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Analyzing Procedure Performance using Abstraction Hierarchy: Implications of Designing Procedures for High-risk Process Operations

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Abstract

Standard operating procedures (SOPs) are a vital element of everyday operations in chemical process industries. Incident investigations also indicate that a majority of adverse events in the processing operations are ascribed to issues associated with SOPs. Although there have been continuous efforts to improve informational and perceptual aspects of SOPs, assessing them from a systems perspective remains a persistent gap. As one novel way to address such gap, this study employs an ecological approach to understand the functional structure of the work domain, that is, abstraction hierarchy (AH) and its relations to SOPs and operator performance. First, this study models a 3-phase separation system, a common gas-oil-water separation process, using an abstraction-decomposition space as a work domain of the system. Second, we assess the AH level, one dimension of the abstraction-decomposition space, of the SOPs developed for three tasks in the 3-phase separation system. In order to consider operators' knowledge about the tasks, experience-task familiarity (E-TF) level is also assessed as a combinatory factor. To this end, a two-way analysis of variance is conducted to find out the effect of E-TF level (high vs. low) and AH level of the SOPs (physical vs. functional) on the operator's performance. Results show significant main effects of the E-TF level and AH level on the successful performance of the SOPs. The interaction effect of the two variables is considered marginally significant. Based on the results, several implications for the design of SOPs in relation to the AH of the chemical processing domain are discussed.

Keywords: human factors, standard operating procedure, man-machine interface, system safety

1 Introduction

It is widely accepted that standard operating procedures (SOPs) play a crucial role in achieving the desired level of safety and productivity in chemical process industries. An SOP is defined as a documented step-by-step instruction that guides operators in carrying out a specific task either routinely or non-routinely required [1]. Primary purposes that SOPs serve include: providing consistent, up-to-date, and recommended operation practices; informing operators of hazards associated with a task and pertinent control measures; and thus conducting a task in a safe, efficient, and effective manner. In pursuit of these advantages, statutory safety and health regulations and guidelines such as the U.S. Occupational Safety and Health Administration (OSHA) Process Safety Management (PSM) [2] and Guidelines for Risk Based Process Safety (RBPS) [3] mandate industrial organizations to utilize SOPs in the course of employee training and actual operations.

Issues associated with SOPs are pointed out as one of the major causes of incidents in chemical process industries. From a review of over 60 incident investigations conducted by the U.S. Chemical Safety Board (CSB), problems regarding SOPs were present in approximately 70% of the incidents [4]. The investigations revealed that SOPs were not properly developed, not complete, or not followed as instructed during the course of incidents. Similarly, an analysis of World Offshore Accident Databank indicated that the absence of procedures and inadequate procedures were responsible for over 80% of human-related causes [5]. More specifically, an investigation of 2005 BP Texas City refinery explosion found out several issues with SOPs in the start-up process including operators' deviations from critical steps of the SOPs and insufficient hazard information to be specified in the SOPs [6].

To address the issues associated with SOPs, three approaches have largely been taken towards the better design of procedures: *informational*, *perceptual*, and *ecological* approaches. First, the *informational* approach has emphasized standardizing and delineating information elements of an SOP. In this approach, a major focus is to specify SOP requirements such as purpose, scope, and general description of a task, hazards and precautions, required tools, equipment and supplies, procedural steps to conduct the task, and data and record management [7, 8]. Second, the *perceptual* approach has sought to examine the visual attributes of SOP components in relation to operators' compliance. For instance, recent studies investigated features of a hazard statement including symbols, signal words (e.g., caution, warning), graphic embellishment (e.g., numbering, boxing, filling) [9, 10]. The findings from the informational and perceptual approaches were beneficial to illuminating what components need to be included in SOPs and how they should be formatted. Hence, their primary focus was mostly fixated on tackling task-specific matters with an ideal aim to make operators strictly comply with SOPs. However, other researchers assert that the zero-tolerance adherence to SOPs may be impossible and even deleterious to achieving safety of complex industrial operations due to constantly changing work environments, being often degraded from what was imagined in the SOPs [11, 12]. In addition, it is also suggested that the usage and role of the SOPs should change as the experience and knowledge of operators matures [13]. Recognizing the dilemma that underlies SOPs, the *ecological* approach views SOPs as decontextualized and abstracted artifacts that *guide*, not *dictate*, operators' problem-solving depending on their experience and knowledge regarding the system to be operated [14]. In light of this standpoint, advocates of the ecological approach insist that under constantly changing or unexpected operating conditions, SOPs should be designed in such a way that they support operators to adjust their actions to unstable circumstances in order to accomplish higher system-level goals [15, 16].

The ecological approach has been taken in designing cognitive work and associated information artifacts in safety-critical domains including chemical process industries. One of the principal concepts of the ecological approach is Abstraction Hierarchy (AH) of a system [17-19]. AH is a framework for representing the functional structure of a complex socio-technical system, consisting of several hierarchical levels that are bound in the goal-means relationship [20, 21]. AH principles have been applied to modeling various complex systems [22-25], devising work analysis method [26-28], and developing ecological interface design (EID) [29, 30]. The EID perspective aimed at externalizing operators' mental model has proven to be effective in supporting detection of unexpected situations and adaptive actions to cope with such anomalies [31]. In particular, previous research indicates that operators who were more knowledgeable and experienced about the functional structure of a system better exploited the utilities of the EID in solving unexpected problems and accomplishing given goals [32, 33]. Similar work was conducted for petrochemical industries. For example, work domains of chemical processing systems such as hydrogenation reactor and fluidized catalytic cracking unit (FCCU) were analyzed using the abstraction-decomposition space method [34, 35]. Furthermore, a control operator interface for the FCCU was developed using EID principles [36].

Although AH has been widely embraced in many studies across different domains and provided advantages in understanding and improving complex cognitive work systems, its application to SOPs used in high-risk environments is not existing to date. Also, research efforts that reflect the system's functional structure (e.g., AH) on SOPs are largely absent in the current body of literature. Furthermore, little is known with respect to what roles operators' knowledge of a task would play in relation to the functional structure of the system. As an exploratory effort to fill such gaps, our study aims 1) to analyze the work domain of a 3-phase separation system, a common crude oil refining process, and 2) to assess how an AH level reflected on the SOPs and an operator's experience and familiarity with a task are related to SOP performance.

2 Background

2.1 Abstraction hierarchy and work domain analysis

A work domain is referred to as a system space being acted upon, independent of any particular operator, event, task, or control interface [37]. Analyzing the work domain, namely, work domain analysis (WDA), is conducted to identify the functional structure of the system under examination and thus the first step of cognitive work analysis (CWA) [21]. WDA is aimed at eliciting the functional abstraction hierarchy (AH) and structural decomposition of the system. Combining the two orthogonal dimensions, an abstraction-decomposition space (ADS) is drawn (Figure 1). As described in Table 1, AH typically consists of five levels that are bound with the goal-means relationship in which a lower-level node acts as a means to achieve its immediate higher-level node. In this sense, higher levels of AH denote goals and abstract functions ('why work is done' and 'what work is done') of the system whereas lower levels are concerned with concrete and physical elements ('how work is done'). Decomposition is laid out on the horizontal dimension incorporating a whole system, sub-system or unit, and component levels.

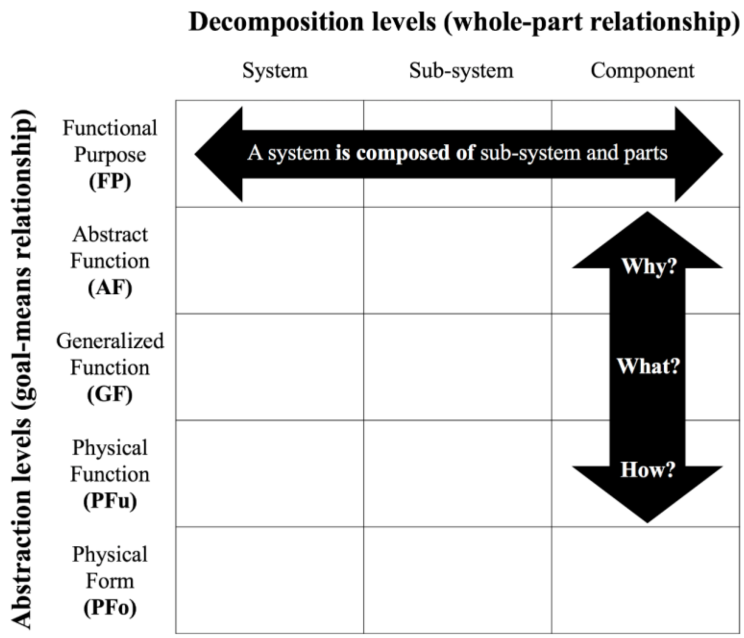

Figure 1. Generic Abstraction-Decomposition Space with two dimensions of abstraction hierarchy and decomposition hierarchy

Table 1. Levels of Abstraction Hierarchy

AH Level	Description
Functional Purpose (FP)	Ultimate goals that a system must achieve
Abstract Function (AF)	Governing laws and principles that constitute the system
Generalized Function (GF)	General processes involved in satisfying the governing principles
Physical Function (PFu)	Capabilities of physical elements to achieve the generalized functions
Physical Form (PFo)	Type, shape, location, and layout of physical elements

2.2 Work domain of 3-phase separation system

2.2.1 A description of 3-phase separation system

A primary purpose of a 3-phase separation system is to separate upstream fluid produced from an oil well into three material components, that is, gas, water, and oil [38]. Of particular importance in the refining process is to completely separate any free water (water not bound to any grains or minerals) because free water is likely to cause corrosion or hydrate formation [39]. As shown in Figure 2, the 3-phase separation system includes several gravity-settling tanks in which heavier molecules (e.g., water, oil) fall down and lighter gases rise over the liquid [38]. After going through multiple separation tanks, each of the components is collected and discharged to respective downstream processes for further treatment.

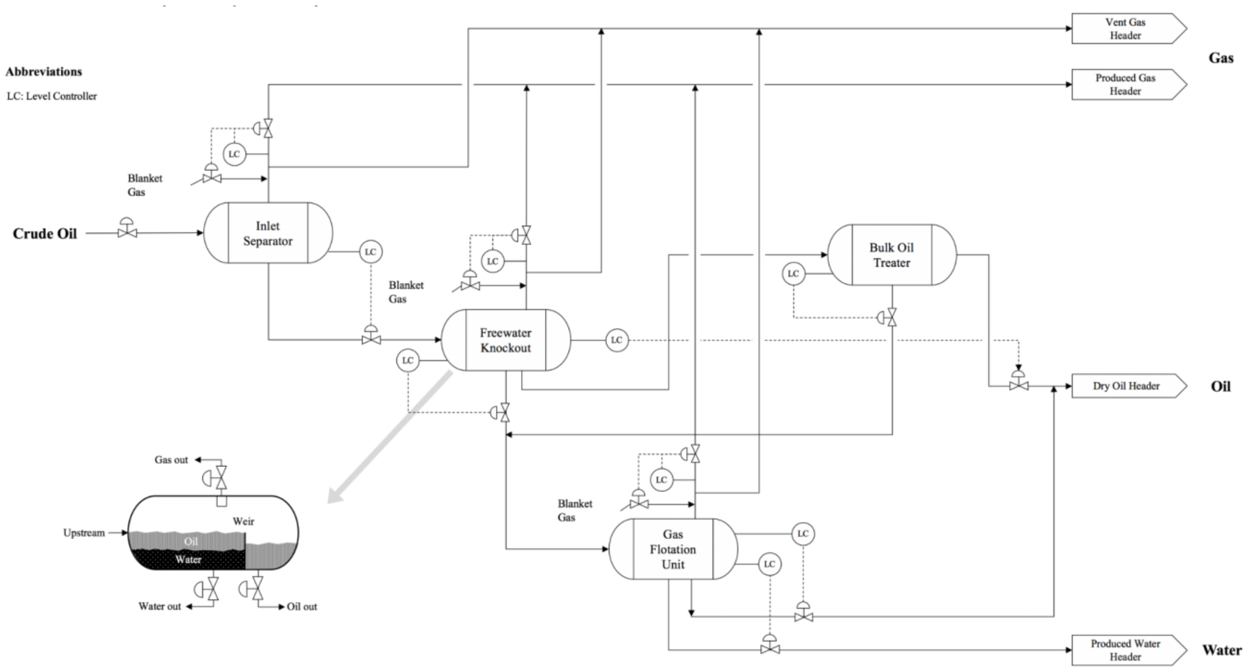

Figure 2. A simplified process flow diagram of the 3-phase separation system

2.2.2 Work domain of 3-phase separation system

As a work domain is independent of operators, tasks, or technical artifacts such as SOPs, we analyzed the work domain of a 3-phase separation system without regard to tasks examined in this study. As the first stage of the work domain analysis, the part-whole decomposition of the 3-phase separation system was conducted (Figure 3). The 3-phase separation system, which constitutes a larger chemical complex by connecting upstream (e.g., crude oil production) and downstream (oil stabilization) processes, is decomposed into multiple units at the sub-system level. The units at the sub-system level provide stream processing functions including fluid input, fluid containment, fluid output, level control, gas releasing, temperature control, pressure control, and energy control. These units are then further decomposed into specific physical functions and components such as fluid feed, pump, valve, separation vessels, and gas, oil, and water outputs.

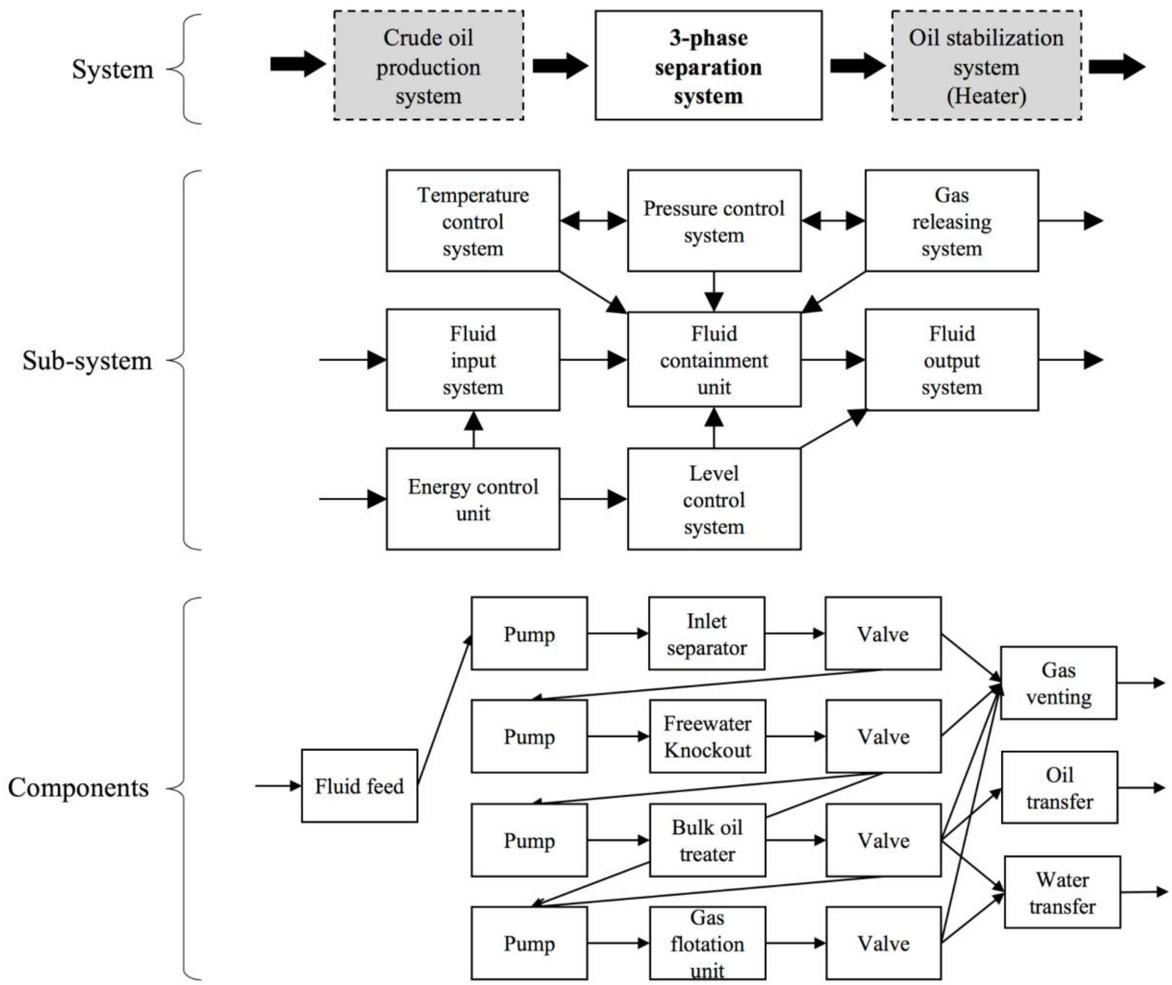

Figure 3. Part-whole decomposition of the 3-phase separation system

Second, the ADS of the 3-phase separation system was generated by adding the AH to the decomposition dimension as shown in Figure 4. At the FP level, the ultimate goals of the system such as production and safety were defined: 'producing oil from raw fluid' and 'securing the safety of separation process'. At the AF level, governing laws of the 3-phase separation system such as maintaining mass flux, separation, pressure, temperature, and energy were identified. At the GF level, generic processes required to satisfy the governing principles of the AF level were modeled. For example, the GF level includes transferring fluid input and output, containing the fluid, releasing gas, removing heat from the fluid, stratifying the fluid, and supplying energy source to enable other functions. As the GF level lies in the interface between functional levels and physical levels, the GFs were also identified both at sub-system and components levels. The PFu level shows capabilities of physical elements of the system such as fluid feed and phase separators, oil and water transfer, and gas venting were identified. Lastly, at the PFo level, specific physical elements such as pumps, valves, vessels, sensors, and topology among them were identified. The line between nodes in the ADS indicates the goal-means relationship in which lower-level nodes are needed to achieve a higher-level node.

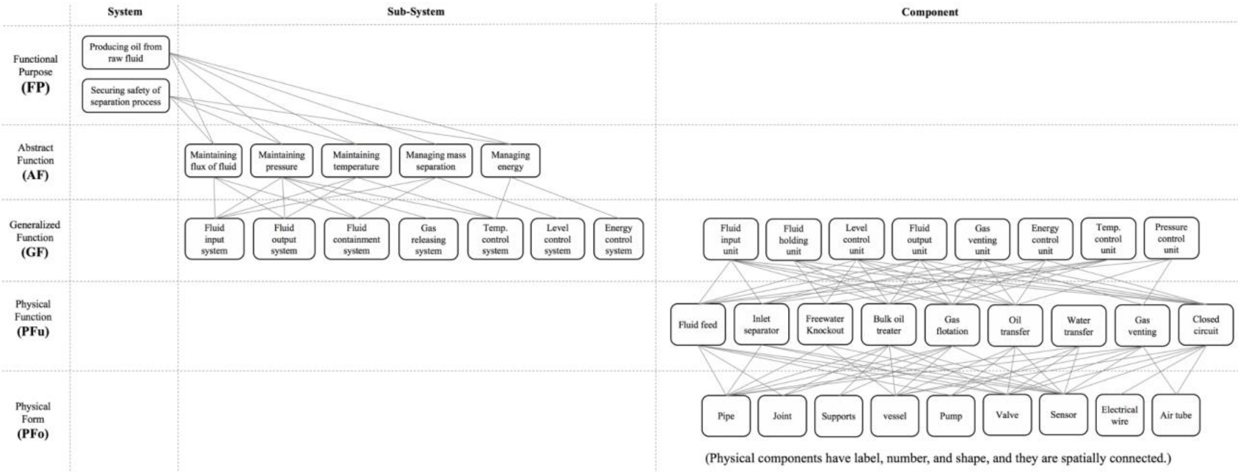

Figure 4. Abstraction-Decomposition Space of the 3-phase separation system

3 Method

3.1 Research setting

To evaluate operators' performance with SOPs in a realistic environment, data for this study were collected in a high-fidelity chemical processing training facility operated by a large petrochemical company located in the south-central U.S. The facility simulates an offshore oil production platform incorporating multiple trains of the 3-phase separation system. To realize the training purpose and eschew any potential risk, the facility uses vegetable oil, running water, and atmospheric air as substitutes for a natural crude oil stream.

3.2 Participants

Participants for this study were recruited via a third-party staffing agency specialized in the oil and gas industry. A total of 25 participants who were active workers in the oil and gas industry were recruited for this study. They were all males and their average age was 40.8 years (SD=12.3, min=20, max=63). The average years of industry experience were 14.3 years (SD=12.2, min=1, max=37). The occupational profile of the participants varied depending on the areas of experience in their career as shown in Table 2.

Table 2. Occupational experience of the participants

Area of occupation in the oil and gas industry	% participants who had experience in the area
Production and transportation	56%
Engineering (e.g., electrical, mechanical)	32%
Installation, maintenance, and repair	28%
Extraction and rig operations	16%
Management and supervisory	8%
Construction	4%

3.3 Tasks and materials

Participants were asked to carry out four tasks: column flushing (CF), level control valve (LCV) replacement, pressure testing (PT), and fluid sampling with a centrifuge (Centrifuge). CF is a task that unloads fluids inside a column attached to a vessel. LCV is a maintenance task that replaces a level control valve that adjusts the fluid level in the vessel. PT is a task that tests high- and low-pressure trips of the vessel. Centrifuge is a task that measures the water content of a sample product. Since Centrifuge is to assess the composition of the product regardless of a processing system type used to separate the stream, it was excluded from the current study.

Prior to conducting a task, participants were given a paper-based SOP prepared by the training facility. The SOP consists of purpose and scope of work, document history, risk information, required permits such Lock-Out/Tag-Out (LOTO), necessary tools and equipment (e.g., PPE), and a series of steps to carry out. An example of the steps of LCV is shown in Figure 5. To record the participants' actions during the SOP implementation, an Akaso Action Camera™ (Akaso Inc.) was attached to a participant's hard hat. Due to technical difficulties associated with the portable video recorders (e.g., inadvertent change of a viewing direction), complete data for CF, LCV, and PT tasks were obtained from 19, 19, 22 participants, respectively.

WORK INSTRUCTION

	Signoff	Operation Step
1.	____	Operator & Craft walk down the equipment to ensure that equipment is ready to be removed from service
2.	____	Notify the Control Room Operator that equipment is ready to be removed from service
3.	____	Perform Job Safety Analysis (JSA) on the task that will be taking place. Check Worksite Hazards, and equipment needed for disassembly and containment
4.	____	Complete a Work Permit
5.	____	Complete a LOTO isolation sheet. Check LOTO points. Highlight points on P&ID's and use for attachment. *Note: Can go to electronic copy and save for reference on LOTO.*
6.	____	Close Manual Valve M101-9
7.	____	Close Manual Valve M101-10
8.	____	Console operator to open LCV-101 to the 100% position
9.	____	Open drain valve upstream of LCV-101
10.	____	Open drain valve downstream of LCV-101
11.	____	Open drain valve downstream of check Valve FSV-M101-29 Trapped pressure may be present. Uncontrolled pressure release could result in bodily injury or death. Wear gloves and safety glasses.

Figure 5. A sample of procedural steps of the LCV task

3.4 Independent variables

3.4.1 Experience-Task Familiarity (E-TF) level of participants

Years of experience may represent an operator's experience in a broad sense. However, the current study considers an individual operator's knowledge as to how to perform a specific task. Therefore, the years of experience may not suffice as a single factor to judge whether or not a participant has adequate knowledge for the task. In addition, the divergence in participants' areas of experience (Table 2) may render the years of experience a less indicative factor. To complement such limitations, participants' experience and task familiarity were incorporated into a matrix as presented in Figure 6. Years of experience were scaled with five-year periods and task familiarity scale was obtained from a post-experiment interview with each participant. A diagonal border that includes either very low experience or very task familiarity was chosen to split a low and a high experience-task familiarity (E-TF) group. Participants having lower than 10 points (white cells in the matrix) were classified into a *low* E-TF group whereas those with equal to or higher than 10 points (gray cells in the matrix) were put into a *high* E-TF group. Based on these criteria, 38% of participants were labeled as a low E-TF group.

	Task Familiarity Scale				
Experience Scale	1 (very low)	2 (low)	3 (medium)	4 (high)	5 (very high)
1 (YE<5)	1	2	3	4	5
2 (5≤YE<10)	2	4	6	8	10
3 (10≤YE<15)	3	6	9	12	15
4 (15≤YE<20)	4	8	12	16	20
5 (YE≥20)	5	10	15	20	25

YE: Years of Experience

Figure 6. Experience-Task Familiarity (E-TF) matrix

3.4.2 AH level of SOPs

As the second categorical factor, the AH level that dominates an SOP was assessed. To do this, individual steps of the SOP was coded either *functional (F)* or *physical (P)* based on the ADS of the 3-phase separation system (Figure 4). To be noted is that the instructions regarding administrative measures such as work permit, LOTO (e.g., steps 1 through 6 in Figure 5) were excluded from the coding because they were considered to be part of another large work system and thus were simulated verbally or virtually.

The coding of AH level was conducted by two of the authors (CS and NA). The average interrater reliability (Cohen's κ) between the two coders for the three SOPs was 0.70, indicating a moderate level of agreement [40]. Finally, the first author's coding was used for analysis. Table 3 presents the results of binary coding (i.e., F/P). Based on the coding, CF and LCV were classified as physical-dominant SOPs and PT as a functional-dominant SOP in a relative sense.

Table 3. Binary (F/P) coding results

SOP (No. of steps)	Physical (%)	Functional (%)
Column Flushing (13)	11 (85%)	2 (15%)
Level Control Valve (16)	14 (88%)	2 (12%)
Pressure Testing (12)	6 (50%)	6 (50%)
Total	31 (76%)	10 (24%)

3.5 Dependent variable: Successful Step Ratio (SSR)

In line with the prescriptive view towards SOPs, a traditional measure of operators' procedure performance was how strictly they comply with procedural steps (e.g., compliance vs. non-compliance) [41, 42]. In addition to this dichotomous measure, we attempted to reflect the ecological approach in the SOP performance measurement. Based on a procedural behavior assessment methodology developed by our research group [43], successful step ratio (SSR) was conceived as an operator's SOP performance measure. SSR considers not only compliant and non-compliant behaviors but also adapted actions from procedural steps and assisted or struggled actions as shown in Figure 7. The logic in this coding scheme enables a coder to label a procedural step whether the step is either compliance (C), adaptation (A), performance with issues (I), or non-compliance (N). When the step was performed correctly without any assistance or struggling, the step was coded as compliance. When the step was performed correctly but with some assistance from instructors or struggling (e.g., spending a long time knowing what to do), the step was coded as performed with issues. When the step was performed correctly but out of order, the step was coded as adaptation. Non-compliance was coded when the step was completely skipped or ended incompletely.

Although non-compliance with procedural steps may be claimed helpful in achieving the goals of a task, it would be an unusual situation such as an emergency event or a highly unstable work environment that warrants the deviation from the SOPs. Considering that the current study was conducted under a relatively stable condition (e.g., no emergency event), steps complied with and adapted were deemed to be successful. To that end, SSR is formulated as a ratio of compliance (C) and adaptation (A) to the total number of steps (Eq.1).

$$SSR = \frac{C + A}{C + A + I + N} \qquad \text{Eq.1}$$

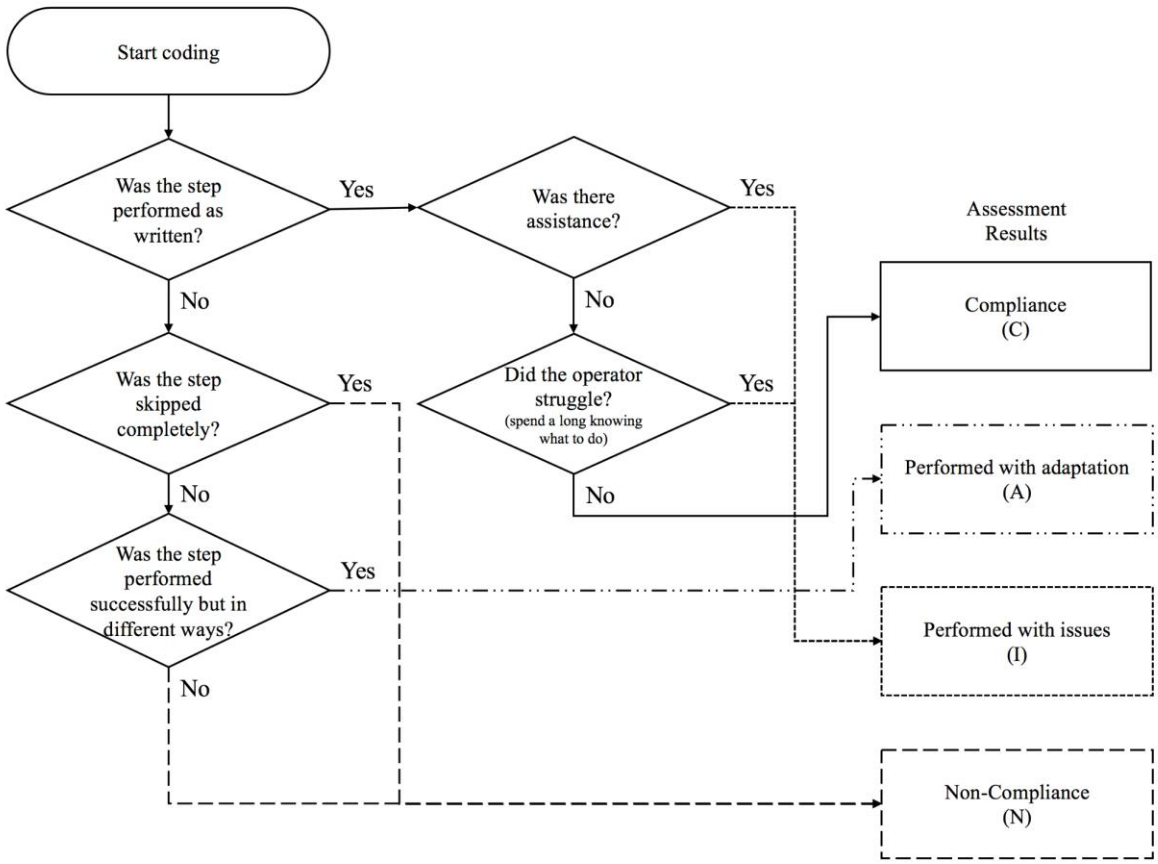

Figure 7. Procedure step performance coding logic (adapted from [43])

3.6 Experiment Protocol

There were six batches of participants with each batch taking two days for data collection. In the afternoon of the first day, a batch of participants checked in to the training facility and was given instructions on basic knowledge of the 3-phase separation process via in-class lecture and a tour to the processing trains in the facility. In total, the instructional session lasted for about three hours. In the morning of the second day, participants came to the facility and were asked to conduct individual tasks. After receiving the SOP for one task, the participant entered the processing trains, located the target equipment, and implemented the SOP. One to two instructors were positioned inside the facility and provided assistance when the participant asked or when the participant's behavior was deemed unsafe. On completion of the task, the participant exited the processing trains and was given another task. An order of assigning tasks to the participants was randomized to control order effects. After all the participants in that batch finished all the tasks, another batch of participants checked in and followed the same protocol. This study was conducted in compliance with research protocols approved by the Institutional Review Board.

3.7 Statistical Analysis

Using the indices introduced in the preceding sections, two-way ANOVA was carried out to examine the main and interaction effects of an operator's E-TF level and AH level of an SOP on

SSR. The assumptions (e.g., normality and equal variance) for ANOVA were found to be satisfied by running Levene's test and inspecting Q-Q plot. Partial eta squared (η_p^2) was used to estimate effect size for the test and reported as being small ($\eta_p^2 < 0.06$), medium ($0.06 \le \eta_p^2 \le 0.14$), and large ($\eta_p^2 \ge 0.14$) [44]. All the statistical analyses were performed using JASP [45]. Statistical significance was concluded when $p < 0.05$.

4 Results

4.1 E-TF level and AH level of SOP on SSR

We analyzed how an operator's E-TF level (high vs. low) and AH level (physical vs. functional) of an SOP are related to SSR. As shown in Figure8, the average SSR was 0.66 for the physical-dominant SOPs and 0.35 for the functional-domain SOP in the low E-TF group. Corresponding values for the high E-TF group were 0.85 and 0.74, respectively. Results of the two-way ANOVA indicate that there are main effects of the E-TF level ($F(1, 56)=29.04$, $p < 0.001$, $\eta_p^2 = 0.342$, large effect size) and the AH level ($F(1, 56)=15.44$, $p < 0.001$, $\eta_p^2=0.216$, large effect size). There was a marginally significant interaction effect of the E-TF level and the AH level on SSR ($F(1,56)=3.40$, $p=0.071$).

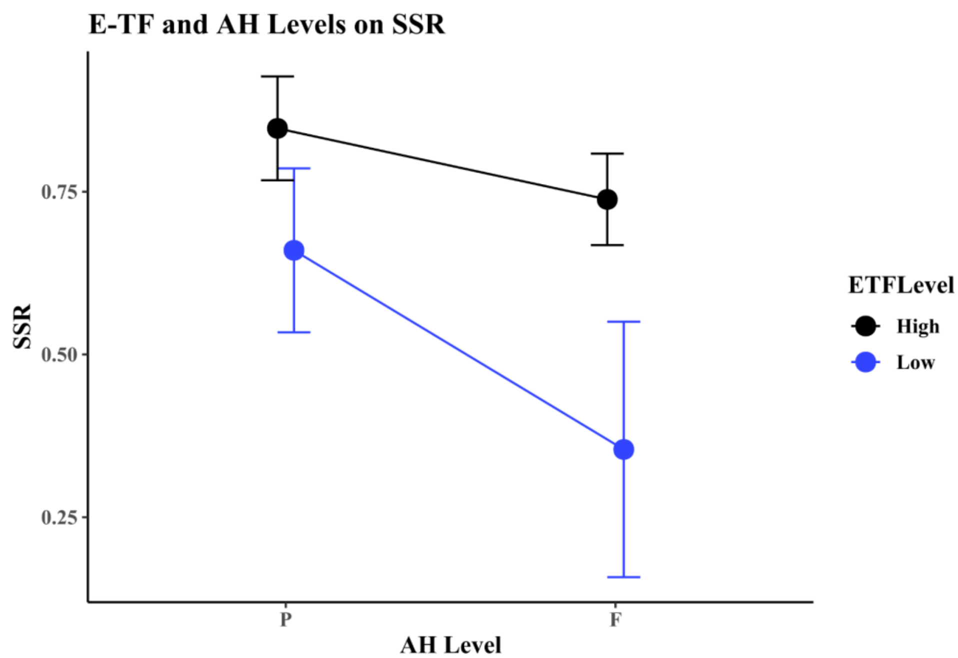

Figure. 8 Successful Step Ratio (SSR) by E-TF level and AH level

5 Discussion

As an exploratory study that embraces the ecological approach towards SOPs, the present study first modeled the work domain of a 3-phase separation system into an abstraction-decomposition space and applied the AH to three SOPs used in the high-fidelity chemical processing facility. We found out that individual steps of the SOPs were representing different AH levels (e.g., physical and functional) of the system. More specifically, our coding results indicated that physical-level steps were more prevalent than functional-level ones. The predominance of physical-level steps appears to be in line with the emphasis on standardization and specification of actions to be taken from the prescriptive approach [3, 4].

Our study then analyzed the relationship among the operators' E-TF level and the AH level of the SOPs, and a ratio of successful steps. The results of the two-way ANOVA first suggest that the more the operator is experienced and familiar with a task, the more successful steps he/she performs. Second, it also indicates that the more physical steps the SOP contains, the more successful steps the operator carries out. Based on this finding, one may insist that the SOPs be designed in such a way that they specify procedural actions at a physical-level and sufficient training be provided to operators so that they become more experienced and familiarized with SOPs for given tasks [41].

While the prescriptive efforts in the design of SOPs may provide some benefits to operators (e.g., gaining experience through training under stable or ideal conditions), it still leaves the SOPs vulnerable to unpredicted and abnormal situations in which the operators have to deviate. To address this *double-bind* issue [46], results of the current study offer an opportunity to exploit the utilities of the ecological approach. As shown in the interaction trend of the E-TF level and AH level, albeit the marginally significant effect, operators with higher experience and task familiarity may have utilized their mental model of the system and thus exhibited comparatively consistent performance in the face of more functional, abstraction step descriptions [32, 33]. This interpretation then implies that SOPs should be designed in a way that they externalize the functional structure (e.g., AH) of the system and thus support operators' goal-achieving behaviors when confronted with unexpected situations [31]. As an example of the SOP reflecting the ecological viewpoint, Figure 9 presents both physical-level actions ('how') and the purpose of doing such actions ('why').

WORK INSTRUCTION

	Signoff	***Physcial Action* Step**	***Purpose***
6.	____	Close Manual Valve M101-9	*To isolate upstream and downstream flow of LCV-101*
7.	____	Close Manual Valve M101-10	
8.	____	Console operator to open LCV-101 to the 100% position	*To release fluid and pressure inside LCV-101*
9.	____	Open drain valve upstream of LCV-101	*To drain the remaining fluid and relieve pressure inside the isolated section surrounding LCV-101 so that removing LCV-101 does not cause bursting pressure incidents*
10.	____	Open drain valve downstream of LCV-101	
11.	____	Open drain valve downstream of check Valve FSV-M101-29  Trapped pressure may be present. Uncontrolled pressure release could result in bodily injury or death. Wear gloves and safety glasses.	

Figure. 9 A sample SOP for LCV that provides both a physical-level description and purpose of actions (changes from the original version, Figure. 5, are italicized)

Notwithstanding the insightful findings presented in this study, limitations of the current study should be acknowledged. First, although the experiment was conducted in a high-fidelity environment, the presence of observers and instructors might have affected participants' behavior representing less of actual operation practices. This limitation can be addressed by conducting similar experiments in real-world work environments. Second, another limitation exists in the design of SOPs used in this study. To maintain the fidelity of the experiment, we used the existing SOPs established by the training facility. Therefore, it was not possible to manipulate the level of AH as indicated in the verdict of PT as a functional-dominant SOP. Hence, in future studies, it is recommend to control the AH levels so that the degree of physical or functional dominance would become more evident. Third, we formulated a couple of novel indices to consider both the operators' knowledge and familiarity with individual tasks (E-TF score) and the variations in the SOP-implementing behaviors (SSR). Due to relatively stable experimental conditions where no adversaries or unexpected situations arose, we found that adherence to the SOP steps largely led to successful outcome although some adaptations were also observed. Thus, future research may consider introducing abnormal or unanticipated events in order to examine how experienced and inexperienced operators comply with or deviate from the SOPs as well as to refine the SOP performance measure in alignment with the ecological approach.

6 Conclusion

As an exploratory research effort, this study employed an ecological approach towards the design of SOPs used in the 3-phase separation system. We found it useful to use AH in modeling a complex chemical processing system and in mapping AH to the steps of the SOPs. By analyzing the relationship among operators' E-TF level and AH level of the SOPs, and the operator's successful step ratio measure, this study identified that the more experienced and familiar with tasks, the more successful steps they carried out, and that the more physical steps the SOP include, the higher the successful step ratio. More importantly, our study results found an interesting tendency that the high E-TF group showed relatively stable performance in the use of the functional-level dominant SOP. To gain more benefits from the ecological approach, future research is warranted to address the limitations of the current study and to design SOPs that support operators' successful performance under variable conditions in high-risk process operations.

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