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The step complexity measure its meaning and applications

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Abstract

According to related studies, it was revealed that procedural error plays a significant role for initiating accidents or incidents. This means that, to maximize safety, it is indispensable to be able to answer the question of “why the operators perpetrate procedural error?”

In this study, the SC (step complexity) measure is introduced to investigate its applicability for studying procedural error, since it was shown that the change of the operators’ performance is strongly correlated with the change of SC scores. This means that the SC measure could play an important role for researches related to procedural error, since it is strongly believed that complicated procedures would affect both the operators’ performance and the possibility of procedural error. Thus, to ensure this expectation, the meaning of the SC measure is investigated through brief explanations including the necessity, theoretical basis and verification activities of the SC measure.

As the result, it is quite positive that the SC measure can be used to explain the change of the operators’ performance due to the task complexity implied by procedures. In addition, it seems that the SC measure may be useful for various purposes, particularly for scrutinizing the relationship between procedural error and complicated procedures.

1. Introduction

It is well known that one of the primary causes, which result in many accidents or incidents, is human error. For instance, the incidence of system failures attributable to human error is 90% in air traffic control systems, 85% in automobiles, 70% in U.S. NPPs (nuclear power plants), 65% in worldwide jet cargo transport, 31% in petrochemical plants and 19% in the petroleum industries (Cott, 1994). Accordingly, in order to prevent an occurrence of similar accidents or to ensure safety, extensive effort has been spent to identify significant factors that can cause human error. As a result, procedures (or written manuals) are identified as one of the important factors.

It was also found that, however, procedural error (i.e., the operators' deviation from operational procedures, such as skipping/missing a procedural step, following procedural steps out of sequence, etc.) plays a significant role for initiating accidents or incidents (Husseiny, 1989; Degani, 1993). Accordingly, to maximize safety, remedies for the reduction of procedural error should be materialized. In addition, to suggest appropriate remedies, it is indispensable to be able to answer the question of "why the operators perpetrate procedural error?"

One of plausible starting points to answer this question is the complexity of procedures, since it is strongly believed that complicated procedures would not only decrease the operators' performance but also increase the possibility of procedural error. This means that an appropriate framework to evaluate the complexity of procedures is very needed.

In this study, thus, the SC (step complexity) measure that has been developed by Park *et al.* is introduced to investigate its applicability as the prior work for studying procedural error. To do this, The remaining paper is organized as follows. In Section 2, as the basis of this study, the relationships among the understandability, complexity, operators' performance and procedural error are explained. After that, in Section 3, activities to verify the appropriateness of the SC measure, which is based on data obtained from emergency training records, are explained. Finally, in Section 4, discussions including the meaning and the applicability of the SC measure are presented, before the conclusion of this study is drawn with further works.

2. The Understandability, complexity, operators' performance and procedural error

2.1 Importance of the understandability

As stated in Section 1, many operators frequently perpetrate procedural error that results in incidents or accidents. Extremely speaking, this tendency even seems to be 'natural' because, according to related studies, it was reported that the operators use procedures not only in a step-by-step manner that is mandatory required by most regulatory bodies but also in a selective manner (EdF, 1992; Dien, 1998; Degani, 1993; Xiao, 1997). On the other hand, it was also reported that the operators have recognized the usefulness of procedures, especially in an emergency (Kondo, 1994; Degani, 1997; Kontogiannis, 1999).

From these observations, it is possible to postulate somewhat contradictory fact that "the operators frequently deviate from procedures, even though they are very useful to effectively cope with on-going situations including emergencies." However, this contradictory fact could be explained, if we consider the following assumption.

> *"In principle, it can be assumed that the operators try to follow procedures as written (i.e., in a step-by-step manner). However, if procedures cannot provide the operators with what they want to know then they are susceptible to deviate from procedures."*

The above assumption could become more feasible from the review of both the role of procedures and requirements to make a good procedure.

Generally, one of the main roles of procedures could be defined as "specifying tasks or activities to be performed by the operators in a controlled manner so that they can safely and effectively cope with on-going situations including emergencies (Degani, 1993; Degani, 1997)." Thus, to make a good procedure (i.e., to provide a procedure that can clearly specify the activities to be performed by the operators), many requirements have been suggested through related studies and field experience, and they can be summarized as: 1) procedures should be technically accurate, 2) procedures should provide complete sets of information/actions needed to accomplish required tasks and 3) procedures should be understandable (i.e., do not provide complicated procedures). From these requirements, major reasons that make the operators difficult in obtaining what they want from procedures can be identified from two different viewpoints - the deficiencies (or inappropriateness) of procedures and the complexity of procedures (Reason, 1990; EdF, 1992; Degani, 1993).

Between these viewpoints, however, it is noted that the second one (i.e., the complexity) seems to be more important to reduce procedural error because of two reasons. Firstly, to cope with on-going situations, the operators have to seek required activities through understanding of procedures before conducting them (Britto, 2002). In other words, although there are accurate procedural steps that include complete sets of information/actions, the possibility of procedural error will increase, if they are so complicated that the operators fail in understanding what to be done.

Secondly, the understandability of procedures also has to be emphasized from the standpoint of the limitation of procedures. For example, let assume a procedure that can be used to certain emergency situation, such as a leakage of hazardous materials due to a break of pipe. Nevertheless, because actual progression of emergencies can be differently and drastically varied with respect to initiating conditions (such as break locations or break sizes, etc.), it is very difficult to prepare a 'unified' procedure that can be commonly used for various initiating conditions. In addition, even though there is a unified procedure, the operators have to select a set of appropriate procedural steps because procedural steps needed to be performed by them may become different with respect to initiating conditions. This means that the operators should understand the context of required tasks specified in procedures so that they can select appropriate activities from prescribed (i.e., static) instructions, in order to cope with dynamically and sometimes unpredictably changed situations (EdF, 1992; Degani, 1997; Dien, 1998; Kontogianns, 1999; Park, 2001B; Brito, 2002).

Based on these reasons, thus, it is safe to say that the possibility of procedural error has to be dealt with the point of view of the complexity that disturbs the understandability of procedures.

2.2 Factors affecting the complexity of procedures

There is important rationale that can be used as a clue to clarify factors affecting the complexity of procedures. According to study to analysis the users' complexity of interactive systems, it was pointed out that the complexity felt by the users relies on demands implied by the task representation that includes procedural activities needed to accomplish required tasks (Kieras, 1985). In other words, the users' complexity can be adequately modeled by demands due to the task representation, describing what to be done to accomplish required tasks. In addition, the users' performance to accomplish required tasks can be properly modeled using this approach (i.e., it is expected that the more the users' complexity increases, the more the users' performance decreases).

From this rationale, it is expected that factors that make the performance of procedures complicated can be used as factors that create the complexity of procedures, since one of the main roles of procedures is the provision of appropriate activities to be conducted by the operators (i.e., the task representation). That is, if procedures provide the operators with what to be done, it can be thought that the complexity felt by them would be created by demands due to conducting activities specified in procedures.

Based on this expectation, to identify factors that make the performance of procedures complicated, many documents including research results, experts' opinions and field surveys were investigated. As the results, three complexity factors such as 1) the number of actions to be performed, 2) the amount of information to be monitored/supervised and 3) logic structure that specifies the sequence of the operators' activities can be classified (Park, 2001A; Park, 2001B; Park 2002A). From these investigations, thus, it is reasonable to expect that the complexity of procedures can be properly evaluated by three complexity factors.

Accordingly, the SC (step complexity) measure that can quantify the complexity of procedural steps included in EOPs was suggested by use of these complexity factors. Table 1 shows brief meanings of both the SC measure for an *i*th procedural step and three sub-measures included in it. It is noted that detailed example demonstrating how to quantify the SC scores for procedural steps is given in Ref. (Park, 2001A). In addition, detailed process to determine weighting factors (i.e., α, β and γ) is presented in Ref. (Park, 2002A; Park, 2002B).

< Table 1. Meaning of the SC measure including three sub-measures>

Notation	Meaning
SC_i	Quantifying step complexity for an *i*th procedural step. $SC_i = \sqrt{(a \cdot SIC_i)^2 + (b \cdot SLC_i)^2 + (g \cdot SSC_i)^2}$
SIC_i	SIC (step information complexity) quantifies the amount of information to be monitored/supervised by the operators, included in an *i*th procedural step.
SLC_i	SLC (step logic complexity) quantifies the logical complexity due to the logical sequence to conduct actions included in an *i*th procedural step.
SSC_i	SSC (step size complexity) quantifies the amount of actions to be conducted by the operators, included in an *i*th procedural step.
α	Relative weighting to represent the contribution (i.e., the importance) of SIC to SC. α = 0.326.
β	Relative weighting to represent the contribution of SLC to SC. β = 0.296.
γ	Relative weighting to represent the contribution of SSC to SC. γ = 0.378.

3. Activities to verify the appropriateness of the SC measure

Activities to verify the appropriateness of the SC measure can be classified in the following two ways: the subjective and the objective evaluation.

3.1 The subjective evaluation

The subjective evaluation means the comparison between SC scores and results estimated from a subjective workload evaluation technique. The purpose of the subjective evaluation is the testimony of the expectation such that “the complexity of procedures, which is felt by the operators due to the task representation, can be explained through evaluating three complexity factors, such as amount of information, logic structure and the amount of actions.”

In Section 2, it was pointed out that the complexity felt by the operators would depend on demands implied by task representation. In addition, it was also pointed out that the operators feel complexity, during the performance of procedures, because of three complexity factors included in the SC measure. Thus, if results from subjective workload evaluation techniques and SC scores show a meaningful correlation, then it is expected that the SC measure can be regarded as an appropriate indicator for evaluating the complexity of procedures originated from the task representation, since the subjective workload is one of the reliable measures to assess the complexity felt by the operators (Wickens, 1992; Liu, 1994; Weinger, 2000; Jacko, 1996).

Based on these considerations, averaged subjective workload scores quantified by the NASA-TLX (task load index) technique were compared to SC scores (Park, 2001A) for 25 procedural steps included in EOPs. It is noted that the total number of subjects who participated in the subjective workload evaluations was 26, and all subjects have SRO (senior reactor operator) license and have experienced MCR (main control room) operations for more than 10 years.

As the result, there is a statistically meaningful correlation between SC scores and averaged NASA-TLX scores. Thus, it is quite positive to say that the SC measure can be regarded as an indicator that can be used to quantify the complexity of procedures. In addition, it is also positive to expect that the variation of the operators’ performance can be explained by the change of SC scores because the complexity of procedures would also affect the operators’ performance. To ensure this expectation, the objective evaluation was additionally conducted.

3.2 The Objective evaluation

The purpose of the objective evaluation is to ensure the expectation such that “if the task representation of a procedural step is so complicated that the operators feel difficulty in understanding the context of it then the elapsed time to perform a procedural step will increase.”

It is noted that elapsed time data were adopted to verify the relationship between the operators’ performance and the complexity of procedures, since time measure seems to be sensitive to perceptual/cognitive demands (Liu, 1994). In other words, as stated in Section 2, since the SC measure was developed based on three complexity factors that are related to demands on the operators (i.e., demands implied by task representation), time measure that is sensitive to cognitive demands could be regarded as appropriate one.

To obtain elapsed time data of procedural steps (i.e., step performance time data), a full scope simulator installed in the training center of the reference NPP was used. This full scope simulator is designed based on a 1000MWe PWR (pressurized water reactor) type NPP with conventional control panels and alarm tiles. In addition, this simulator has been used for both the training of operating crews and the qualifying for SRO license since sufficient V&V (validation and verification) activities has been performed to secure its functional appropriateness.

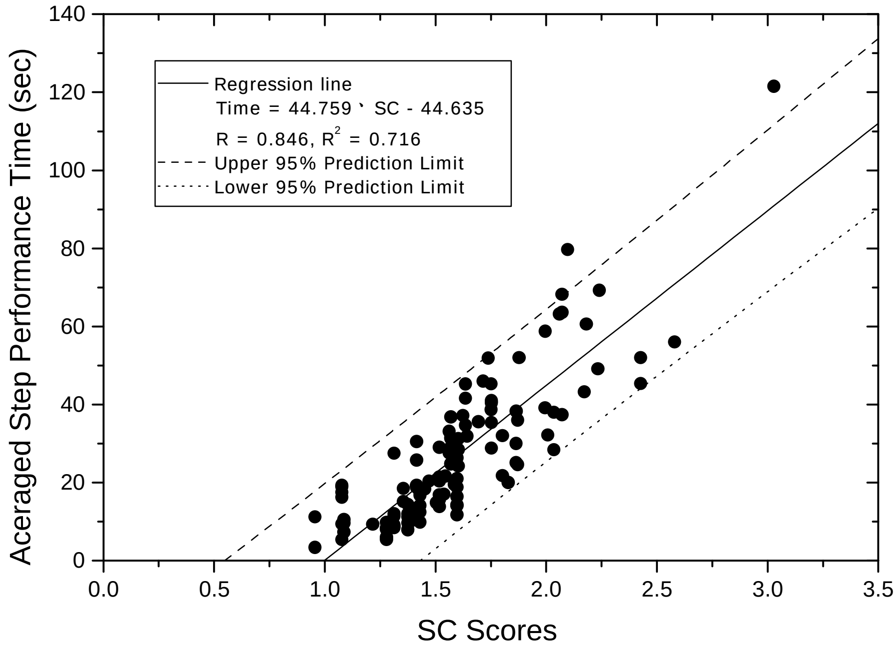
Table 2 shows summarized information for the collection of the emergency training records.

< Table 2. Summaries for the collection of emergency training records >

Record collection period	Emergency training scenario	The number of collected records
September 1999 ~ December 1999	SGTR (steam generator tube rupture)	5
	LOAF (loss of all feedwater)	5
January 2000 ~ July 2000	LOCA (loss of coolant accident)	18
	ESDE (excess steam dump event)	18
August 2000 ~ December 2000	SGTR	18
	LOAF	18
January 2001 ~ April 2001	LOOP (loss of offsite power)	10
	SBO (station black out)	10
	LOCA	10

Total: 112

From these records, step performance time data were retrieved through the timeline analysis. In total, step performance time data for 1340 procedural steps were retrieved, and averaged step performance time data for 120 procedural steps were obtained (Park, 2002B). Using these data, averaged step performance time data for procedural steps are compared with their SC scores, and results are shown in Fig. 1.



< Figure 1. Comparing averaged step performance time data and SC scores >

From Fig. 1, it seems that the operators' performance would be mainly affected by the complexity of procedures, since averaged step performance time data positively rise in proportion to a rise in SC scores. From this result, it can be said that the operators' performance would be degraded, if the task representation of a procedural step is so complicated that the operators feel difficulty in understanding the context of it. Thus, the SC measure can be regarded as an indicator that can be used to quantify the complexity of procedures.

4. Discussions and conclusion

Up to now, the necessity, theoretical basis and verification activities for the SC measure were briefly explained. Based on these explanations, the conclusion of this study is drawn with further works, after discussions about the meaning and the applicability of the SC measure are presented.

4.1 Meaning of the SC measure

As explained in Section 3, to verify the appropriateness of the SC measure, the subjective and the objective evaluation have been considered, respectively. From the subjective evaluation, it was shown that the complexity of procedures felt by the operators seems to be reasonably quantified by the SC score, since the averaged subjective workload scores have clear relationship to SC scores.

In addition, in the objective evaluation, SC scores were compared with averaged step performance time data in order to clarify the expectation such that “the complexity of procedures will affect the operators’ performance.” And the result shows that the complexity of procedures seems to be quite dominant for the operators’ performance because averaged step performance time data positively rise in proportion to a rise in SC scores. However, to clarify the meaning of the SC measure, detailed review for the relationship between the operators’ performance and the complexity may be requisite.

In general, the complexity that affects the performance of human could be classified into four types, such as system complexity, task (operational) complexity, interface complexity and subjective complexity. Table 3 shows brief summary of each complexity type, and detailed descriptions including factors related to each type of complexity are well summarized in Ref. (Collier, 1998; Jacko, 1996; Wood, 1986).

< Table 3. Complexity types that affect the operators’ performance >

Complexity type	Description	Example of related factors
System complexity	Including structural and functional complexity that is inherent in the system architecture	● Number of control loops ● Number of parameters ● Size of system, etc.
Task (operational) complexity	Complexity due to demands of required tasks on the operators.	● Volume of information to be processed ● Number of required actions ● Number of decisions, etc.
Interface complexity	Complexity concerning both the adequacy of the user-interface and interactions among crew or team members	● Number of VDU (visual display unit) pages ● Navigability ● Level of interactions, etc.
Subjective complexity	Complexity depending on the task environment or the individual differences among the operators	● Stress ● Fatigue ● Experience ● Capability ● Knowledge, etc.

From Table 3, two findings that are important for explaining the meaning of the SC measure have to be emphasized.

Firstly, it is clear that the SC measure can quantify task complexity, among four types of the complexity, since three complexity factors included in the SC measure are a subset of complexity factors that can cause task complexity. This means that the result obtained from the comparison between SC scores and averaged step performance time data seems to be insufficient to clarify the expectation (i.e., “the complexity of procedures will affect the operators’ performance”), since the other types of complexity can also degrade the operators’ performance. In other words, although SC scores and averaged step performance time data show statistically meaningful correlation, it is still doubtful whether the degradation of the operators’ performance is mainly affected by the complexity of procedures (i.e., task complexity) or not.

Nevertheless, as the second finding, the operators’ performance seems to be mainly governed by task complexity, at least if the operators have been trained so that they have to be performed their tasks on the basis of procedures, because of the following reasons.

- It can be assumed that factors creating system complexity are already implied in procedures, since task descriptions to specify the operators’ activities become complicated as systems become complicated..
- All emergency training were performed in the training center of the reference NPP. This means that step performance time data used in the objective evaluation represent the operators’ performance collected under the identical interface. Thus, it can be assumed that the effects on the operators’ performance variations due to interface complexity (i.e., the adequacy of the user-interface) is negligible.
- The operators who participated in the emergency training would have different experience, knowledge, stress level or job attitude that can result in subjective complexity. Thus, it is quite positive to assume that step performance time data extracted from emergency training records already reflect the variation of the operators’ performance due to subjective complexity.

Although uncertainties (such as the effect of interface complexity originated from crew communication patterns) still remained, result obtained from the comparison between SC scores and averaged step performance time data is quite encouraging because the change of the operators’ performance is significantly correlated with the change of SC scores. In other words, it is safe to say that "among many types of the complexity that can affect the operators' performance, a large portion of the operators' performance variations can be explained by task complexity, when the procedures are given."

From the above findings and explanations, thus, the meaning of the SC measure may be clearly stated as below.

"*Under the situation in which the operators have to perform their tasks using procedures, the operators' performance would be mainly governed by the task complexity that is originated from demands implied by the task representation of procedures. And the SC measure seems to be an appropriate measure that can quantify the task complexity due to complicated procedures.*"

4.2 Applicability of the SC measure

If the SC measure can properly quantify task complexity then many kinds of applications would be possible. Among them, three applications seem to be more feasible than others. They are: 1) the provision of requisite information for HRA (human reliability analysis) and 2) the provision of useful insights to identify the relationship between the task complexity and procedural error.

Firstly, one of the direct applicable domains of the SC measure is the provision of useful information for HRA. Generally, since HRA has been recognized as one of the major activities to enhance safety of many industries, many types of HRA methods have been suggested so as to not only quantify the possibility of human error but also identify the critical points that can cause human error.

In addition, it is well known that various kinds of information, such as "the time data needed to perform required tasks" and "demands of perception, cognition and actions to accomplish required tasks," should be provided in order to conduct HRA more properly and efficiently (IAEA, 1990). Under these needs, the SC measure can provide useful information because not only the task complexity due to demands implied by procedures (i.e., demands of perception, cognition and actions to accomplish required tasks) can be quantified by it but also the SC measure can be used as a 'predictor' for estimating appropriate range of the task performance time, as shown in Fig. 1.

Secondly, the SC measure could be used as a 'probe' to scrutinize the relationship between the task complexity and procedural error, since the task complexity plays an important role to explain procedural error. For example, as presented in Section 2, if the operators cannot understand the context of procedures then the possibility of skipping or following steps out of sequence will increase. In contrast, if the operators understand the context of procedures then the possibility of shortcutting have to be considered.

Shortcutting means the operators' behavior such that several actions/items were categorized in one group and then checking them at once (i.e. the combination of both skipping and following out of sequence of steps). In addition, there is a tendency to perform shortcutting when checklists are somewhat lengthy (Degani, 1993). In other words, the operators try to shorten a time-consuming procedure through finding another path to accomplish required tasks. Obviously, to clarify the tendency of shortcutting, the change of understandability affected by the task complexity should be examined because shortcutting cannot be done without understanding. Thus, to proceed further researches for procedural error, an appropriate framework that can evaluate the understandability of procedures is indispensable. This means that the SC measure may be useful to proceed further researches related to procedural error because the task complexity that interferes with the understandability can be properly quantified by it.

4.3 Conclusion and further works

In this study, the meaning and the applicability of the SC measure are presented with brief explanations including the necessity, theoretical basis and verification activities. As the results, it is quite positive that the SC measure can be used to explain the change of the operators' performance due to the task complexity implied by procedures.

However, to enhance the applicability of the SC measure, several problems that have to be resolved still remained. For example, it is well known that the stress level and the operators' experience (or knowledge) causing in subjective complexity can affect the operators' performance (Wickens, 1992; Brito, 2002; Kieras, 1985). This means that, even if the task complexity implied by procedures is low, the operators' performance can be changed due to subjective complexity. In addition, several factors such as crew coordination and adequacy of user-interface that can cause interface complexity have to be scrutinized because it is pointed out that interface complexity can also degrade the operators' performance (Jacko, 1996; Degani, 1997; Kieras, 1985). For example, the operators' performance may become different, if advanced (or computerized) interfaces in which the operators have to navigate many VDU pages so as to find information what they need are used, instead of conventional interfaces that consist of indicators, switches and alarm tiles.

Nevertheless, if we can remind the fact that many accidents or incidents are caused by procedural error, and if we consider the situation such that an appropriate evaluation framework for the task complexity due to complicated procedures is very scant (Degani, 1993; Nagel, 1988; Wood, 1986), it is no doubtful to conclude that “the SC measure may be useful for various purposes, particularly for scrutinizing the relationship between procedural error and complicated procedures.”

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