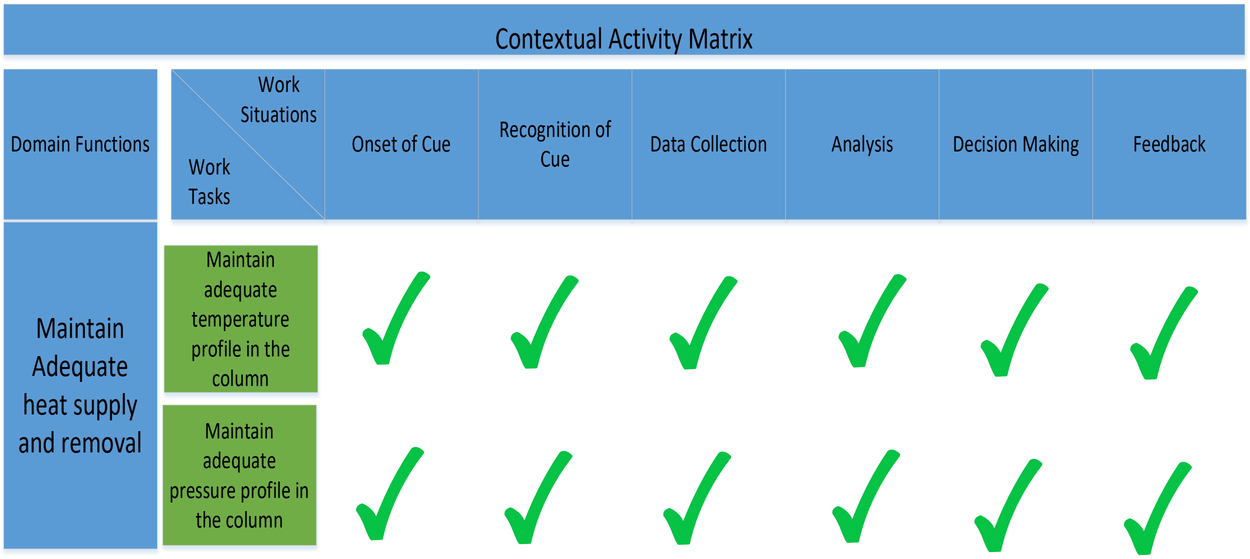
WDA is one component of a broader framework known as Cognitive Work Analysis (CWA). One definition of CWA is “a framework for the analysis, design, and evaluation of complex socio-technical systems” [69]. The stages involved in CWA are as follows [25]:

1. **Functional Work Structure (i.e., WDA):** determine the domain functions. The output is the ADS, as shown in **Error! Reference source not found.**
2. **Work Organization Analysis:** identify the work tasks associated with the domain functions. The output is the contextual activity matrix shown in Figure 14.
3. **Cognitive Transformation Analysis:** identify the cognitive processes and states. The output product is a decision ladder for each identified work task, as shown in Figure 15.
4. **Strategies Analysis:** identify the cognitive strategies employed in transferring between cognitive states. The output product is a description of the different strategies for each cognitive state transition along with their advantages and disadvantages.
5. **Cognitive Processing Analysis:** determine the cognitive modes (skill-based, rule-based, and knowledge-based) used in the cognitive strategies. The output product is a description of the activity elements associated with each cognitive mode.

6. **Social Transaction Analysis:** determine the peer-to-peer interactions and management-worker interactions. The output product is a Social Transactions Matrix.

The discussion and details of the stages from 2 to 6 can be found in [25].

In this case study, we have applied stages 2 to 3 to demonstrate how CWA can be used to help produce EID guidelines.



Contextual Activity Matrix

Domain Functions	Work Situations / Work Tasks	Onset of Cue	Recognition of Cue	Data Collection	Analysis	Decision Making	Feedback
Maintain Adequate heat supply and removal	Maintain adequate temperature profile in the column	✓	✓	✓	✓	✓	✓
	Maintain adequate pressure profile in the column	✓	✓	✓	✓	✓	✓

Figure 14: Contextual Activity Matrix for CDU case study

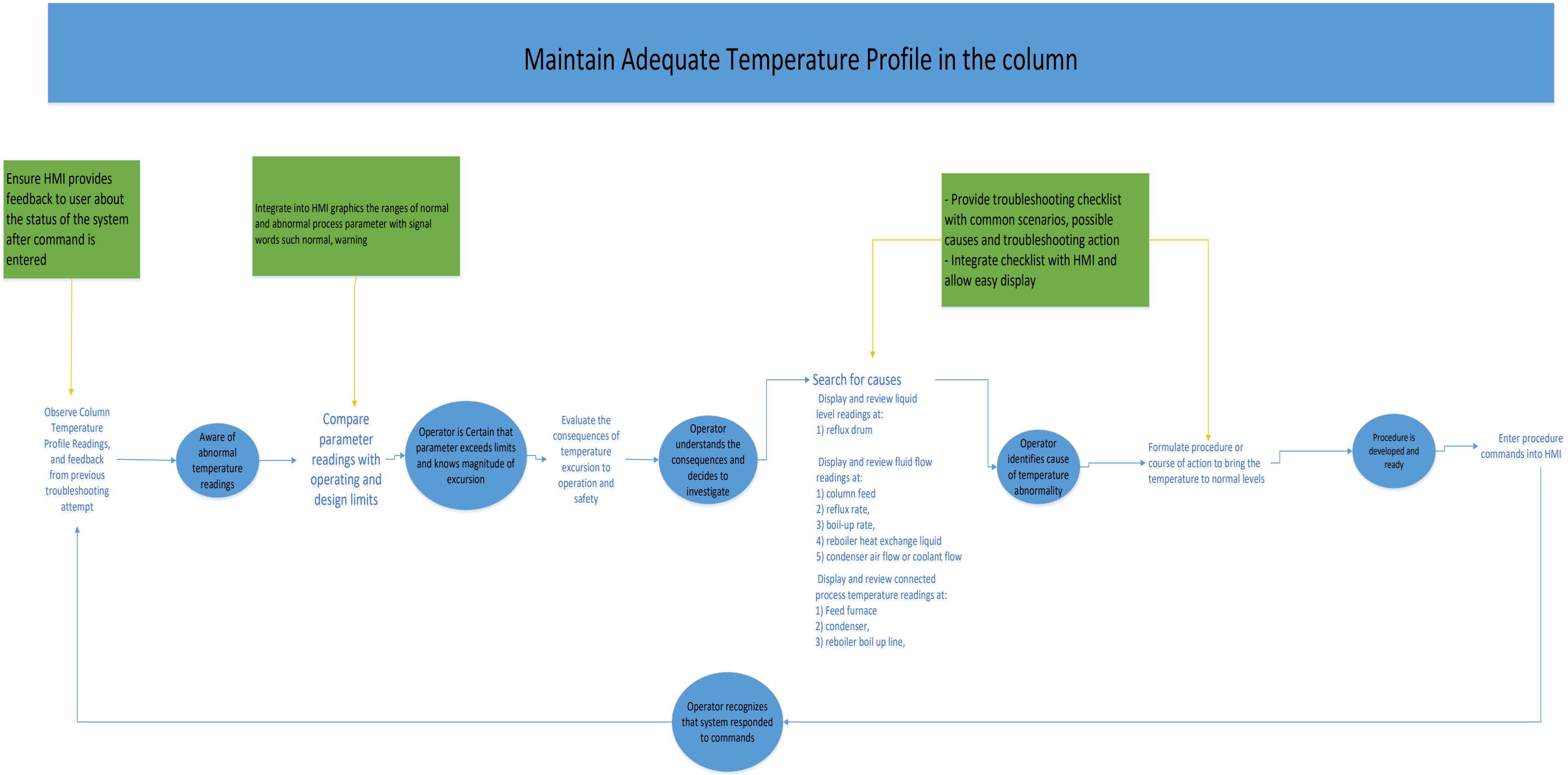


Figure 15: decision tree showing cognitive states and cognitive processes for a work task

The blue circles in Figure 15 are cognitive states (e.g., being aware, understanding, knowing, made a decision, has a mental image, being certain, recognition). The text boxes represent the cognitive processes (e.g., identify alternatives (search), interpreting, comparing, selecting, observing, assessing, reading, seeking information, planning, reflecting (reviewing), deciding, imagining, viewing, understanding, identifying, mentally stimulating a procedure, executing). The green boxes are possible interventions to make the decision more human-error tolerant. From this analysis, the following recommendations can be made at the conceptual design stage of the CDU:

- Ensure HMI provides feedback to users about the status of the system after the command is entered
- Integrate into HMI graphics the ranges of normal and abnormal process parameter with signal words such as normal or warning
- Provide troubleshooting checklist with common scenarios, possible causes, and troubleshooting action in addition, integrate the checklist with HMI and allow easy display

This case study demonstrates the strength of CWA in identifying design principles at the conceptual design stage. HFE integration framework presented by Chua and Feigh [70] recommended the use of CWA in the conceptual design stage. Nevertheless, the construction of the model using CWA requires input from subject matter experts and a clear understanding of the unit in question.

2.4 Approach 3: Use the ADS results to calculate HEP

The HEP calculation is carried out by determining the following:

- Estimated Maintenance Task load factor for each equipment identified by equipment release frequencies published in IOGP 343.01 [71]
- PSF investment multipliers for HMI and procedures identified by PetroHRA (see Table 11)
- Minimum number of displays or screens set as a typical value of 6 screens per unit in a petrochemical plant as reported in [18] [72]
- Investment level multipliers for Procedures and HMI

The following formula was used to compute the overall HEP for the domain value in ADS. Each physical function has a different set of physical objected connected to it based on the links in Figure 13; hence the adjusted HEP can differ from one physical function to another.

$$Physical\ functions = Number\ of\ Required\ Displays\ xHMI\ Investment\ x\ Procedure\ \ Investment\ x\ Max\ (EMT\ of\ associated\ physical\ objects) \qquad \text{Eq. (4)}$$

Table 7: Physical Functions HEP Estimation with Assumed Investment Multipliers

IOGP 434.01 Release Frequency per Year Full Bore Rupture Scenario	Physical Object	HMI Investment multiplier	Procedure Investment multiplier	Physical Functions	Estimated HEP
0.00093	Condenser	0.5	50	Temperature Control System	0.13950
0.00024	Inlet furnace	0.5	0.5	Pressure Control System	0.00140
0.00024	Reboiler	0.5	0.5	Level Control System	0.00036
0.00024	Reflux Drum	0.5	0.5	Flow Control System	0.00018
0.00012	Column Bottom Section	0.5	10	Desalter Control System	0.0072
0.00024	Overhead accumulator				
0.00012	Column overhead section				
0.00024	Desalter				

This approach allows a very simple estimate of HEPs in the absence of simulated and real data. However, it is noted that the choice of the investment multiplier levels relies heavily on subject matter experts. This is why prospective analysis statements are provided in APPENDIX Table 12 and Table 13. It is also noted that this estimation cannot be aggregated to the Domain Function, values, and purpose level. Because at these levels, the system is described in very abstract device-independent statements, which makes it difficult to propagate numerical HEP values above the physical function level.

2.5 Approach 4: Process Simulation and Economic Analysis

2.5.1 Use of ROI index

At the early design stages, senior executives and project managers review the financial viability of projects. Some of the metrics calculated for this purpose include Net Present Value, Payback Period, and Return on Investment (ROI). It is not surprising to see many improvements to safety and usability being ignored since this assessment does not usually involve safety professionals and human factors practitioners; furthermore, the assessment purely looks at the financial aspect of the project. This is quite unfortunate since this stage offers great maneuverability and flexibility to prioritize projects and make decisions that will save companies from detrimental events such as industrial accidents. The conventional ROI is expressed as follows:

$$ROI_p = \frac{AEP_p}{TCP_p} \qquad \text{Eq. (5)}$$

Where $\boldsymbol{AEP_p}$ is the Annual Net Economic Profit for project **p**, and $\boldsymbol{TCP_p}$ is the Total Capital Cost for project **p**. If the ROI meets the company's acceptability threshold, the company may choose to pursue the project. To counteract the tendency to overlook essential design objectives other than profitability, companies can use a modified version of the ROI index, capturing both the financial aspect and other objectives of concern [73]. Several papers explored the potential for modifying ROI index to capture organizational objectives. El-Halwagi [73] modified the $\boldsymbol{AEP_p}$ given in Eq. (5) to capture sustainability objectives such as the reduction of carbon dioxide emission, elimination of hazardous waste to the environment and reduction in volatile organic compound emissions. the modified $\boldsymbol{AEP_p}$ is given below

$$ASP_p = AEP_p \left[1 + \sum_{i=1}^{N_{Indicators}} w_i \left(\frac{Indicator_{p,i}}{Indicator_i^{Target}} \right) \right] \qquad \text{Eq. (6)}$$

Where:

- $Indicator_{p,i}$ is the ith indicator of interest to used to measure sustainability for the p^{th} project
- $\mathrm{Indicator}_{\mathrm{i}}^{\mathrm{Target}}$ is the target or optimum level of performance for $\mathrm{Indicator}_{\mathrm{p,i}}$ determined through benchmarking with other companies, past performance, regulations, and other sources of data
- $\mathrm{w_i}$ is the company assigned importance or priority factor ranging from 0 to 1 for $\mathrm{Indicator}_{\mathrm{p,i}}$

Thus Eq. (6) can be substituted into Eq. (5) to result in the below expression

$$SWROIM_p = \frac{ASP_p}{TCP_p} \qquad \text{Eq. (7)}$$

Where $SWROIM_p$ is the Sustainability Weighted Return on Investment Metric for the pth project. Nevertheless, equation Eq. (6) does not consider base case design values, which are frequently used, starting values based on previous company experience and requirements. To account for base case values and avoid the situation where the SWROIM curve never intersects with the ROI curve, Eq. (6) is modified to

$$ASP_p = AEP_p \left[1 + \sum_{i=1}^{N_{Indicators}} w_i \left(\frac{Indicator_{base,i} - Indicator_{p,i}}{Indicator_{base,i} - Indicator_i^{Target}}\right)\right] \qquad \text{Eq. (8)}$$

Where:

- $Indicator_{base,i} - Indicator_{p,i}$ quantifies improvements (when the difference is positive) or deterioration of the pth project.
- $Indicator_{base,i} - Indicator_i^{Target}$ quantifies the maximum improvement range for the pth project.
- $\frac{Indicator_{base,i} - Indicator_{p,i}}{Indicator_{base,i} - Indicator_i^{Target}}$ quantifies the ratio of improvements contributed by $Indicator_{p,i}$ compared to the maximum improvement range

The $\mathrm{SWROIM_p}$ can be further expanded by considering indicators not only related to sustainability objectives but also safety objectives using the formula given in Eq. (8) thus changing the title of the index to Safety and Sustainability Weighted Return on Investment Metric (SASWROIM).

Using SAWROIM allows decision-makers to review different design process routes by considering the impact or outcome they have on sustainability and safety objectives. In the work done by [28], the impact of dimerization temperature on both ROI and SAWROIM is compared. The choice of the dimerization temperature as an independent variable is primarily due to its significant impact on yield, cost, safety, and sustainability.

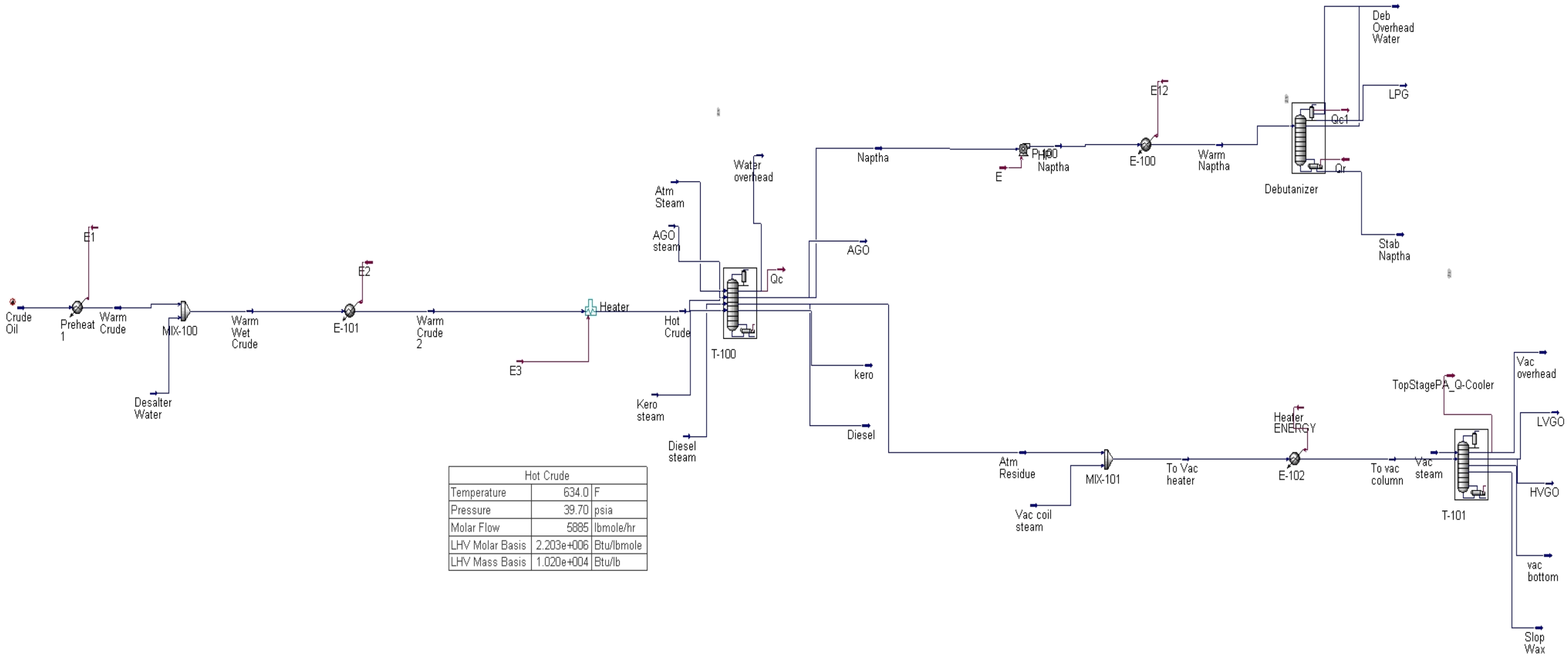
2.5.2 Human Error ROI

Applying the ROI concept to human factors requires that human factors are quantified; however, since minimal information is available, an approximative approach is attempted by leveraging the power of HEPs. The values of HEPs can be computed from PSF values taken from widely used HRA techniques. For this paper, the technique used here will be the PetroHRA, a modified version of SPAR-H, a first-generation HRA method. The reason for selecting the PetroHRA technique is its specificity to the petroleum industry [39], which is the intended application of this paper. Eq. (7) and Eq. (8) can be re-written as follows:

$$Human\ Error\ ROI_p = \frac{ASP_p}{TCP_p} \qquad \text{Eq. (9)}$$

$$ASP_p = AEP_p \quad \left[1 + \sum_{i=1}^{N} w_i \left(\frac{HEP_{base,i} - HEP_{p,i}}{HEP_{base,i} - HEP_i^{Target}}\right)\right] \qquad \text{Eq. (10)}$$

A model of CDU was developed in Aspen HYSYS, as shown in Figure 16



Hot Crude		
Temperature	634.0	F
Pressure	39.70	psia
Molar Flow	5885	lbmole/hr
LHV Molar Basis	2.203e+006	Btu/lbmole
LHV Mass Basis	1.020e+004	Btu/lb

Figure 16: Aspen HYSYS Model of a simplified CDU

However, upon closer examination, it became clear that process simulation software do not offer the capability to model HFE integration. Based on the typical information available in the conceptual stage design, the only sources of information is via subject matter experts from:

- HFE screening and workshops where HF requirements are defined based on predecessor plants, previous incidents, and interviews with workers. These requirements may be associated with detailed design features such as HMI, valve orientation, handwheel design, workplace arrangement
- Functional requirements and their allocation via the use of CWA

The issue is that most of these requirements cannot be modeled at the conceptual design stage due to a lack of information and with some requirements, such as functional requirements being too abstract to be added to a purely physical system.

2.6 Approach 5: Bayesian Belief Network

Bayesian Belief Network (BBN) is a probabilistic graphical model. The network itself is characterized as a directed acyclic graph consisting of nodes and directed links (arcs or edges). Nodes represent states, while links represent the relationship between states. The main governing characteristic of BBN is its capability to model conditional probability as stipulated in Bayes theorem (see Eq. (10))[74].

$$P(Y|X) = \frac{P(X|Y)P(Y)}{P(X)} \qquad \text{Eq. (11)}$$

$$P(X) = \prod_{i=1}^{n} p(\,X|Y_i)\; p(Y_i) \qquad \text{Eq. (12)}$$

The conditional probabilistic nature of BBN allows them to model system interdependencies and update existing knowledge based on observation of new evidence. BBN can be used to model stochastic systems where data uncertainty is high, data sources are diverse, and subjective expert judgment is necessary. These features make BBN an attractive tool for applications where the analyst is interested in performing diagnostic, predictive, and inter-causal reasoning [74]. Such applications include biotechnology, healthcare system, management efficiencies, and operational risks [75].

Figure 17 shows a simple example of a BBN. The network is composed of four nodes (O, T, M, and N) and three links. Node O is considered a parent node of M, and similarly, node T is a parent node of M and N. Nodes M and N are child nodes. If a node has no parent node, it is regarded as a root node [74]. Each node can be modeled as using either discrete or continuous distributions. In Figure 17, the nodes are modeled incorporating a discrete Boolean distribution with two states, “False” and “True.”

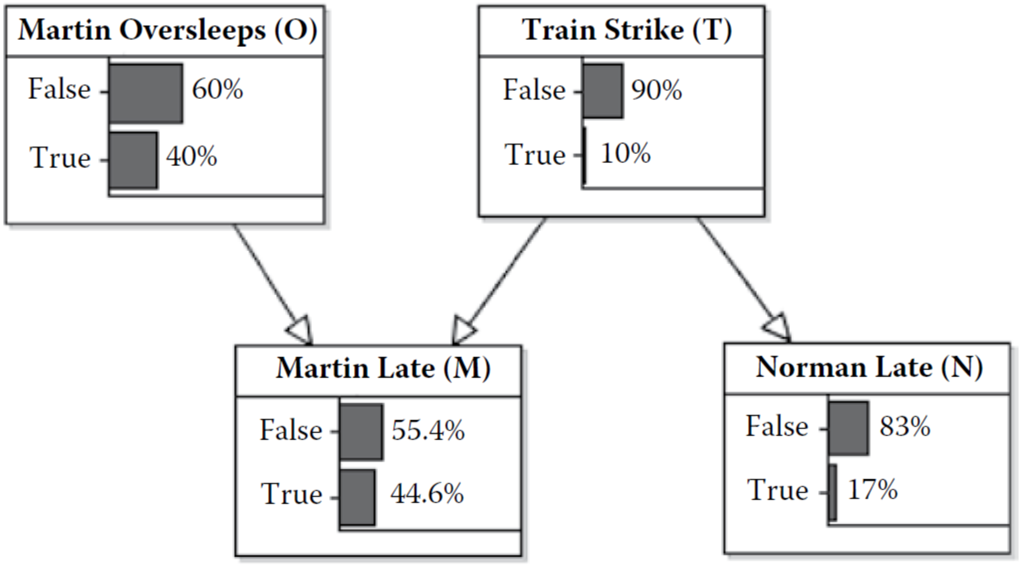


Figure 17: Example of a BBN[7] [74]

To build a discrete model such as the one shown in Figure 17, one must enter prior probability values (known as the Nodal Probability Table (NPT) values for root nodes and Conditional Probability Table (CPT) values for the child nodes). Then the model computes the marginal probabilities displayed in the states by the application of the law of total probability in Eq. (12) and the chain rule in Eq. (13):

$$P(X_1, \dots, X_n) = \prod_{i=1}^{n} p(X_i | Parents\ (X_i)) \qquad \text{Eq. (13)}$$

Multiple software programs exist to help analysts construct and analyze BBNs. Examples of such software include AgenaRisk, BNT, BayesiaLab, NETICA, HUGIN,

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[7] Reprinted from *Risk assessment and Decision Analysis with Bayesian Networks,* by N. Fenton and M.Neil, 2018, by CRC Press, United States. Copyright 2018 by N. Fenton and M.Neil

JavaBayes, GeNIe, and ProBT [76]. In this paper, we will use AgenaRisk commercial software.

Modeling Human and Organizational Factors (HOF) is of particular interest to HRA practitioners who are interested in calculating the HEP associated with tasks. The complexity of HOF, the relationship among them, the limitation of reliable data, and the need to solicit expert judgment make it a perfect candidate for a BBN analysis. Numerous papers used BBN to model HRA for nuclear, oil and gas, and aviation industry. One particular study reviewed these applications and classified the BBN-based HRA into the following [77]:

1. **Management and Organizational Factors (MOF) impact assessment:** This class of BBN aims to represent the possible impact of MOF on human reliability. MOFs are complex because they are numerous, can be direct or indirect, and are difficult to measure. The graphical structure of BBN allows the analyst to model the hierarchal nature of MOF and the relationship between each other.
2. **PSF relationship assessment:** The PSFs found in HRA methods are used to take into account the contextual factors of the job. Thus PSF multipliers are used to scale the HEP based on the situation and PSF applicability to that situation. It is noted that there is no standardized set of PSFs among different HRA methods, which is considered a problem. Another problem with HRA tools that use PSF is not properly incorporating the dependence among different PSFs. If, for a given situation, multiple PSFs are applicable many methods use their cumulative effect as the sum of their individual effect. BBN allows the

analyst to graphically represent the relationship between PSFs and model their effect for a different combination of PSFs acting together in the same situation.

3. **HRA method extension:** This class models existing HRA methods using BBN. The objective to counteract the shortcomings of HRA methods by leveraging the strength of BBN. Some of the shortcomings noted are partial information, dependence among PSFs, and ability to perform both predictive and diagnostic reasoning
4. **Modeling human failure event dependence:** Dependence assessment, which refers to situations where the failure of one task influences the failure of the task preceding it. Examples of things that might influence the dependability between tasks are their closeness in time, the similarity of cues and goals, and the similarity of task performers. Dependence assessment exists in some HRA methods, such as SPAR-H [78]. However, as is the case with many BBN applications, the strength of BBN is leveraged to make better and more repeatable results
5. **BBN for Situation Awareness:** Situation awareness is defined as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and a projection of their status in the near future”[79]. This class of BBN allows modeling emergency scenarios in high-risk plants such as emergency shutdowns, flare out, blowouts, or loss of cooling liquid. The use of this class of BBN allows the analyst to represent the different plant states via the pattern of alarms and process indicators and match

them to the correct emergency scenario, thereby allowing the proper diagnosis of accident scenarios and observing possible errors.

The model in this case study follows from the BBN class that deals with MOFs impact on HEP, 19 accident investigation reports were analyzed, and identified root causes were collected. These root causes were then coded into the TapRoot root cause categories. The reason for choosing the TapRoot methodology is its popularity in the oil field and its proper coverage of MOFs [59]. The model will provide the analyst with a tool to help at the early stage conceptual HFE screening. At this stage, management will be interested in the level of investment needed for HFE engineering [17]. Data is collected for two sources of information:

1. Incident data related to the specific unit from Company incident investigation reports, industry investigations, and other forms of process data such as API 754 Tier 3 indicators
2. HFE screening workshop ratings assigned to each one of the 5 categories of task complexity, unit criticality, task frequency, novelty, design scope flexibility, known problems. Each category is rated from 1 to 10. It is recommended that this workshop be facilitated by an experienced HF practitioner [17]

The method used for constructing the network followed the first three steps outlined in [80]:

1. **Selection of nodes and states**: Three categories of nodes were used. Organizational factors are collected from incident root causes, which are then encoded using the TapRoot taxonomy for generic root causes. Human error

events identified from incident causal factors and then encoded using taxonomy adopted in [80]

2. **Build BBN Structure:** building the structure by connecting the relevant root nodes to the relevant parent nodes
3. **Populate NPT and CPT:** the NPT for the root nodes were calculated from their relative frequency of occurrence among the incidents analyzed

Table 8: Investment Decision Matrix

Investment Level Ranking				
HEP	$>10^{-3}$	M	H	H
	10^{-3} - 10^{-5}	L	M	H
	$\leq 10^{-5}$	L	L	M
		≤0.3	0.6 – 0.3	>0.6
		HFE Screening workshop overall rating		

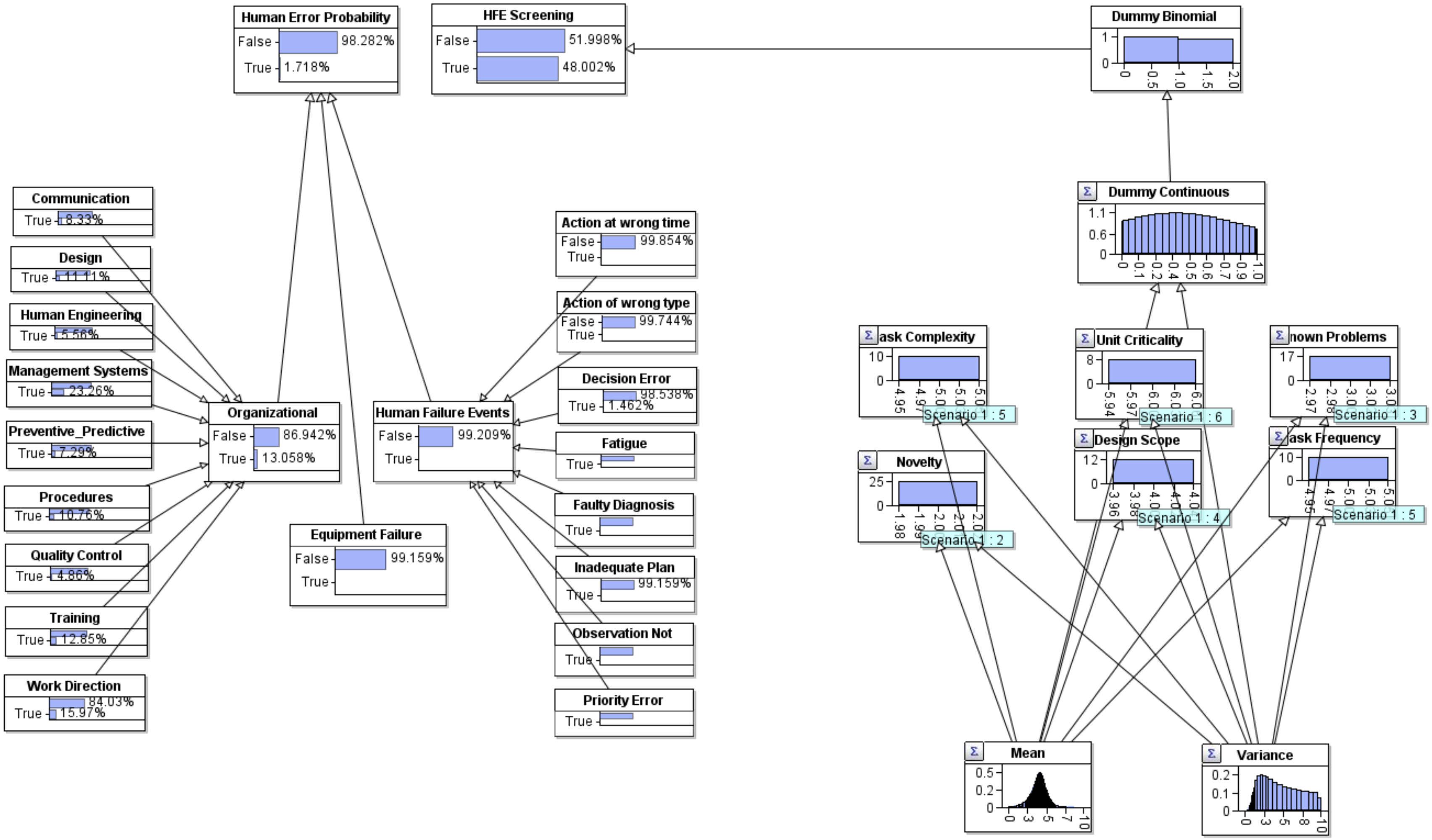

Figure 18: HFE Screening BBN

Figure 18 shows the BBN for HFE screening with two outputs. The HFE screening workshop ratings and the estimated HEP. Based on these values, we can use the decision aid matrix in Table 8 to decide the investment level, which in this case would be a level of High based on a HEP of 0.017 and an HFE screening rating of 0.48. Then the analyst can use these results to decided what level of HF input is required based on Figure 19 and whether or not a detailed HF Integration Plan (HFIP) is required from Figure 20. In this particular case study, a high HF input is required, and a standalone HFIP for this project

3. CONCLUSION

In this study, we highlighted that HF is a contributory cause to most accidents and that it is influenced by work tasks, organizational context, environmental context, work tools and work equipment, workspace, and work area. Moreover, the field s concerned with addressing these influencers is HF Integration, in which HF can be integrated at the design stage (commonly referred to HFE integration) or at the operational stage. When discussing the operational stage integration, the integration model must align with the organization's management systems, most preferably its PSMS, and should be embedded at all levels of the PSMS document hierarchy. At the design stage, most HPI and CPI companies follow the Waterfall System Development Lifecycle (SDLC) approach to system design; hence the integration strategy should be aligned with this approach. At the conceptual design stage, there is limited information available; however, there is still an opportunity to make decisions that can improve human performance. Such decisions include the identification of the user requirements, functional requirements, preliminary allocation of these functions, and project management requirements. We presented five approaches to HFE integration at the conceptual design stage. In the first approach, we highlighted that HF KPIs could be used for operational stage and design stage integration; however, there are challenges to their incorporation at the conceptual design stage where most of the KPIs are valid at the operational stage, and the ones that are valid at the design stage require information that is only available in later design stages. Furthermore, the KPIs rely on HPI and CPI companies’ past experiences in HFE, not to mention the lack of a validated

HFE integration model to give companies more confidence in following a specific HFE integration approach. In the 2nd approach, we showed how CWA could be used to help define HMI functional requirements and decision support principles at the conceptual stage. However, this requires input from operational personnel and people familiar with CWA. In the 3rd approach, we showed a simple numerical analysis tool based on WDA results to help estimate HEP for the physical functions of the plant. This approach has its limitation due to the inability to aggregate physical function probabilities to high-level probabilities. In the 4th approach, we showed how inherently safer design can be successfully integrated into the conceptual design and how this may not be applicable to HFE due to the limitation of process modeling software in addressing human performance requirements. Finally, in the 5th approach, we built a BBN to help the project team decide the level of resources needed for HFE Integration. This was demonstrated by incorporating incident data and HFE screening rating of several facets of HFE. This research highlights the difficulty associated with currently available models of HFE integration and how more refinement and guidance is need for HFE Integration at the conceptual design stage. Nevertheless, all of the approaches show some promise and make important steps toward not only integrating HFE into the conceptual design stage but also shows how HFE can be quantified in terms of financial metrics.

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APPENDIX

Table 9: Generic Tasks and Nominal Human Unreliability (revised version) [63] [81]

Letter designation	Generic Tasks	Nominal Human Unreliability	
A	A Totally unfamiliar, performed at speed with no real idea of the likely consequences	0.41	(0.2 - 0.85)
B	Shift or restore the system to a new or original state on a single attempt without supervision or procedures	0.24	(0.06 - 1)
C	A complex task requiring a high level of comprehension and skill	0.17	(0.05- 0.6)
D	A fairly simple task performed rapidly or given scant attention	0.06	(0.02 - 0.19)
E	Routine, highly practiced, a rapid task involving a relatively low level of skill	0.02	(0.005 - 0.09)
F	Restore or shift a system to original or new state following procedures with some checking	0.001	(0.00002 - 0.04)
G	Entirely familiar, well-designed, highly practiced, routine task occurring several times per day, performed to highest possible standards by highly motivated, highly trained, and experienced personnel, with time to correct the potential error, but without the benefit of significant job aid	0.002	(0.0002 - 0.01)

Table 9: Generic Tasks and Nominal Human Unreliability (revised version) [63] [81]

Letter designation	Generic Tasks	Nominal Human Unreliability	
H	Respond correctly to system command even when there is an augmented or automated supervisory system providing an accurate interpretation of system state	0.00004	(0.000006 - 0.009)

Table 10: HEART Methodology's PSF Multipliers [63] [81]

#	Performance Shaping Factor (PIF/EPC)	Maximum Nominal Predicted Effect Factor
1	Unfamiliarity with a situation which is potentially important but which only occurs infrequently or which is novel	17
2	A shortage of time available for error detection and corrections	11
3	A low signal to noise ratio	10
4	A means of suppressing or over-riding information or features which is too easily accessible	9
5	No means of conveying spatial and functional information to operators in a form which they can readily assimilate	8
6	A mismatch between an operator's model of the world and that imagined by a designer	8
7	No obvious means of reversing an unintended action	8
8	A channel capacity overload, particularly one caused by simultaneous presentation of non-redundant information	6
9	A need to unlearn a technique and apply one which requires the application of an opposing philosophy	6
10	The need to transfer specific knowledge from task to task without loss	5.5
11	Ambiguity in the required performance standards	5
12	A mismatch between perceived and real risk	4
13	Poor, ambiguous or ill-matched system feedback	4

Table 10: HEART Methodology's PSF Multipliers [63] [81]

#	Performance Shaping Factor (PIF/EPC)	Maximum Nominal Predicted Effect Factor
14	No clear direct and timely confirmation of an intended action from the portion of the system over which control is to be exerted	4
15	Operator inexperience (e.g. a newly-qualified tradesman, but not an “expert”)	3
16	An impoverished quality of information conveyed by procedures and person/person interaction	3
17	Little or no independent checking or testing of output	3
18	A conflict between immediate and long-term objectives	2.5
19	No diversity of information input for veracity checks	2.5
20	A mismatch between the educational achievement level of an individual and the requirements of the task	2
21	An incentive to use other more dangerous procedures	2
22	Little opportunity to exercise mind and body outside the immediate confines of a job	1.8
23	Unreliable instrumentation (enough that it is noticed)	1.6
24	A need for absolute judgments which are beyond the capabilities or experience of an operator	1.6
25	Unclear allocation of function and responsibility	1.6
26	No obvious way to keep track of progress during an activity	1.4
27	A danger that finite physical capabilities will be exceeded	1.4
28	Little or no intrinsic meaning in a task	1.4
29	High-level emotional stress	2
30	Evidence of ill-health amongst operatives, especially fever	1.2
31	Low workforce morale	1.2
32	Inconsistency of meaning of displays and procedures	3
33	A poor or hostile environment (below 75% of health or life-threatening severity	2
34	Prolonged inactivity or highly repetitious cycling of low mental workload tasks	1.1
35	Disruption of normal work-sleep cycles	1.2
36	Task pacing caused by the intervention of others	1.06

Table 10: HEART Methodology's PSF Multipliers [63] [81]

#	Performance Shaping Factor (PIF/EPC)	Maximum Nominal Predicted Effect Factor
37	Additional team members over and above those necessary to perform task normally and satisfactorily	1.2
38	Age of personnel performing perpetual tasks	1.16
39	Distraction /Task Interruption	4
40	Time-of-Day	2.4

Table 11: PetroHRA PSF Levels and Multipliers [39]

#	PSF	Action Levels	Level	Level description
1	Time	Extremely high negative effect on performance.	Set HEP to 1	Operator(s) does not have enough time to successfully complete the task.
		Very high negative effect on performance	50	The available time is the minimum time required to perform the task or close to the minimum time to perform the task. In this situation, the operator(s) has very high time pressure, or they have to speed up very much to do the task in time.
		Moderate negative effect on performance.	10	The operator(s) has limited time to perform the task. However, there is more time available than the minimum time required. In this situation the operator(s) has high time pressure, or they have to speed up much to do the task in time.

#	PSF	Action Levels	Level	Level description
Table 11: PetroHRA PSF Levels and Multipliers [39]				
		Nominal effect on performance.	1	There is enough time to do the task. The operator(s) only has a low degree of time pressure, or they do not need to speed up much to do the task. When comparing the available time to the required time, the analyst concludes that time would neither have a negative nor a positive effect on performance
		Moderate positive effect on performance	0.1	There is extra time to perform the task. In this situation, the operator(s) has considerable extra time to perform the task, and there is no time pressure or need to speed up to do the task in time.
		Not applicable	1	This PSF is not relevant for this task or scenario
2	Threat Stress	High negative effect on performance.	50	The operator(s) experiences very high threat stress. In this situation, the operator's own or other person's life is in immediate danger.
		Low negative affect on performance	10	The operator(s) experiences moderate threat stress. The operator experiences that there is a threat to their own or others' personal safety or a very high threat to self-esteem or professional status.
		Very low negative effect on performance	2	The operator(s) experiences some threat stress. The operators experience some threat to their self-esteem or professional status
		Nominal effect on performance.	1	Operator(s) does not experience threat stress. Threat stress has not a

Table 11: PetroHRA PSF Levels and Multipliers [39]

#	PSF	Action Levels	Level	Level description
				negative effect on performance
		Not applicable	1	This PSF is not relevant for this task or scenario.
3	Complexity	Very high negative effect on performance.	50	The task contains highly complex steps. One or several of the complexity categories are present and influence performance very negatively. For example, several parallel goals are present, the size of the task is huge with many information cues and many steps, it is unclear which task elements to perform, if an order is relevant, if tasks have any effect on the situation, and the task environment changes.
		Moderate negative effect on performance.	10	The task is moderately complex. One or several of the complexity categories are present and influence performance negatively.
		Very low negative effect on performance.	2	The task is, to some degree, complex. One or several of the complexity categories are to some degree present and are expected to have a low negative effect on performance.
		Nominal effect on performance.	1	The task is not very complex, and task complexity does not affect operator performance. Task complexity has neither a negative nor a positive effect on performance.

Table 11: PetroHRA PSF Levels and Multipliers [39]

#	PSF	Action Levels	Level	Level description
		Low positive effect on performance.	0.1	The task is greatly simplified, and the problem is so obvious that it would be difficult for an operator to misdiagnose it. E.g., detecting a single alarm or sensory information such as clear visual and auditory cues.
		Not applicable	1	This PSF is not relevant for this task or scenario.
4	Experience/ Training	Extremely high negative effect on performance.	Set HEP to 1	There is a strongly learned knowledge or skill (either from experience or training) that is a mismatch with the correct response to this task step in this scenario. An example could be that the operator(s), during experience or training, has developed a strong mindset about the development of a scenario and actions that do not fit with the scenario in question and therefore cannot be expected to perform the task correctly.
		Very high negative effect on performance.	50	The operator(s) does not have any experience or training and does not at all have the necessary knowledge and skills to be prepared for and to do the task(s) in this scenario.
		Moderate negative effect on performance.	15	The operator(s) has low experience or training and does not have the necessary complete knowledge and experience to be prepared for and to do the task(s) in this scenario.

Table 11: PetroHRA PSF Levels and Multipliers [39]

#	PSF	Action Levels	Level	Level description
		Low negative effect on performance	5	The operator(s) has experience or training but this is lacking, and they do not have the complete knowledge and experience to be fully prepared for and to do the task(s) in this scenario
		Nominal effect on performance	1	The operator(s) has the experience and/or training on the task(s) in this scenario and has the necessary knowledge and experience to be prepared for and to do the task(s) in this scenario. Experience/Training does not reduce performance nor, to a large degree, improve performance.
		Moderate positive effect on performance	0.1	The operator(s) has extensive experience and/or training on this task, and the operator(s) has extensive knowledge and experience to be prepared for and to do the task(s) in this scenario.
		Not applicable	1	This PSF is not relevant for this task or scenario.
5	Procedure	Very high negative effect on performance.	50	No procedures available, or the procedures are not used during the scenario or training. This level should also be used if the procedures are strongly misleading in such a way that they are not helpful for the operator(s).

Table 11: PetroHRA PSF Levels and Multipliers [39]

#	PSF	Action Levels	Level	Level description
		High negative effect on performance.	20	The procedure lacks steps and important information that is needed to do the task, or the procedures are briefly used during scenarios or training. An example could be that they are briefly looked at at the beginning of the scenario. This level should also be used if the procedures themselves are highly complex or it is very difficult for the operators to navigate between different procedures
		Low negative effect on performance.	5	The procedures are complete, but there are some problems (formatting, language, structure) with the procedures, or the procedures are not followed in an optimal way. This level should also be used if the procedures are complex (e.g., revealed through interviews) or if there are some problems to navigate between different procedures
		Nominal effect on performance	1	The quality of the procedures is adequate, and they are followed. The quality of procedures does not affect performance either positively or negatively.
		Low positive effect on performance.	0.5	Procedures are exceptionally well developed, they are followed, and they enhance performance.

Table 11: PetroHRA PSF Levels and Multipliers [39]

#	PSF	Action Levels	Level	Level description
		Not applicable.	1	This PSF is not relevant for this task or scenario.
6	Ergonomics/ HMI	Extremely high negative effect on performance.	Set HEP to 1	A situation where it is not reasonable to assume that the operator/crew will be successful in carrying out the task. An example of this would be a situation where the HMI does not provide the operator/crew with the required information or possibility to perform the task. Alternatively, the information provided is misleading to the extent that the operator will not correctly carry out the task.
		Very high negative effect on performance.	50	The HMI causes major problems in either obtaining relevant information or carrying out the task. For example, the HMI is not designed for the task leading to a difficult workaround, some of the relevant information required for a reliable decision is not made available or, the inter-page navigation creates severe difficulties in obtaining the relevant information or carrying out the task.

Table 11: PetroHRA PSF Levels and Multipliers [39]

#	PSF	Action Levels	Level	Level description
		Moderate negative effect on performance.	10	The HMI causes some problems in either obtaining relevant information or carrying out the task. For example, the HMI does not conform to the stereotypes the operators are used to (e.g., icons, colors, and intuitive placements) or, several page changes in the inter-page navigation increases the difficulty in obtaining the required information or carrying out the task.
		Nominal effect on performance.	1	While the HMI is not specifically designed for making human performance as reliable as possible for this task/tasks of this type, it corresponds to the stereotypes held by the operators. All of the safety critical information is easy available and no HMI related issues are interfering with carrying out the task. HMI does not reduce performance nor to a large degree improve performance.
		Low positive effect on performance.	0.5	The HMI is specifically designed to make human performance as reliable as possible in this task/tasks of this type.
		Not applicable.	1	This PSF is not relevant for this task or scenario.

Table 11: PetroHRA PSF Levels and Multipliers [39]

#	PSF	Action Levels	Level	Level description
7	Attitudes to Safety, Work and Management Support	Very high negative effect on performance.	50	In this situation safety is not at all prioritized over other concerns when it is appropriate or there are extremely negative attitudes to work conduct (for example the operators are not monitoring or awake when they should be). There is very low mindfulness about safety. The operators do not experience management support, for example in strong management pressure for production even if safety is clearly in question.
		Moderate negative effect on performance.	10	In this situation it is not specified by management that safety should be prioritized when that is appropriate. The operators are uncertain if safety should be prioritized or not, or the operators are uncertain about rules and regulations that are important for performing the task.
		Nominal effect on performance.	1	The operators have adequate attitudes to safety and work conduct and there is management support to prioritize safety when that is appropriate. The operator(s) shows mindfulness about safety. Attitudes to safety, work and management support have neither a negative nor a large positive effect on performance.

Table 11: PetroHRA PSF Levels and Multipliers [39]

#	PSF	Action Levels	Level	Level description
		Moderate positive effect on performance	0.5	The operator(s) has very good attitudes to safety and work conduct and there is explicit management support to prioritize safety when that is appropriate. The operator(s) shows a very high degree of mindfulness about safety.
		Not applicable.	1	This PSF is not relevant for this task or scenario.
8	Teamwork	Very high negative effect on performance.	50	The teamwork is very poor on one or several teamwork factors that have been identified as important for the performance of the task or scenario in question.
		Moderately negative effect on performance.	10	The teamwork is poor on one or several teamwork factors that have been identified as important for the performance of the task or scenario in question.
		Very low negative effect on performance.	2	The teamwork is to some degree poor on one or several teamwork factors that have been identified as important for the performance of the task or scenario in question
		Nominal effect on performance.	1	The teamwork is adequate on one or several teamwork factors that have been identified as important for the performance of the task or scenario in question. Teamwork has neither a negative nor a large positive effect on performance.
		Low positive effect on performance.	0.5	The team is very good on one or more teamwork factors that have been identified as important for the task(s) or scenario in

Table 11: PetroHRA PSF Levels and Multipliers [39]

#	PSF	Action Levels	Level	Level description
				question and teamwork increase performance.
		Not applicable.	1	This PSF is not relevant for this task or scenario.
9	Physical Working Environment	Very high negative effect on performance.	Set HEP to 1	The task cannot be completed due to the tools required or the area in question being inaccessible or unavailable
		Moderate negative effect on performance.	10	There are clear ergonomic challenges in completing the task. This could be due to the area where work is conducted being hard to reach, the manual field activation is difficult or physically demanding, or there are extreme weather conditions that decrease performance.
		Nominal effect on performance.	2	Physical working environment does not have an effect on performance.
		Not applicable.	1	This PSF is not relevant for this task or scenario.

Table 12: HMI Investment Multiplier Levels and Description

Investment levels	Multiplier	Retrospective Rating	Prospective Rating
No investment	50	Operators find it easy to keep track of the process in normal conditions, potential problems: - insufficient process information - unreliability of sensors or displays - other tasks operators are required to perform - distractions, such as maintenance permit writing and telephone calls -operators working from multiple screens or consoles, or paging through several displays or manuals to gather and analyze information	Physical ergonomics were addressed, but no effort to the presentation of information regardings the tasks that the worker needs to accomplish

Table 12: HMI Investment Multiplier Levels and Description

Investment levels	Multiplier	Retrospective Rating	Prospective Rating
Low Investment	10	in upset and emergency conditions, all relevant operators and supervisors can accurately and reliably assess the condition and behavior of the plant within the available time without disturbing each other or blocking each other's access to information.	Physical ergonomics were addressed, and information regarding one or two of the tasks was assessed, but there is no consideration of the integration of this information
Moderate investment	1	-Non-operating tasks are not required of the operator during upset or abnormal conditions. - the operators have absolutely no responsibility other than monitoring the process during times of abnormal or unusual conditions	Physical ergonomics were considered, physical tasks were considered information needed for those tasks as well, as the integration of those tasks are considered, but communication with other workers was not considered

Table 12: HMI Investment Multiplier Levels and Description

Investment levels	Multiplier	Retrospective Rating	Prospective Rating
Significant investment	0.5	sound operator information strategies for routine as well as abnormal situations, a distraction-free environment, and minimal disruptions from the primary task of monitoring the process unit.	all the above and communication with other workers

Table 13: Procedure Investment Multiplier Levels and Description

Investment levels	Multiplier	Retrospective Rating	Prospective Rating
No investment	50	No procedures available, or the procedures are not used during the scenario or training. This level should also be used if the procedures are strongly misleading in such a way that they are not helpful for the operator(s).	No procedure is considered, and it is not incorporated in the training

Table 13: Procedure Investment Multiplier Levels and Description

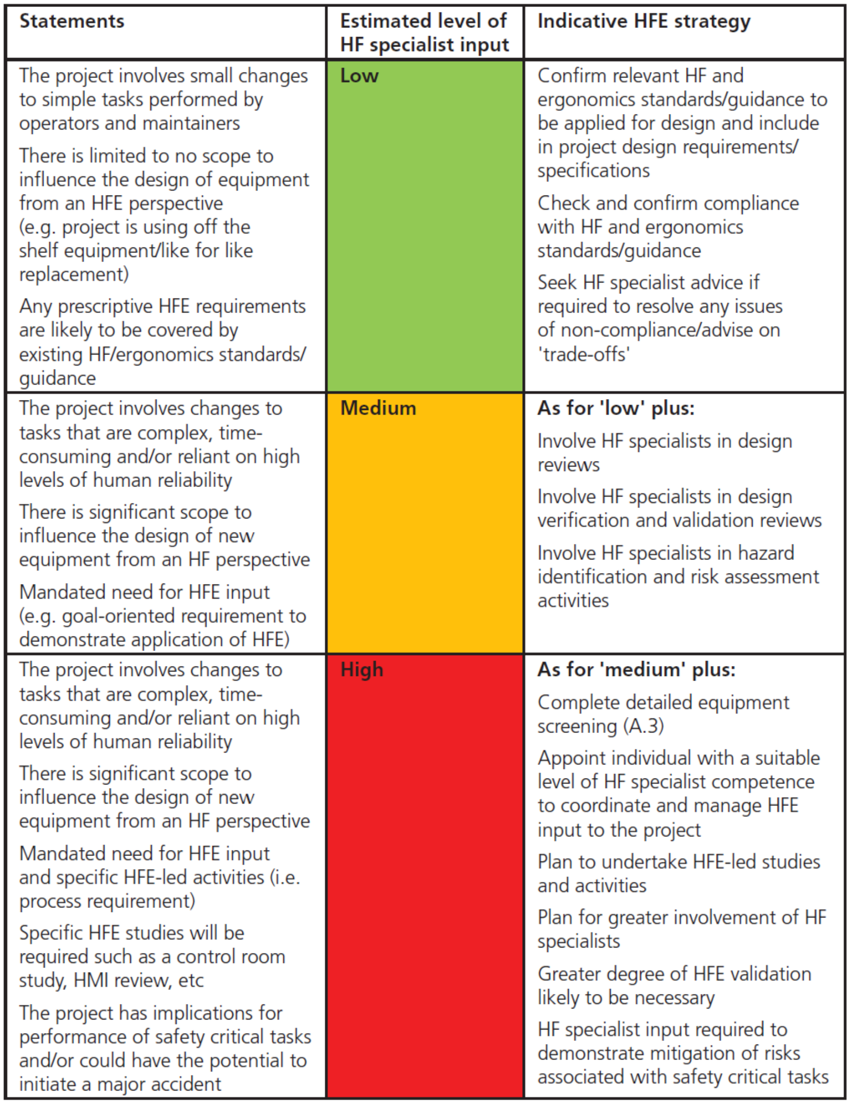
Investment levels	Multiplier	Retrospective Rating	Prospective Rating
Very Low Investment	20	The procedure lacks steps and important information that is needed to do the task or the procedures are briefly used during scenario or training. An example could be that they are briefly looked at in the beginning of the scenario. This level should also be used if the procedures themselves are highly complex or it is very difficult for the operators to navigate between different procedures	a procedure is developed; however, critical stakeholders (operation, maintenance, engineering) are not included in the development of the procedure. Training material is co-developed with the procedure but with a limited effort

Table 13: Procedure Investment Multiplier Levels and Description

Investment levels	Multiplier	Retrospective Rating	Prospective Rating
Low investment	5	The procedures are complete, but there are some problems (formatting, language, structure) with the procedures, or the procedures are not followed in an optimal way. This level should also be used if the procedures are complex (e.g., revealed through interviews) or if there are some problems to navigate between different procedures	Procedures are developed, key stakeholders are involved, and training material are sufficiently co-developed with procedures; however, there are no consistent guidelines for formatting, language, and structure

Table 13: Procedure Investment Multiplier Levels and Description

Investment levels	Multiplier	Retrospective Rating	Prospective Rating
Moderate investment	1	The quality of the procedures is adequate, and they are followed. The quality of procedures does not affect performance either positively or negatively.	All the above and consistent guidelines for formatting, language, and structure are applied across all procedures. The procedure is considered acceptable. Additionally, The procedure is digital and Smart, making it easy for stakeholders to access the procedure (such as using tablets) and to provide appropriate document control
Significant investment	0.5	Procedures are exceptionally well developed, they are followed, and they enhance performance.	The procedure is digital and Smart, making it easy for stakeholders to access the procedure (such as using tablets) and to provide appropriate document control



Statements	Estimated level of HF specialist input	Indicative HFE strategy
The project involves small changes to simple tasks performed by operators and maintainers There is limited to no scope to influence the design of equipment from an HFE perspective (e.g. project is using off the shelf equipment/like for like replacement) Any prescriptive HFE requirements are likely to be covered by existing HF/ergonomics standards/ guidance	**Low**	Confirm relevant HF and ergonomics standards/guidance to be applied for design and include in project design requirements/ specifications Check and confirm compliance with HF and ergonomics standards/guidance Seek HF specialist advice if required to resolve any issues of non-compliance/advise on 'trade-offs'
The project involves changes to tasks that are complex, time-consuming and/or reliant on high levels of human reliability There is significant scope to influence the design of new equipment from an HF perspective Mandated need for HFE input (e.g. goal-oriented requirement to demonstrate application of HFE)	**Medium**	**As for 'low' plus:** Involve HF specialists in design reviews Involve HF specialists in design verification and validation reviews Involve HF specialists in hazard identification and risk assessment activities
The project involves changes to tasks that are complex, time-consuming and/or reliant on high levels of human reliability There is significant scope to influence the design of new equipment from an HF perspective Mandated need for HFE input and specific HFE-led activities (i.e. process requirement) Specific HFE studies will be required such as a control room study, HMI review, etc The project has implications for performance of safety critical tasks and/or could have the potential to initiate a major accident	**High**	**As for 'medium' plus:** Complete detailed equipment screening (A.3) Appoint individual with a suitable level of HF specialist competence to coordinate and manage HFE input to the project Plan to undertake HFE-led studies and activities Plan for greater involvement of HF specialists Greater degree of HFE validation likely to be necessary HF specialist input required to demonstrate mitigation of risks associated with safety critical tasks

Figure 19: HF Specialist Input Levels[8] [17]

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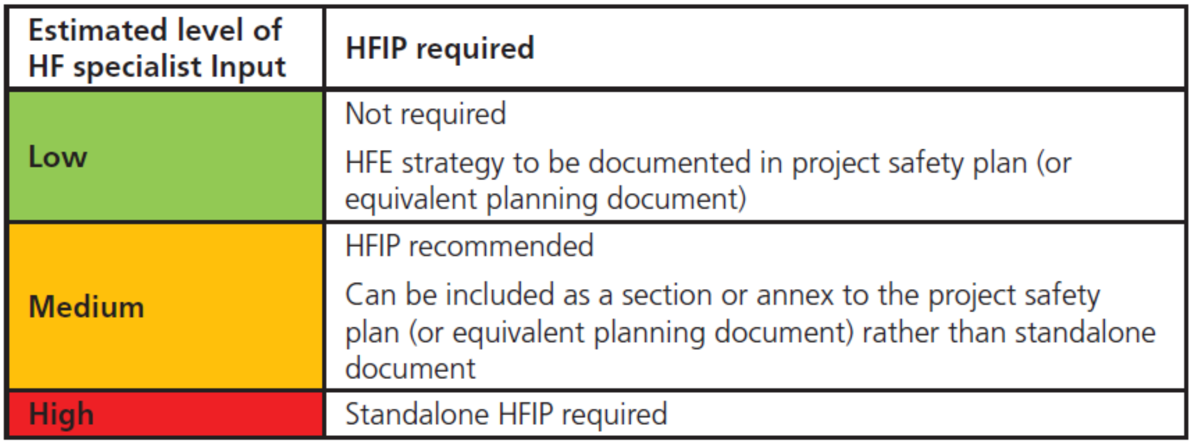

Estimated level of HF specialist Input	HFIP required
Low	Not required HFE strategy to be documented in project safety plan (or equivalent planning document)
Medium	HFIP recommended Can be included as a section or annex to the project safety plan (or equivalent planning document) rather than standalone document
High	Standalone HFIP required

Figure 20: HF Integration Plan (HFIP) Requirement[9] [17]

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