Nuclear Engineering and Technology xxx (xxxx) xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Analysis of interface management tasks in a digital main control room

Jeonghun Choi [a], Hyoungju Kim [b], Wondea Jung [c], Seung Jun Lee [a, *]

[a] Ulsan National Institue of Science and Technology, 50, UNIST-gil, Ulsan, 44919, South Korea
[b] KEPCO Nuclear Fuel Co., Ltd., 242 989 Road Daedeok Blvd, Youseong-gu, Daejeon, South Korea
[c] Integrated Safety Assessment Division, Korea Atomic Energy Research Institute, P.O. Box 105, Yuseong, Daejeon, 305-600, South Korea

ARTICLE INFO

Article history:
Received 12 December 2018
Received in revised form
9 April 2019
Accepted 9 April 2019
Available online xxx

Keywords:
Digitalized main control room
Soft controls
Secondary tasks
Operator support system

ABSTRACT

Development of digital main control rooms (MCRs) has greatly changed operating environments by altering operator tasks, and thus the unique characteristics of digital MCRs should be considered in terms of human reliability analysis. Digital MCR tasks can be divided into primary tasks that directly supply control input to the plant equipment, and secondary tasks that include interface management conducted via soft controls (SCs). Operator performance regarding these secondary tasks must be evaluated since such tasks did not exist in previous analog systems. In this paper, we analyzed SC-related tasks based on simulation data, and classified the error modes of the SCs following analysis of all operational tasks. Then, we defined the factors to be considered in human reliability analysis methods regarding the SCs; such factors are mainly related to interface management and computerized operator support systems. As these support systems function to reduce the number of secondary tasks required for SC, we conducted an assessment to evaluate the efficiency of one such support system. The results of this study may facilitate the development of training programs as well as help to optimize interface design to better reflect the interface management task characteristics of digitalized MCRs.

1. Introduction

With the technical development of the nuclear industry, nuclear power plants (NPPs) have significantly changed, and especially the instrumentation and control systems. Some recently constructed NPPs are equipped with completely digitalized instrumentation and control systems and digital main control rooms (MCRs). Fundamental variables of plant status are shown on the large display panel (LDP), as well as the information flat panel display (IFPD) that each operator in the MCR has. Operators can manipulate the components using either a mouse or a touch panel called the engineered safety features—component control system soft control module (ESCM). These soft controls (SCs) are one of the biggest changes affecting operation. Operators manipulate SCs in the sitting position instead of going to an analog control board and pressing buttons or confirming alarms. Further, operational and accident procedures have been computerized, so that operators check their screens to confirm the manuals and proper procedure steps [1–3].

While these newly adopted designs are intended to reduce performance time and improve human performance, evidence to support such goals is insufficient. Moreover, some negative effects have recently been pointed out such as secondary tasks, which refer to additional tasks required to perform the primary tasks that include supervisory cognitions or controls of the plant [10]. Examples of secondary tasks include screen navigations to the target screen or clicking the mouse for system alarm confirmation. Such tasks need to be analyzed, because they may increase the workload of operators or potentially negatively affect the primary task.

In this paper, we focus on interface management tasks as one aspect of SC secondary tasks. Analysis is based on data obtained from an Advanced Power Reactor 1400 (APR-1400) simulator. The data include operator control logs from a computerized procedure system (CPS) and a man—machine interface (MMI) system and are classified into primary and secondary tasks. Following a statistical analysis of the data, results are used to discuss the effects of applied interface management design.

The rest of the paper is organized as follows. Section 2 characterizes SCs and interface management tasks, as well as the new human error modes involved in digital MCRs. Section 3 defines the specific issues related to the effects and drawbacks of interface management. These issues are compared to the results of a

* Corresponding author.
E-mail address: sjlee420@unist.ac.kr (S.J. Lee).

https://doi.org/10.1016/j.net.2019.04.010

Please cite this article as: J. Choi et al., Analysis of interface management tasks in a digital main control room, Nuclear Engineering and Technology, https://doi.org/10.1016/j.net.2019.04.010

statistical analysis based on simulation data in Section 4, and Section 5 provides discussion and conclusions.

2. Soft controls

2.1. New tasks in the digital MCR

Conventional MCR operator tasks are quite different from those in digital MCRs. For example, in an emergency situation, the shift supervisor (SS) in a conventional MCR instructs the board operators to perform particular tasks to confirm and control specific plant variables according to paper-based procedures. The board operators, including the reactor operator (RO), turbine operator (TO), and electric operator (EO), stand near the board. Following instruction from the SS, they acquire information or control the NPP components using analog devices. Operators in conventional MCRs must determine the appropriate board for executing a task and move to that board.

In a digital MCR on the other hand, there are seats for each operator with individual IFPDs, ESCMs, and mouses available (Fig. 1). The IFPDs consist of four separate screens that display the shared CPS, MMI, and alarms, and operators can freely change the contents of the screens. The SS instructs the operators to perform tasks following a given procedure, which operators follow using the shared procedure that can be individually confirmed. Considering such examples, the transition from conventional to digital MCRs can be most clearly expressed as the updates in the *man—machine interfaces*—with the introduction of MCR digitalization, operator tasks involving MMIs have totally changed.

Here, digital MCR tasks refer to the related cognitive, communicative, and operational activities, which can all be divided into primary tasks that directly control plant equipment and additional secondary tasks (Fig. 2). All tasks have changed significantly from conventional MCR tasks, and may vary due to the influence of environmental factors. For example, considering cognitive tasks, the various devices that indicate the state of the plant should be considered. As the conventional analog indicators and alarms are displayed as computer-based systems in digital MCRs, information is communicated to operators in different ways. Communicative tasks also differ in terms of the communication method and content in different operating environments, and these differences should be considered when analyzing each task. Among these tasks, the most significant change is to the operational activities, where generic primary tasks are conducted by mouse clicks or observing the display, and a wholly new set of secondary tasks have emerged [5].

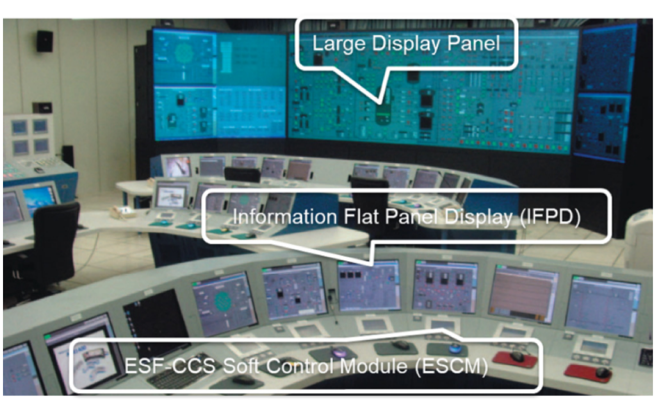


Fig. 1. Digital MCR [4].

2.2. Interface management tasks

The MMI, also called the human—system interface, is the main field where the interactions between humans and plant systems occur. Operators should handle digitalized devices to monitor or get information, and detect the process parameters from the systems in digitalized MCRs. Plant systems provide information to operators through video display units, which are implemented in NPPs in the form of IFPDs. These displays are the size of universal monitors, as seen in Fig. 1, with the mouse and ESCMs used as input devices. As the display is not large enough to show all the process parameters of the plant simultaneously, considerations were undertaken about how to properly display the parameters in the limited space. The operator actions dealing with such MMIs are called interface management tasks [9]. Interface management is part of operators' generic secondary tasks, as shown in Fig. 3.

Absent in conventional facilities, interface management presents some issues for the digital environment. In NUREG-6690, examples of interface management tasks such as configuring, navigating, arranging, interrogating, and automating were presented [11]. Here, configuring refers to the activities required to set up the MMIs of a computer workstation in a desired arrangement. Navigating refers to the searching and accessing of specific aspects of the MMIs. Arranging tasks adjust the information in the operator's view, and interrogating tasks involve questioning the MMI to determine plant status. Automating refers to setting up shortcuts to make interface management easier. Among them, the configuring, arranging, and automating tasks are classified as pre-performed tasks that the interface designers set up during the design process of the system. This paper considers one example of an automating task, meant to reduce the secondary tasks load, called the direct link button. This connects the CPS screen to the required MMI screens, so that operators can change the screen with minimal effort. Fig. 4 shows an example display image of the CPS in a digital MCR containing a direct link button. In this figure, the operator can access the containment spray (CS) screen on one display with one click of the button; this operation has the effect of displaying the system screen next to the CPS screen immediately. In typical operations without a screen link button, the operator changes the screen via the hierarchy system as in Figs. 5 and 6, where the operator must determine the correct path to the target component and execute the screen changes by clicking the system buttons [3]. Including the given example, various other kinds of operator support systems have been proposed and developed to reduce the possibility of human error and increase the probability of recovery from errors [7,16]. Otherwise, operators should perform navigating tasks to reach the desired screen. Demonstrating their importance, interface management tasks have been raised as a new human factor issue in digital MCRs, as shown in Table 1 [8].

2.3. Human error modes at soft control

In Fig. 7, the possible error modes in SC operation are depicted. The first error is called *Operation omission*, where the operator selects the proper operation according to the procedure but fails to implement it. Alternatively, the operator may select the correct screen and controller, but mistakenly perform a different operation while omitting the correct one. The second error, *Wrong object*, occurs when the operator selects and operates the wrong controller, for example, by selecting a different screen or a similar controller located near the intended controller on the correct screen. The third error is *Wrong operation* and refers to when the operator selects the correct screen and target controller but executes it incorrectly. For example, the aim may be to close a valve, but the "OPEN" button is pressed instead of the "CLOSE" button. The

Please cite this article as: J. Choi et al., Analysis of interface management tasks in a digital main control room, Nuclear Engineering and Technology, https://doi.org/10.1016/j.net.2019.04.010

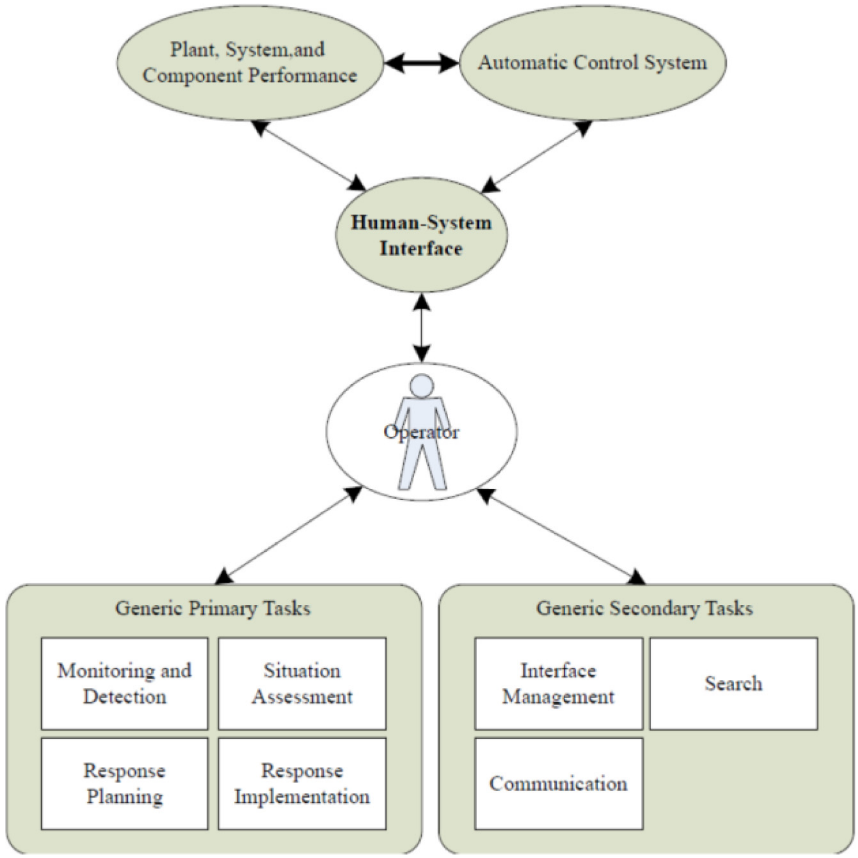


Fig. 2. Generic tasks in digital MCRs [5].

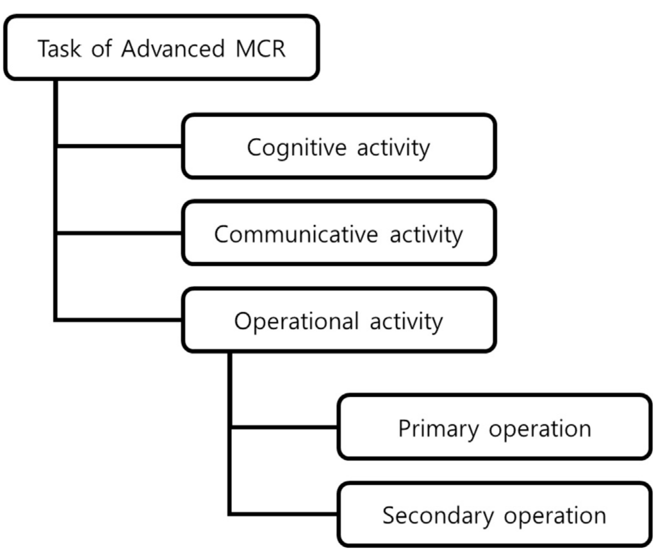


Fig. 3. Task of digital MCRs [9].

fourth error is called *Mode confusion*, which refers to the case when an incorrect operation may be performed in a control window having several control modes, by implementing operations without modifying the operation mode appropriately. For example, pressure may not be changed by manual operation if the control mode remains in "AUTO", which is operated automatically by the system, and the operator does not click "MAN" to enable manual operation.

The fifth error, *Inadequate operation*, refers to the case when an operation is not performed sufficiently. Such errors can occur when completion of the operation (with the correct controller) is not confirmed. The last error is *Delayed operation*, where delays accumulate caused by incorrect selection of the screen or controller, its restoration process, or interface operation, resulting in a delay in the overall operation [4].

3. Issues concerning interface management tasks

As described in the previous section, new types of human error modes or negative effects have emerged along with the adoption of digital MCRs and their related interface management tasks. In the assessment of human error, the operator support systems in these digital MCRs should be considered. To identify the characteristics of interface management tasks and demonstrate the practicality of applied operator support systems, specifically the direct link button in this paper, we present the following issues. These can be verified based on simulation training data subject to current operators.

The questions to be addressed are listed below.

(1) How many total secondary tasks are performed in the SCs for operational activity? How frequently are secondary tasks performed compared with primary tasks? These questions can clarify how many additional tasks are loaded to operators following the change of environment.
(2) Which secondary tasks are performed most often in simulations? This question can derive what kinds of secondary tasks give higher numbers of tasks to operators.

Please cite this article as: J. Choi et al., Analysis of interface management tasks in a digital main control room, Nuclear Engineering and Technology, https://doi.org/10.1016/j.net.2019.04.010

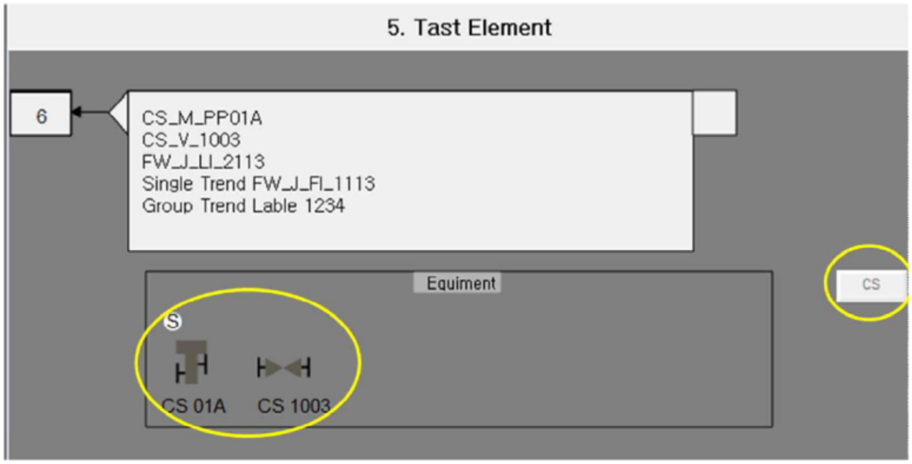


Fig. 4. CPS display [6]. Yellow circles show the containment spray components and direct link button.

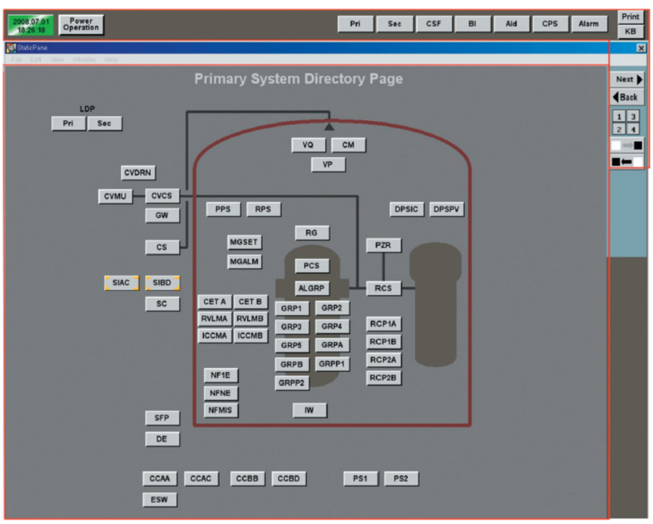


Fig. 5. Initial display frame of the operator workstation [3].

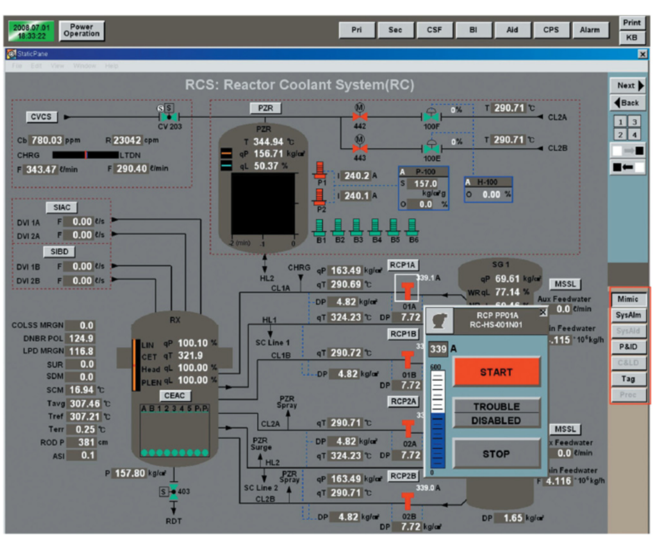


Fig. 6. First level of the IPS (reactor coolant system display page) [3].

(3) Does a failure of any secondary task cause a failure of any primary task? This question can evaluate the criticality of the secondary tasks.
(4) How many screen changes are executed compared with the minimum number of changes required? This question can show operator efficiency in terms of screen changes.
(5) How often are screen link buttons used during an operation? Do screen link buttons reduce the number of screen changes? These questions can be a factor in determining the eligibility of designs.

To examine the above issues, the number of tasks and screen link button executions were counted from simulation data. These were analyzed quantitatively and statistically, with results compared to the above issues in the Discussion section.

4. Simulation analysis

Simulations were executed in a simulation room mirroring the digital MCR of the APR-1400. To extract secondary task data from the SC-based operations, four camcorders recorded the displays as well as the actions of the SS and the three operators (RO, TO, and EO). All of their actions, including what they see through the displays and what they click using the mouse, are contained in the data files. In this analysis, data from the RO and TO are used because they have numerous operational activities in the performance of the procedure. Two emergency scenario simulations— steam generator tube rupture (SGTR) and station black out (SBO)—were conducted. The number of accident simulations for SGTR and SBO are 14 and 6, respectively, each conducted by separate operation teams, for which data is contained in a video file of each complete simulation from initiation to completion.

For quantitative analysis of the data, tasks were first classified into individual activities, as listed in Table 2. All activities during operation were then grouped into three different categories: navigation, manipulation, or acknowledgement. Here, navigation and acknowledgement tasks are secondary tasks, which are performed in order to support the primary tasks (manipulation). Based on the classification in Table 2, the number of total activities conducted was counted.

To evaluate operator proficiency and the usability of the screen link button, we propose two new ratios: screen navigation and screen link button usage. These two factors are calculated as follows. The 'smallest number of screen navigations by design' means

Please cite this article as: J. Choi et al., Analysis of interface management tasks in a digital main control room, Nuclear Engineering and Technology, https://doi.org/10.1016/j.net.2019.04.010

Table 1
Human factor issues in digital MCRs [8].

Design element	Human factor issue	Description
Information display based on computer	Information overload	• Overlapping windows • Too much information • Faster information than visual process of human
	Interface management tasks	• Navigation task before the primary task • Losing the information because of secondary task
Computerized procedure	Team performance	• Communication dis-connection between operators
	Situation awareness	• The depending on the computerized procedure
	Level of automation	• Automation level
	Keyhole effect	• The limitation of parallel process
	CPS failure in complex situation	• The conversion problem of the paper procedures
Soft controller	Unintentional activation	•Unintended activity
	Description errors	•Slip by ambiguous information
	Mode errors	•Mode error
	Disordering the components of an action sequence	•Skip by the continuous task, repetition, reverse procedure
	Capture error	•Confusion with the task frequency
	Loss of activation errors	•Task Fail because of the limited memory of operator

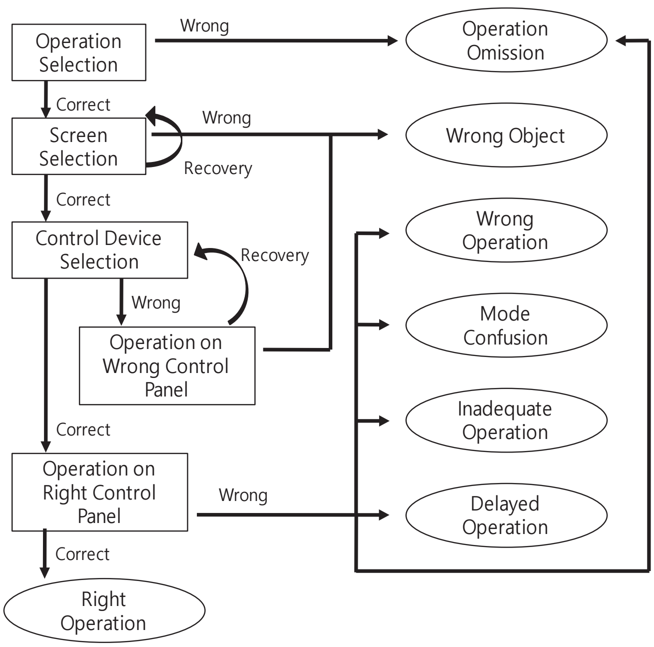


Fig. 7. Error modes of SC operation [4].

the shortest path to reach the desired system screen through using maximum screen link buttons available. The minimum number of screen navigations for a given situation was derived by demonstrating the scenarios.

$$\text{Screen navigation ratio} = \frac{\text{Number of screen navigations used by the operator}}{\text{Smallest number of screen navigations by design}} \tag{1}$$

$$\text{Screen link button usage ratio} = \frac{\text{Number of screen link button usages by the operator}}{\text{Maximum number of screen link button usages available}} \tag{2}$$

4.1. Secondary tasks analysis results

The numbers of primary and secondary tasks for the two accident simulations were counted as shown Fig. 8. It can be seen that the number of secondary tasks exceeds that of primary tasks; particularly, in the case of "SGTR_RO" and "SBO_RO", four times more secondary tasks were performed than primary tasks. We also confirmed here that no primary task failure was caused by secondary task failure. Information acquisition tasks were excluded from this analysis because they cannot be directly observed in the video data. Additionally, the "ACK_ALRM" activity to clear the alarm was also excluded as it does not affect actual operation.

The total numbers of secondary tasks are listed in Fig. 9 by type. They differ depending on the particular operator and the scenario.

Table 2
Detailed classification of operational tasks [15].

Classification	Activity Name	Contents
Navigation (Secondary Tasks)	SWITCH_SCR	Activity that change the screen to identify or manipulate the system state
	OPEN_CTRPNL	Activity that open pop-up operation windows on the IFPD or ESCM for operation of a particular system
	CLOSE_CTRLPNL	Activity to close the operation window on the IFPD or ESCM for the operation of a particular system
Manipulation (Primary Tasks)	CLICK_EXECUTE	Activity to manipulate a particular system
	CLICK_REGU_UPDN	Activity to press up and down arrow buttons during operation to adjust a particular system
	CLICK_ENABLED	Activity to press the "enable" button on an interface for operation of a particular system
	CLICK_MANUAL	Activity to press the "manual" button on an interface for operation of a particular system
Acknowledgement (Secondary Tasks)	CONF_STEP	Activity confirming the completion of a step in the procedure
	CONF_SUBSTEP	Activity confirming the completion of each instruction in the step of a procedure
	ACK_ALARM	Activity to check and clear alarms
	CONF_CHANN	Activity to press the "channel check" button on an interface for channel identification before operation of a particular system

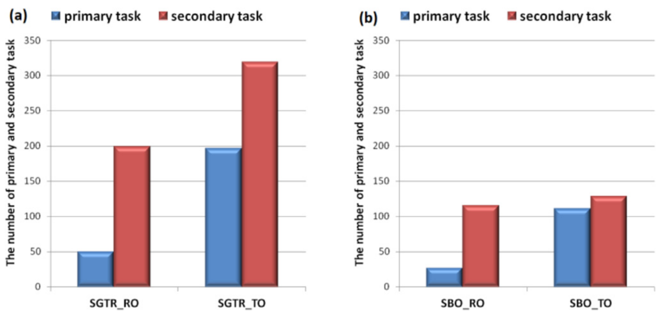
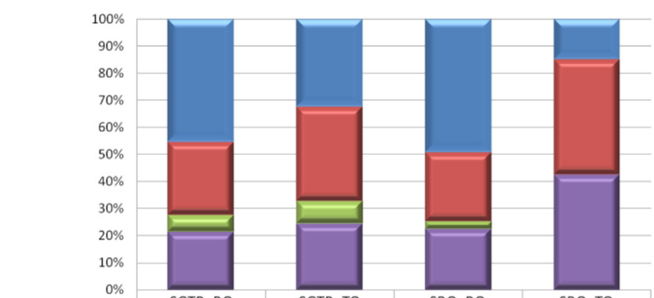


Fig. 8. Total numbers of primary and secondary tasks performed by the RO and TO for (a) SGTR and (b) SBO events.



	SGTR_RO	SGTR_TO	SBO_RO	SBO_TO
SWITCH_SCR	90	103	52	22
OPEN_CTRLPNL	54	111	27	63
CLOSE_CTRLPNL	12	27	3	0
CONF_CHANN	43	78	24	63

Fig. 9. Total number of activities corresponding to each secondary task for SGTR and SBO events.

The “SWTICH_SCR” activity had the highest total number among the activities, and “CLOSE_CTRLPNL” had the lowest. Notably, “CLOSE_CTRLPNL” had quite a lower number in comparison with “OPEN_CTRLPNL”.

4.2. Screen navigation analysis results

We analyzed the number of operator screen changes and the usability of the screen link button. The two proposed factors, screen navigation ratio and screen link button usage ratio, were calculated using Eqs. (1) and (2) with collected data. The screen navigation ratio is the percentage of screen navigations used by operators from the minimum number of screen navigations as designed. It indicates how well the operator finds the correct path in the MMI system. The mean value of this ratio was 2.115 (median = 2.000, SD = 1.282), indicating that the operators made almost twice as many screen changes as necessary to reach the desired screen for the primary task. In the case of the screen link button usage ratio, 27 cases of screen link button usages were observed out of 108 possible opportunities, giving a derived ratio of 0.250 (25%).

To determine whether using the screen link button decreases the total number of screen changes, we specified two groups: one using the screen link button and one without it. We performed a *t*-test to verify the statistical difference of the screen navigation ratios between the two groups. The group that used the screen link button had a mean value of 1.000, while the other group (without the screen link button) had a value of 2.411. Such a difference between the two groups is significant ($t = 12.35$, $df = 80$, p-value $< 2.2e-16$).

To visualize the effect of screen link button usage, graphs comparing the two ratios are plotted in Fig. 10. Normalized lines show the trends among the simulation data points. Overall, it can be said that the screen navigation ratio decreases as the screen link button usage ratio increases, as the total number of secondary task screen changes implemented by the operator during screen navigation (i.e. “SWITCH_SCR”) is reduced by the proper use of the screen link button in the CPS. As indicated by all coefficients of determination being over 0.65, the total number of screen navigations performed by operators who used the screen link button tend to be fewer than those by other operators.

5. Discussion

With the analyzed simulation data, all raised issues in Section 3 can be checked. The number of counted secondary tasks greatly exceeds that of the primary tasks in every case, with over four times more in the maximum case “SBO_RO” (issue 1). This shows that these additional tasks are a matter to be recognized in order to evaluate human reliability in digitalized MCRs. Among the secondary tasks, “SWTICH_SCR” had the highest frequency of execution (issue 2); therefore, it can be assumed that this task takes the largest portion of secondary task operation. Despite the high frequency of secondary tasks though, there was no failure of primary

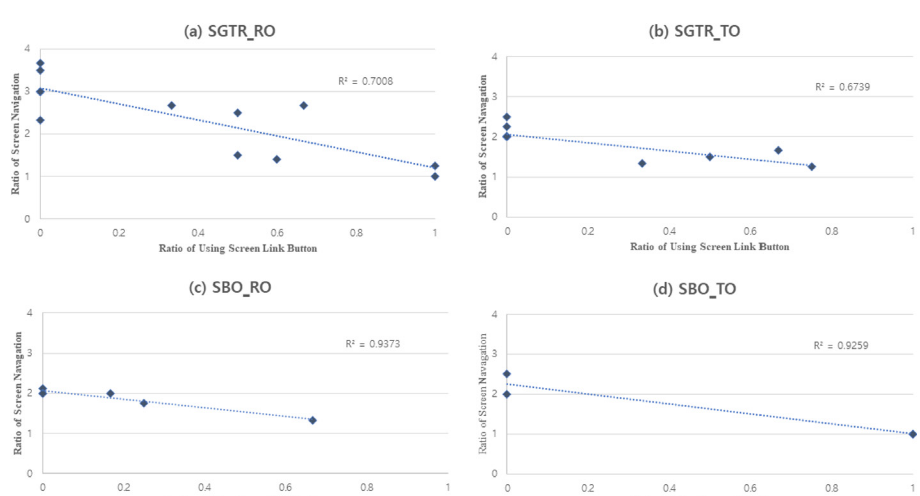


Fig. 10. Screen navigation ratios and screen link button usage ratios for the RO and TO in (a–b) SGTR and (c–d) SBO, respectively.

Please cite this article as: J. Choi et al., Analysis of interface management tasks in a digital main control room, Nuclear Engineering and Technology, https://doi.org/10.1016/j.net.2019.04.010

tasks caused by secondary tasks (issue 3). This is because failure of secondary tasks does not directly affect primary operation activities, and further, it is hard to observe secondary task failures since they can be easily recovered by information from the MMIs. From another point of view, such primary failure may not have been observed here due to the small number of simulations.

In the results of the screen link button analysis, the derived ratio indicated that operators perform two times more secondary tasks than the designed number (issue 4). This means that there is room to improve the working environment of operators to reduce this number of performed secondary tasks. Finally, we found that usage of screen link buttons reduced the number of screen changes compared to the two proposed ratios (issue 5). However, this designed support function had a low frequency of use at only 22.1% in the simulation; this can be interpreted to mean that improvements in the usability of the support system will decrease the number of performed secondary tasks.

6. Conclusion

Operation environments of digitalized MCRs differ from those of conventional MCRs. As such, the human reliability factors associated with operators are significantly affected by these different operating environments, and it is necessary to carefully evaluate this influence [14]. Digitalized MCRs, with a variety of designs, possess new features such as computerized procedures and operator support systems, and digitalized alarm systems. Among them, the use of soft controls has the biggest influence on operator error.

In this paper, the issues to be considered in human reliability analyses of SC operation have been defined. For this purpose, the characteristics of interface management tasks were described, followed by SC task and accident simulation data analyses.

First, the results of this study show how properly the interface management tasks are performed in digital MCRs by counting number of interface management tasks performed during plant operation and comparing to the number of primary tasks. Failure of primary tasks caused by failure of secondary tasks was not observed, even though the number of secondary tasks is larger. The high frequency of secondary tasks can increase the complexity of tasks for operators; therefore, countermeasures should be prepared to reduce task loads from the secondary tasks. Possibilities for such measures may include education for operators or improvements to MMI setups. As a result of data analysis, the “OPEN_CTRPL” and “SWITCH_SCR” activities were found to be performed at the highest frequencies; such quantitative results may be combined with previous qualitative results, such as Kim et al. (2014) where operator task loads according to the activities were derived [12]. Second, through analyzing the two proposed ratios, we confirmed that operators tended to make more screen changes than the designed number, with the support system (screen link button) not properly utilized. Thus, education on proper navigation techniques is needed, along with further analysis on screen navigation characteristics. For human reliability analyses of operators in digital MCRs, future studies should reflect the present findings along with related studies such as Park et al. (2016) that showed that screen change patterns are related to operators’ careers through process mining [13].

The limitations of this study are as follows. First, only two accident scenarios were considered for the analysis; more scenarios should be considered to observe more diverse patterns of interface management tasks. Second, the operational environment of the simulations differed from a real accident situation regarding operator workload, stress, and decision burden. Third, although the scenarios provided to all operating teams were the same across each accident simulation, the procedure steps and operations performed differed, depending on the knowledge of each team and their selected strategy. Fourth, the effectiveness of the secondary tasks was not considered in this study, despite urgent or otherwise high-pressure conditions greatly influencing task performance. In future work, we will conduct a timeline study for analyzing performance times and frequencies to show the criticality of secondary tasks in an accident situation.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP: Ministry of Science, ICT and Future Planning) (No. 2018M2B2B1065653).

References

[1] Emilie M. Roth, Randall J. Mumaw, William F. Stubler, Human factors evaluation issues for advanced control rooms: a research agenda, in: Human Factors and Power Plants, 1992., Conference Record for 1992 IEEE Fifth Conference on, IEEE, 1992.
[2] D.Y. Kim, J. Kim, How does a change in the control room design affect diagnostic strategies in nuclear power plants? J. Nucl. Sci. Technol. 51 (10) (2014) 1288–1310.
[3] M.S. Lee, et al., Development of human factors validation system for the advanced control room of APR1400, J. Nucl. Sci. Technol. 46 (1) (2009) 90–101.
[4] S.J. Lee, J. Kim, S.C. Jang, Human error mode identification for NPP main control room operations using soft controls, J. Nucl. Sci. Technol. 48 (6) (2011) 902–910.
[5] Ying-Lien Lee, Sheue-Ling Hwang, Eric Min-Yang Wang, Reducing cognitive workload of a computer-based procedure system, Int. J. Hum. Comput. Stud. 63 (6) (2005) 587–606.
[6] N. Seong, S. Lee, A Study on Requirements of Data Base Translator for APR1400 Computerized Procedure System at Shin-Hanul Unit 1 and 2, Transactions of the Korean Nuclear Society Spring Meeting Jeju, Korea, 2015.
[7] S.J. Lee, P.H. Seong, Development of an integrated decision support system to aid cognitive process of operators, Nuclear Eng. Tech. 39 (6) (2007) 703–717.
[8] J. Kim, et al., “HuRECA: the Human Reliability Analysis Method for Computer-Based Advanced Control Rooms,” KAERI/TR-4385/2011, 2011.
[9] S.J. Lee, W. Jung, H. Kim, “Analysis of Interface Management Tasks in Advanced Main Control Rooms Based on Simulator Data”, TR-5193/2013, Korea Atomic Energy Research Institute, 2013.
[10] Stubler, J.M. O’Hara, “Soft Control: Technical Basis and Human Factors Review Guidance”, BNL-NUREG-52565, NUREG/CR-6635, 2000.
[11] O’Hara, William S. Brown, “The Effects of Interface Management Tasks on Crew Performance and Safety in Complex”, Computer-Based Systems, BNL-NUREG-52656, NUREG/CR-6690, 2002.
[12] Y. Kim, W. Jung, S. Kim, Empirical investigation of workloads of operators in advanced control rooms, J. Nucl. Sci. Technol. 51 (6) (2014) 744–751.
[13] J. Park, J.Y. Jung, W. Jung, The use of a process mining technique to characterize the work process of main control room crews: a feasibility study, Reliab. Eng. Syst. Saf. 154 (2016) 31–41.
[14] S.J. Lee, J. Kim, W. Jung, Quantitative estimation of the human error probability during soft control operations, Ann. Nucl. Energy 57 (2013) 318–326.
[15] S. Kim, Y. Kim, W. Jung, “The Development of an Framework to Measure Workload of MCR Operators in Nuclear Power Plants”, KAERI/TR-4741/2012, 2012.
[16] S.J. Lee, P.H. Seong, Experimental investigation into the effects of decision support systems on operator performance, J. Nucl. Sci. Technol. 46 (12) (2009) 1178–1187.

Please cite this article as: J. Choi et al., Analysis of interface management tasks in a digital main control room, Nuclear Engineering and Technology, https://doi.org/10.1016/j.net.2019.04.010