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A study on the identification of cognitive complexity factors related to the complexity of procedural steps

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Abstract

In complex systems, it is well recognized that the provision of understandable procedures that allow operators to clarify "what needs to be done" and "how to do it" is one of the requisites to confirm their safety. In this regard, the step complexity (SC) measure that can quantify the complexity of procedural steps in emergency operating procedures (EOPs) of a nuclear power plant (NPP) was suggested. However, the necessity of additional complexity factors that can consider a cognitive aspect in evaluating the complexity of procedural steps is evinced from the comparisons between SC scores and operators' performance data.

To this end, the comparisons between operators' performance data with their behavior in conducting prescribed activities of procedural steps are conducted in this study. As a result, two kinds of complexity factors (the abstraction level of knowledge and the level of engineering decision) that could affect operators' cognitive burden are identified. Although a well-designed experiment is indispensable in confirming the appropriateness of cognitive complexity factors, it is strongly believed that the change of an operator's performance can be more authentically explained if they are taken into consideration.

1. Introduction

The provision of good procedures provides several benefits including the reduction of the opportunity for human errors, particularly if a task should be carried out under very complicated and stressful conditions [1-3]. At the same time, however, significant portions of human errors can be attributed to procedures [4]. Ironically, this fact even seems to be natural because they directly affect an operators' cognitive and physical behavior by prescribing detailed activities including "what needs to be done" and "how to do it," etc. [3, 4].

The more remarkable problem is that the possibility of human errors can increase due to complicated procedures, since they not only distract operators from subsequent tasks [1] but also encumber operators in understanding instructions (i.e., operators could fail in identifying and/or carrying out what they have to do due to the misunderstanding of instructions) [3, 4]. Therefore, it seems obvious that a systematic approach that can properly assay the complexity of procedures is indispensable in preparing countermeasures that are helpful in reducing the side effects of complicated procedures [1-3, 5].

From this standpoint, in order to quantify the task complexity implied by procedural steps of the emergency operating procedures (EOPs) in nuclear power plants (NPPs), Park et al. suggested the step complexity (SC) measure based on a graph entropy concept [6]. In addition, it was statistically demonstrated that the SC measure could be used to quantify the complexity of procedural steps [7]. However, further comparisons between SC scores and operators' performance data that are collected under a more stressful condition strongly allude to the necessity of cognitive complexity factors in quantifying the complexity of procedural steps [8].

In this study, in order to elucidate additional complexity factors, operators' performance data are compared with their behavior in conducting prescribed activities of procedural steps. As a result, two kinds of complexity factors that could affect an operator's cognitive burden are identified. The first one is the abstraction level of knowledge that can represent a complexity due to the amount of knowledge for recognizing the problem space needed to accomplish prescribed activities. In addition, the second factor is the level of engineering decision, and it can express a complexity due to the amount of cognitive resources to establish decision criteria that discriminate whether prescribed activities are satisfied or not.

This paper is organized as follows. In section 2, background information that explains the necessity of this study is described. After that, detailed activities to identify additional complexity factors are expounded upon in Section 3. The results of this study including the characteristics of additional complexity factors are explained in Section 4. Finally, in section 5, discussions will be given with the conclusion of this study.

2. Background of This Study

The following succinct explanations about both the SC measure and the result of the previous study may be serviceable in understanding the background of this study.

2.1 The Meaning of SC Measure

The SC measure is comprised of three sub-measures that evaluate the complexity of procedural steps due to three kinds of complexity factors: 1) the amount of activities to be done by operators, 2) the amount of information to be processed by operators, and 3) the logic structure that specifies the sequence of prescribed activities [9].

The complexity scores for these factors are quantified by two types of graphs, namely an information structure graph and an action control graph, which can be constructed from the results of task analysis. It is noted that the information structure graph depicts the amount of information to be processed by operators, and the action control graph represents both prescribed activities and their sequence to be followed by operators.

Based on these graphs, three kinds of complexity scores for the *i*th procedural step can be quantified by the first-order and the second-order entropy measure [9]. Firstly, step information complexity (SIC) pertaining to the amount of information to be processed by operators can be quantified by the second-order entropy of an information structure graph. Secondly, step logic complexity (SLC) that originates from the logical sequence to conduct prescribed activities can be quantified by the first-order entropy of an action control graph. Thirdly, step size complexity (SSC) relating to the amount of activities to be conducted by operators can be quantified by the second-order entropy of an action control graph.

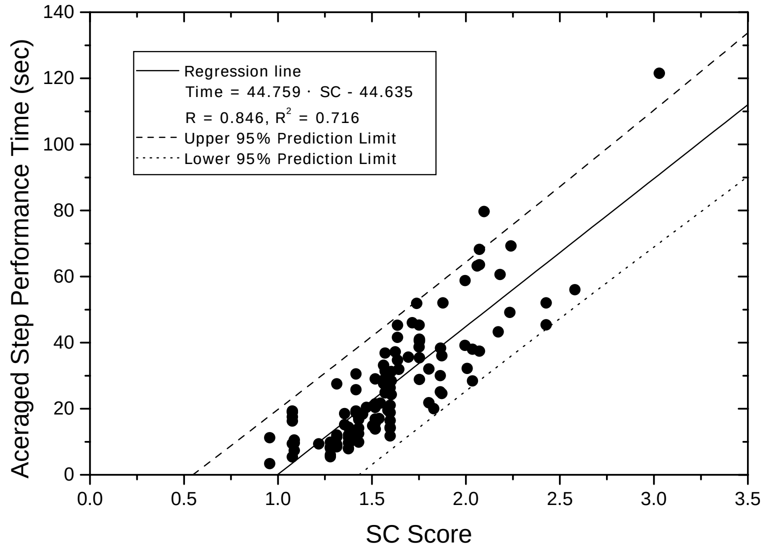
Based on these sub-measures, the SC score of the *i*th procedural step is determined by a weighted Euclidean norm as shown below [10].

$$SC_i = \sqrt{(\alpha \cdot SIC_i)^2 + (\beta \cdot SLC_i)^2 + (\gamma \cdot SSC_i)^2}$$

where, α = 0.326, β = 0.296, γ = 0.378.

The appropriateness of the SC measure is verified through a comparison with operators' performance data that are collected under emergency training sessions (i.e., simulated emergency situations) of the reference NPP [6, 9]. In total 112 emergency training sessions conducted by 24 different operating crews are recorded on videotapes.

From these videotapes, operators' performance data measured by the elapsed time from a procedural step entry to exit are retrieved through a time-line and a protocol analysis [10, 11]. Fig. 1 shows the comparison result between operators' performance data and SC scores.



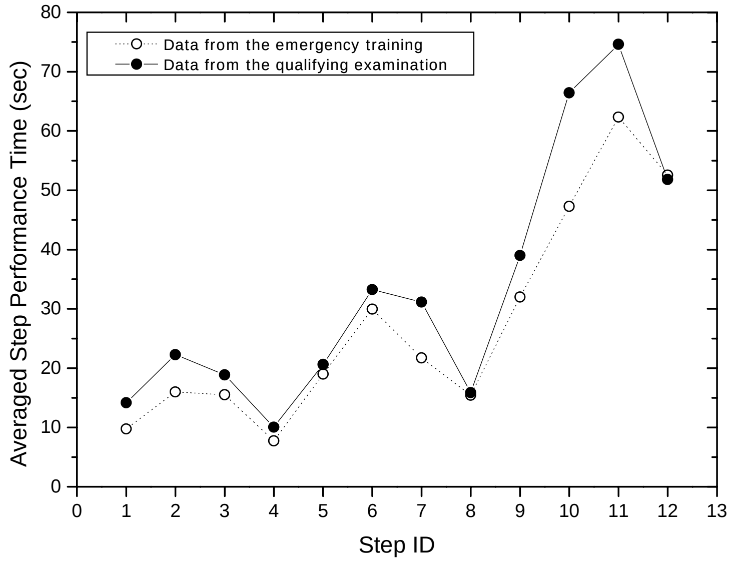
< Figure 1. The comparison result between SC scores and operators' performance data >

From Fig. 1, it appears that the change of an operator's performance can be reasonably explained by the SC measure [7, 10]. However, another insight is found when SC scores are compared with two sets of operators' performance data –one came from a less stressful condition and the other from a more stressful condition [8].

2.2 Operators' Performance and Different Stress Levels

As one of the verification activities, it is unavoidable to answer whether the SC measure can suitably explain the change of an operator's performance under a real situation in which they feel much more stress or burden than a simulated situation. To do this, operators' performance data that are collected from the qualifying examination for taking a senior reactor operator (SRO) license are compared with SC scores, since it is obvious that operators may feel more stress during their examination.

Two sets of operators' performance data are compared with identical procedural steps (i.e., identical SC scores). Fig. 2 depicts the change of an operator's performance with respect to two kinds of stress levels.



< Figure 2. The change of operators' performance data that are obtained from a less stressful as well as a more stressful condition >

From Fig. 2, one important question quickly arises – "why the amount of changes of operators' performance data is varied with respect to procedural steps?"

Ideally, if the SC measure suitably contains the complexity factors that make the performance of procedural steps difficult, then it is expected that the change of operators' performance due to a stress level will show a homogeneous pattern. However, a heterogeneous pattern shown in Fig. 2 strongly suggests the necessity of additional complexity factors that could become salient under a stressful condition.

This inkling appears to be more meaningful if we descry the characteristics of operators' activities from the point of view of a cognitive burden – "the amount of cognitive resources to be spent by operators [8]." For example, if there is a procedural step in which most of the activities to be done by operators require binary decisions (i.e., a simple activity that might demand very little cognitive resources), then it is expected that the change of an operator's performance will be very small regardless of a stress level. Meanwhile, if operators have to conduct more complicated activities (such as selecting an alternative, which might require a lot of cognitive resources), then it is supposed that their performance could be largely degraded because the amount of available cognitive resources are drastically dwindled under a stressful condition [12, 13].

Therefore, to elucidate additional complexity factors, operators' performance data that are collected from emergency training secessions are pearly reviewed by a two-stage approach. The first stage is a categorization and the second stage is a comparison of operators' performance with their behavior in conducting prescribed activities of procedural steps.

3. Categorization of Operators' Performance Data

The goal of categorization is to facilitate the peer reviews for identifying additional complexity factors, and the categorization consists of three steps.

First of all, operators' performance data that are collected from emergency training sessions are rearranged based on each distinct procedural step. As a result, operators' performance data for 65 distinct procedural steps are obtained.

As for the second step, procedural steps that fulfill the following criteria are selected from 65 distinct procedural steps.

- Expected time is positive
- Absolute value of relative percentage error is smaller than 100%
- Value of relative dispersion is smaller than 100%
- A procedural step for which at least 5 performance data are available

To explain the purport of the first and the second criterion, it is needed to introduce relative percentage error that is defined by Eq. (1) [14].

$$\text{Relative percentage error} = \frac{\text{Expected value} - \text{Measured value}}{\text{Expected value}} \times 100 \quad (1)$$

As can be seen in Eq. (1), relative percentage error is useful in quantifying the amount of differences between expected and actual operators' performance time as well as its direction (i.e., whether a positive or a negative value). It is accentuated that, in this study, the direction is the main concern rather than the amount of differences, since the primary goal is not finding factors that dominate the amounts of differences but identifying factors that can make the performance of procedural steps more difficult (i.e., factors for a performance loss) or easy (i.e., factors for a performance gain). From this concern, the values of relative percentage error are calculated for all the procedural steps.

It is noted that four procedural steps that could give inappropriate results are regarded as outliers. For example, calculating relative percentage error for two procedural steps that have a negative expected time seem to be meaningless. In addition, two other procedural steps are excluded, since the expected time is so small in comparison with the actual time (over four times larger than the expected time) that their directions seem not to be useful. Thus, to facilitate in selecting inadequate procedural steps, procedural steps for which the absolute value of relative percentage error is over 100% are regarded as outliers.

The third criterion is based on relative dispersion that can quantify the degree of scattering among operators' performance data. Relative dispersion is defined by Eq. (2) [15].

$$\text{Relative dispersion} = \frac{\text{Standard deviation}}{\text{Average}} \times 100 \tag{2}$$

From Eq. (2), the meaning of relative dispersion is apparent, since a dispersion of 1 second in measuring 100 seconds is quite different from that of 1 second in 10 seconds. Therefore, if we use the relative dispersion of procedural steps, then it is reasonable to suppose that complexity factors dispersing an operator's performance could be distinguished. In this vein, the values of relative dispersion for all procedural steps are calculated.

It is noted that, although it is a rule of thumb, the border between small and large relative dispersion is assumed as 50% in this study. In addition, similar to the case of relative percentage error, two procedural steps are regarded as outliers because their relative dispersions are over 100%.

The last criterion is the number of available data, since both the second and the third criterion pertain to statistical measures that represent 'representative' tendencies of a given data set. In other words, a sufficient number of data should be secured to properly use these statistical measures, since right decisions could be obfuscated by meager data.

Ideally, according to the Central Limit Theorem, it can be said that sufficient data are collected if the number of available data is over 30 [15]. Unfortunately, in this study, it seems very difficult to continue with a further analysis when the above touchstone is applied, since only a few procedural steps satisfy it. Thus, because of a practical reason (i.e., to secure as many as possible procedural steps for further analysis), it is assumed that at least 5 data are needed to appropriately characterize the tendency of procedural steps. In other words, if at least 5 data are available, then the tendencies of operators' performance will be consistently denoted by their statistical values (i.e., relative percentage error and relative dispersion).

Based on these criteria, in total 46 procedural steps are selected, and they are subdivided into four categories so that important tendencies of operators' performance can be meaningfully manifested. Table 1 summarizes 46 procedural steps with respect to their categories.

< Table 1. Procedural steps subdivided into four categories >

Step ID	SC	N[a]	Exp.[b]	Avg.[c]	SD[d]	Error[e]	Dispersion[f]	Category
1	1.313	10	14.13	27.50	15.01	-94.57	54.58	I
2	1.451	6	20.31	27.40	19.11	-34.91	69.74	I
3	1.562	16	25.28	29.75	20.38	-17.69	68.50	I
4	1.570	66	25.64	29.95	15.35	-16.83	51.25	I
5	1.603	28	27.11	29.54	22.26	-8.95	75.36	I
6	1.624	5	28.05	37.20	21.32	-32.62	57.31	I
7	1.715	6	32.13	37.20	25.81	-15.79	69.38	I
8	1.753	6	33.83	40.67	32.34	-20.23	79.52	I
9	1.996	13	44.70	58.77	35.05	-31.46	59.64	I
10	2.060	5	47.57	63.20	47.88	-32.86	75.76	I
11	2.072	16	48.11	58.00	37.68	-20.57	64.97	I
12	2.097	5	49.22	55.33	32.41	-12.4	58.58	I
13	1.279	51	12.61	7.75	4.76	38.55	61.42	II
14	1.313	31	14.13	9.00	4.60	36.32	51.11	II
15	1.355	14	16.01	15.14	9.85	5.45	65.06	II
16	1.375	63	16.91	9.76	5.79	42.28	59.32	II
17	1.430	67	19.37	15.51	9.16	19.93	59.06	II
18	1.518	63	23.31	19.02	12.73	18.40	66.93	II
19	1.585	14	26.31	19.50	12.54	25.88	64.31	II
20	1.597	66	26.85	16.00	9.60	40.40	60.00	II
21	1.643	13	28.90	27.69	15.39	4.20	55.58	II
22	1.737	58	33.11	21.74	16.07	34.34	73.92	II
23	1.753	33	33.83	33.21	21.08	1.83	63.47	II
24	1.803	8	36.07	30.88	23.79	14.38	77.04	II
25	1.803	9	36.07	23.00	18.52	36.23	80.52	II
26	1.864	13	38.80	26.62	17.32	31.38	65.06	II
27	1.872	9	39.15	29.67	18.72	24.22	63.09	II
28	1.355	6	16.01	18.50	7.40	-15.53	40.00	III
29	1.694	5	31.19	35.60	3.65	-14.15	10.25	III
30	1.738	7	33.16	51.86	16.47	-56.41	31.76	III
31	1.751	13	33.74	42.23	14.36	-25.17	34.00	III
32	1.753	5	33.83	41.00	19.70	-21.20	48.05	III
33	1.874	22	39.24	43.62	21.45	-11.15	49.17	III
34	1.878	10	39.42	54.70	22.72	-38.75	41.54	III
35	2.182	10	53.03	60.60	24.18	-14.28	39.90	III
36	3.029	7	90.94	122.43	33.57	-34.63	27.42	III
37	1.217	6	9.84	9.33	4.46	5.15	47.80	IV
38	1.385	30	17.36	10.83	5.39	37.60	49.77	IV
39	1.504	6	22.68	14.83	5.23	34.62	35.27	IV
40	1.865	7	38.84	38.29	16.47	1.42	43.01	IV
41	1.995	14	44.66	39.14	13.74	12.36	35.10	IV
42	2.007	6	45.20	32.17	9.79	28.82	30.43	IV
43	2.035	8	46.45	32.00	11.14	31.11	34.81	IV
44	2.234	9	55.36	52.56	25.30	5.05	48.14	IV
45	2.427	15	64.00	47.27	17.52	26.13	37.06	IV
46	2.580	6	70.84	62.33	19.46	12.02	31.22	IV

a. 'N' means the number of operator's performance data.
b. 'Exp.' denotes the expected time calculated by the result of a regression analysis in Fig. 1 (i.e., $\text{Exp.} = 44.759 \times \text{SC} - 44.635$).
c. 'Avg.' indicates the averaged performance time of a given procedural step.
d. 'SD' is short for standard deviation.
e. 'Error' implies relative percentage error.
f. 'Dispersion' designates relative dispersion.

4. Scrutinizing Operators' Behavior

As stated in the previous section, operators' performance data are categorized based on four peculiarities – a performance loss/gain represented by the value of relative percentage error and a high/low dispersion represented by the value of relative dispersion. Thus, the next process is to obtain an appropriate answer for the question of "what factors create these peculiarities?" To this end, reinvestigations for operators' behavior in carrying out prescribed activities are conducted.

For example, let us consider Fig. 3 that shows the 5th procedural step in Table 1 [16]. From Fig. 3, it is apparent that operators have to successfully carry out several prescribed activities along with a predefined sequence as depicted in Fig. 4 [9].

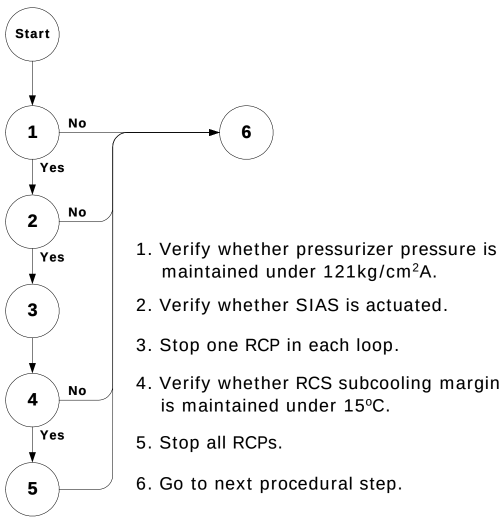
IF pressurizer pressure is maintained under 121kg/cm^{2}A
AND SIAS is actuated,
THEN perform **BOTH** of the following:

- Stop **ONE** RCP in each loop.
- **IF** RCS subcooling margin is maintained under 15^{o}C,
  THEN stop **ALL** RCPs.

Acronyms (these acronyms are not shown in a real procedure)

SIAS	Safety Injection Actuation Signal
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System

< Figure 3. The 5th procedural step >



< Figure 4. Operators' activities and their sequence for the 5th procedural step >

Therefore, it is reasonable to suppose that more authentic explanations about the reasons why operators' performance data are different from expectations could be obtained from scrutinizing operators' behavior to carry out prescribed activities. In addition, if we can identify several reasons that are frequently and commonly observed, then, without a logical jump, they could be regarded as complexity factors making the performance of procedural steps difficult.

Based on these concerns, the peer reviews of operators' behavior are conducted for procedural steps included in Table 1. As a result, several plausible reasons are identified as summarized in Table 2.

< Table 2. Plausible reasons for operators' performance deviation >

Plausible reasons	Contribute to
Context dependency (in connection with operators' inherency)	Dispersion
Non-compliancy (in connection with operators' inherency)	
High abstraction level High level of engineering decision	Performance loss
Low abstraction level Low level of engineering decision	Performance gain

4.1 Reasons for the Dispersion of Operators' Performance

As shown in Table 2, two items are listed as plausible reasons for the dispersion of operators' performance. To clarify the meaning of each item, it may be helpful to reconsider Fig. 4 that depicts prescribed activities for the 5th procedural step.

Firstly, to understand the dispersion of operators' performance data due to a context dependency, let us assume two different situations when operators are confronted with this procedural step. The first situation is that all the reactor coolant pumps (RCPs) are running, while the second situation is that all the RCPs are already stopped because one of previous procedural steps requires their stoppage.

In the case of the later, it is obvious that operators can quickly accomplish this procedural step, since what operators have to do is only confirming the stoppage of RCPs. In contrast, in the case of the former, operators will take more time to accomplish it because they have to not only check the status of plant parameters but also stop RCPs with respect to predefined conditions. Thus, the deviation among operators' performance data could become quite large because of these extreme values.

As for the second, operators' non-compliance behavior seems to be critical to the dispersion of operators' performance data. According to the previous study, two types of operators' non-compliance behavior are discerned: "skipping redundant activities" and "modifying a predefined sequence" [7]. This means that the dispersion of operators' performance will increase, since several operators who adopt the modified sequence can accomplish this procedural step faster than those who strictly follow the predefined sequence.

It should be emphasized that the effect of both the context dependency and the non-compliancy on the dispersion of operator's performance data increases in connection with operators' inherency such as aptitude or ability, etc.

For example, let us assume the situation in which RCS subcooling margin is 14^{o}C but gradually increasing. Under this situation, when operators are faced with the prescribed activity of "Verify whether RCS subcooling margin is maintained under 15^{o}C", it is roughly desired that their behavior could be classified into two kinds: one is strict obedience as written and the other is waiting for a while in order to obtain a more clearer trend [11]. Thus, the amount of dispersions due to the context dependency will become more conspicuous with respect to operators' inherency. Similarly, the amount of dispersions due to the non-compliancy will be deepened because one of its dominant reasons is known as operators' inherency [17].

From these characteristics, it seems that the reasons making operators' performance dispersive are inappropriate to regard as additional complexity factors, since they are varied along with an unpredictable nature, such as the context of different situations. Thus, it is reasonable to postulate that peer reviews for operators' performance data that have small dispersions will give a reliable insight into identifying additional complexity factors.

4.2 Reasons for performance gain and loss

As listed in Table 2, two kinds of plausible reasons for performance gain/loss are distinguished through scrutinizing how operators actually conduct prescribed activities. To understand them more clearly, let us consider two predefined activities, such as 1) "Determine the most affected SG based on a dropping SG pressure" and 2) "Verify at least one vital DC bus is energized."

The intention of the former activity is to determine, between two steam generators (SGs), which SG is damaged by an excess steam demand event (ESDE) that includes several events, such as a break in a main steam line, a break of a main and/or auxiliary feed water line and an inadvertent opening of main steam system valves, etc [16]. In other words, when an ESDE has occurred, the most affected SG can be determined by comparing the trends of several key parameters (such as both SGs' pressures and levels, etc.), since the parameters associated with the affected SG will be lower than those of the intact SG. In addition, the intention of the later activity is to confirm the provision of vital direct current (DC) busses.

From these predefined activities, two plausible reasons for deteriorating (i.e., performance loss) and ameliorating (i.e., performance gain) an operator’s performance could be commonly identified.

The first one is that the abstraction level of knowledge. Here, the abstraction level of knowledge denotes the amount of knowledge for recognizing the problem space that is needed to accomplish prescribed activities. This means that operators are likely to feel a cognitive burden (i.e., demanding large amount of cognitive resources), if they have to carry out a prescribed activity that requires a high level of knowledge for many processes and/or systems. In contrast, it can be anticipated that operators could easily accomplish a prescribed activity that is restricted to a simple component [18].

Based on the Rasmussen's abstraction paradigm of knowledge representation [19], four levels are suggested to classify the abstraction level of knowledge for prescribed activities included in EOPs [20]. They are: 1) component function (CF) level, 2) system function (SF) level, 3) process function (PF) level and 4) abstraction function (AF) level. Accordingly, it seems that the abstraction level of knowledge for the former prescribed activity is relatively higher than that for the later prescribed activity. Table 3 shows four abstraction levels of knowledge.

< Table 3. Four abstraction levels of knowledge >

Level	Description
AF	Activities that delineate mass or energy based on two or more process functions.
PF	Activities describing mass or energy flow for which two or more system functions are associated.
SF	Activities representing system function that can be varied due to a change of two or more component functions.
CF	Activities related to states and/or manipulations of a component (such as valve, pump, heater, vital bus, battery, etc.).

As for the second plausible reason that can explain an operator’s performance gain/loss, the level of engineering decision seems to be worth emphasizing. Let us consider the former prescribed activity. As stated earlier, operators have to decide on the affected SG by a comparison of both SGs’ pressures. At first glance, this activity seems to be easy because it requires an operator’s simple decision – which SG’s pressure is smaller than the other. However, this activity appears to demand a great deal of operators’ cognitive resources, since the decision criterion to determine the affected SG is not clearly given. This means that operators have to establish a proper decision criterion that can be varied with respect to the situation they are faced with.

For example, it is evident that the lowering trend of SGs' pressure is very susceptible not only to the initiating conditions (such as break locations and break sizes, etc.) but also the status of many components that are connected to SGs [16]. In other words, in order to properly decide on the affected SG, operators have to establish a decision criterion through answering the question of "how amount of a dropping rate is enough to ensure the affected SG in this situation?" Consequently, operators may need not only additional cognitive resources but also their engineering knowledge of the plant. In contrast, operators will easily conduct the later prescribed activity, since they do not need to use any kind of engineering knowledge for establishing the decision criterion – "energized" DC bus.

Therefore, it is desirable to anticipate that operators' performance will be degraded (i.e., performance loss) when they have to carry out an activity that requires a high level engineering decision, while operators' performance will be improved (i.e., performance gain) for an activity demanding a low level engineering decision. Based on this anticipation, all the activities included in EOPs are investigated. Table 4 shows four levels of engineering decision obtained from the investigation.

< Table 4. Four levels of engineering decision >

Level	Description
1	A simple decision based on a clear decision criterion
2	Deciding the satisfaction of a given decision criterion through comparing reference information
3	Making a decision by use of a decision criterion that is established by identifying plant status or conditions based on associated knowledge and/or information.
4	Selecting one among two or more alternatives, without any decision criterion.

5. Discussions and Conclusions

Up to now, to identify additional complexity factors that make the performance of procedural steps difficult, operators' performance data that are classified into four categories are meticulously reviewed. As a result, the abstraction level of knowledge and the level of engineering decision are identified as plausible complexity factors. Here, it may be meaningful to elucidate why these additional complexity factors are important for evaluating the complexity of procedural steps.

In general, as systems are becoming more complicated, the provision of a good procedure is getting more difficult. In particular, the importance of understandability seems to be more salient for procedures in complicated systems. Thus, the necessity of a systematic method that can quantify the understandability of procedural steps seems to be indispensable. Actually, this necessity was the prime motive for the SC measure development.

However, three factors included in the SC measure seem to have a basic limitation because they mainly emphasize a physical aspect (such as the amount of information and/or activities to be processed by operators) in evaluating the understandability of procedural steps. In this vein, as stated in Section 4.2, two additional complexity factors will play an important role, since they can deal with a cognitive aspect (i.e., the amount of cognitive resources) in evaluating the understandability of procedural steps.

Although more studies, such as an experimental verification for the effect of additional complexity factors on operators' performance and a systematic way to quantify the complexity due to them, are essential, the following conclusions can be drawn from the result of this study.

- Through intensive comparisons between operators' behavior and their performance data, two kinds of complexity factors (the abstraction level of knowledge and the level of engineering decision) are additionally identified.
- The abstraction level of knowledge can be used to represent the complexity due to the amount of knowledge required for describing the problem space of prescribed activities.
- The level of engineering decision can be used to indicate the complexity due to the degree of cognitive resources to establish decision criteria of prescribed activities.
- The result from comparisons between operators' behavior and their performance strongly supports the belief that the change of operators' performance can be more authentically explained by considering additional complexity factors.

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Reference

[1] R. L. Gross, and Staff of Flight Safety Foundation. Studies suggest methods for optimizing checklist design and crew performance. Flight Safety Digest 1995;14(5), 1-10.

[2] R. Hattemer-Apostel. Standard operating procedures - a novel perspective. The Quality Assurance Journal 2001;5, 207-219.

[3] A. Degani, M. Heymann and M. Shafto. Formal aspects of procedures: the problem of sequential correctness. Proceedings on Human Factors and Ergonomics Society (HFES) Annual Meeting, Vol. 43, p. 1113-1117, 1999.

[4] A. Degani and E. L. Wiener. Procedures in complex systems: the airline cockpit. IEEE Transactions on Systems, Man and Cybernetics - Part A: Systems and Humans 1997;27(3), 302-312.

[5] Y. Dien. Safety and application of procedures, or 'how do they have to use operating procedures in nuclear power plants?' Safety Science 1998;29, 179-187.

[6] J. K. Park, W. D. Jung, J. J. Ha and C. K. Park. The step complexity measure for emergency operating procedures: measure verification. Reliability Engineering and System Safety 2002;76, 45-59.

[7] J. K. Park and W. D. Jung. The operators' non-compliance behavior to conduct emergency operating procedures – comparing with the work experience and the complexity of procedural steps. Reliability Engineering and System Safety 2003;82(2), 115-131

[8] J. K. Park, J. W. Kim and W. D. Jung. Comparing the complexity of procedural steps with the operators' performance observed under stressful conditions. Reliability Engineering and System Safety 2004;83(1), 79-91.

[9] J. K. Park, W. D. Jung and J. J. Ha. Development of the step complexity measure for emergency operating procedures using entropy concepts. Reliability Engineering and System Safety 2001;71(2), 115-130.

[10] J. K. Park, W. D. Jung, J. W. Kim and J. J. Ha. Step complexity measure for emergency operating procedures – determining weighting factors. Nuclear Technology 2003;143(3), 290-308.

[11] J. K. Park and W. D. Jung. The requisite characteristics for diagnosis procedures based on the empirical findings of the operators' behavior under emergency situations. Reliability Engineering and System Safety 2003;81(2), 197-213.

[12] D. Wieringa, C. Moore and V. Barnes. Procedure Writing: principles and practices (2nd edition). Battelle Press, 1998.

[13] C. D. Wickens. Engineering psychology and human performance (2nd edition). University of Illinois at Champaign-Urbana. Haper Collins Publishers, 1992.

[14] M. Abramowitz and C. A. Stegun (Editors). Handbook of mathematical functions with formulas, graphs, and mathematical tables (9th printing). New York, 1972.

[15] M. R. Spiegel and R. W. Boxer. Schaum's outline of theory and problems of statistics in SI unit (1st edition). McGraw-Hill International Book Company, New York, 1972.

[16] Combustion Engineering (CE) Owner’s Group. Combustion Engineering Emergency Response Guidance. CEN-152, Rev. 04. 1996.

[17] J. Reason, D. Parker and R. Lawton. Organizational controls and safety: The varieties of rule-related behavior. Journal of Occupational and Organizational Psychology 1998;71, 289-304.

[18] W. D. Jung, W. C. Yoon and J. W. Kim. Structured information analysis for human reliability analysis of emergency tasks in nuclear power plants. Reliability Engineering & System Safety 2001;71(1), 21-32.

[19] J. Rasmussen. Information processing and human–machine interaction: an approach to cognitive engineering, North-Holland, New York, 1986.

[20] W. D. Jung. Structured information analysis for human reliability assessment of emergency tasks in nuclear power plants. Ph.D. Thesis, Korea Advanced Institute of Science and Technology, 2001.