Risk Analysis of Nuclear Power Plant (NPP) Operations by Artificial Intelligence (AI) in Robot

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***Abstract*—The cognitive architecture is investigated for the management in the nuclear power plant (NPP) site in which artificial intelligence (AI) is incorporated. The normal operation and accident are modeled for the simulations incorporated with the robot intelligence algorithm, where random sampling plays a major role in the quantifications. The Accident Dynamics Simulator paired with the Information, Decision, and Action in a Crew context cognitive model (ADS-IDAC) and the Cognitive skill for plant operations are calculated for the study. Simulations show the ADS-IDAC modeling and simulation results of two peaks in 21st and 21.75th sequences. Otherwise, there are several peaks with one big peak in 13.25th sequences. The big peak is in the 25.75th sequence in Mental State, Circumstances, and Identity. The accident situation is related to actions through the cognitive systems. In the operation case, a variety of signals are shown in which the operations of the plant could show several kinds of actions to be done by the robot. The figure shows the procedure of nuclear cognitive architecture. A nuclear accident is investigated by the designed modeling in which the actions of robots are quantified by the artificial brain. The developed algorithm of this paper could be applied to the other kinds of complex industrial systems like airplane operations and safety systems, spacecraft systems, and so on.**

Keywords—Nuclear Power Plants (NPPs); Risk; Robot; Cognitive Architecture; Dynamics

I. Introduction

Following the successful resurrection of nuclear power plant (NPP) constructions [1] in the United States after the Three Mile Island (TMI) Accident, the enhanced and advanced safety strategy has been focused on, including safety improvements. The newly constructed four units in Georgia and South Carolina states in the country have initiated dozens of plants construction plans in the country. Hence, the safety concept should follow the newly developed stuff in this century where the convergence–based cyborg technology has been studied in post-accident treatment. When the Fukushima disaster had affected the environment by the core-melted severe accident, the treatment methods were very limited due to the highly exposed radiations. Although the primitive robot system was used, it was very limited to the monitoring of the collapsed state in the inner plant building. Hence, the intelligent robot is a very crucial necessity to control the stuff in the exploded building substituted with the human workers.

After Fukushima nuclear disaster, the usage of robotics has been challenged where the human-robot interface and mobility are incorporated with the perception [2]. The environment of accident areas is very harsh and nearly non-accessible by a biological substance like humans. So, it is very useful for the cyborg, a human-like robot, to do any work in highly radioactive contaminated areas. Even the massive power of the machine could handle heavy derbies and dangerous shape materials where the robot would move to clean up the exploded places following the operator's orders. By the way, the automatic decision could be made by itself in urgent situations for the tasks. Therefore, the robot intelligence should be equipped for commercialization. In fact, robotics could be used in normal operations, which can prepare for a possible accident, even multi-combinational caused accident.

Since the brain is composed of neural systems, the neurological investigation in robot manufacturing is an important part of a whole robot system. Sandamirskaya and Burtsey studied the Dynamic Neural Fields (DNFs) implementation of the low-level elementary behaviors and a Functional System Network (FSN) where the neurocognitive features are simulated in a dynamical manner. Cognitive perception is the first step of the actions of robotics. Therefore, the research is to make the cognitive architecture of perceptions which is a triggering stage to produce the robot behaviors, where the simulations are performed with dynamical calculations. The whole strategy is a complex non-linear trend because the elemental stuff is valued as the random samplings with the dynamic job. The computer code is the Vensim which could be used for the quantifications with random number generations [3]. This code is used for the randomized feature in nature or humanity-related organizations. Usually, it is applicable to dynamical modeling of business simulations where the basic events are considered as random sampling with the mean and variance values decided by the operator.

In the conventional operations of the NPPs, all decisions are made by humans, which is very easy to provoke human errors by many reasons such as fatigue, emotional, and other kinds of commonly produced malfunctions of human. Even the machine could make any mistakes in the operations for a complex system like the NPP. Therefore, it is necessary to design a highly intelligent robot to cope with interesting situations in commercial and research nuclear reactors, including radioactive materials [4-8]. The strategy should be compromised by the characteristics of the NPP facility. Fig. 1 shows the configurations of the intelligence of robots in the nuclear industry. In this figure, the critical factor of NPP is radioactive materials which are major characteristics of nuclear fuel management facilities. The robot has a non-biological body that can withstand the highly radioactive circumstances in the accident situation. The intelligence could make the robot control the nuclear disaster area even with the normal operation area. Hence, this study treats the intelligential modeling of robotics for diagnostics and monitoring in nuclear facilities [9-11].

Fig. 1. Configurations for the intelligence of robots in the nuclear power plant.

There are some previous studies for cognitive architecture. Miyazawa et al. [12] studied the cognitive architecture for the multimodal categorization as multilayered multimodal latent Dirichlet allocation (mMLDA). In addition, Carvalho et al. [13] showed the cognitive issues related to the operational work of NPP during their time on the job in the control room and during simulator training (emergency situations) for nuclear safety. Glöckner et al. [14] worked for a single mechanism model in decision making based on parallel constraint satisfaction processes (PCS-DM). Section 2 explains the method of the study. Section 3 describes the results of the study. There are some conclusions in section 4.

II. METHOD

A. Cognitive story representation

In the modeling of this study, the cognitive story representation with reasoning is constructed following the previous work by Nancy et al. [15] in Fig. 2. The supposed event is assumed by the randomized quantifications. The Evidence is progressed as a Story incorporated with the Relevant knowledge until the Verdict category. This algorithm shows the procedure of the AI of the robot to make the best decision. In the conditional elements, Evidence is described as four cases from E1 to E4 in this work of Fig. 3. Each value has randomized numbers with normal distribution, which are in Table 1. Similarly, Relevant World Knowledge is constructed from K1 to K8. The modeling is to flow of event as two Physical States, Goals, Actions, and Consequences. Eventually, the Verdict Category is obtained as four states of Actions, Mental State, Circumstances, and Identity. In order for the robot to make any decision, it is supplied to select the conditional cases in situations of the accident. That is, many conditional cases are identified by the robot, and the final decision is obtained. Actually, the decision would be made very fast, which is happened in the human brain, such as a man confronts the nuclear accident in the plant site.

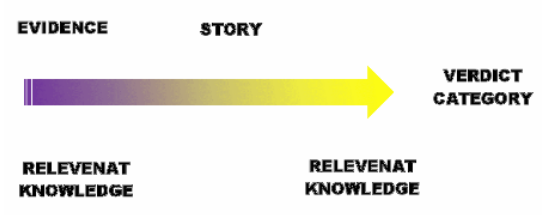


Fig. 2. Simplified configuration of interfaces connected evidence with world knowledge and evolving story.

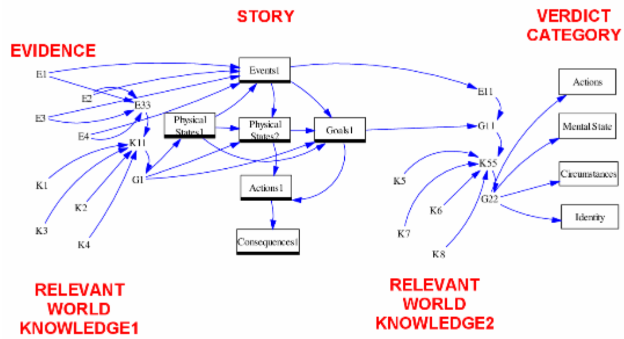


Fig. 3. Randomly sampled modeling of a modified configuration of interfaces connected evidence with world knowledge and evolving story.

TABLE 1. VALUES OF A MODIFIED CONFIGURATION OF INTERFACES CONNECT EVIDENCE WITH WORLD KNOWLEDGE AND EVOLVING STORY

Event		Value
Evidence	E1	random normal(0, 1, 0.4, 0.3, 0)
	E2	random normal(0, 1, 0.1, 0.3, 0)
	E3	random normal(0, 1, 0.2, 0.1, 0)
	E4	random normal(0, 1, 0.5, 0.1, 0)
	E33	if then else(random 0 1 () < 0.3, E1, if then else(random 0 1 () < 0.5, E2, if then else(random 0 1 () < 0.7,E3, E4)))
Relevant World Knowledge1	K1	random normal(0, 1, 0.2, 0.1, 0)
	K2	random normal(0, 1, 0.7, 0.1, 0)
	K3	random normal(0, 1, 0.3, 0.1, 0)
	K4	random normal(0, 1, 0.6, 0.2, 0)
	K11	if then else(random 0 1 () < 0.3, K1, if then else(random 0 1 () < 0.5, K2, if then else(random 0 1 () < 0.7,K3 ,K4))) *E33
	G1	K11
Story	Events1	if then else(random 0 1 () < 0.3, E1, if then else(random 0 1 () < 0.5, E2, if then else(random 0 1 () < 0.7,E3, E4)))*Physical States1
	Physical States1	G1
	Physical States2	G1*Physical States1*Events1
	Goal1	Physical States1*Physical States2* G1* Events1
	Actions1	Goals1*Physical States2
	Consequences1	Actions1
	E11	Events1
	G11	Goals1*E11
Relevant World Knowledge2	K5	random normal(0, 1, 0.4, 0.3, 0)
	K6	random normal(0, 1, 0.2, 0.3, 0)
	K7	random normal(0, 1, 0.7, 0.3, 0)
	K8	random normal(0, 1, 0.4, 0.3, 0)
	K55	if then else(random 0 1 () < 0.3, K5, if then else(random 0 1 () < 0.5, K6, if then else(random 0 1 () < 0.7,K7 ,K8))) *G11
	G22	K55
Verdict Category	Actions	if then else(random 0 1 () < 0.3, G22, 0)
	Mental State	if then else(random 0 1 () < 0.5, G22, 0)
	Circumstances	if then else(random 0 1 () < 0.7, G22, 0)
	Identify	if then else(random 0 1 () < 0.9, G22, 0)

In the modeling of the Verdict Category, the robot is divided into four cases in which the Actions could be the motions of the robot, Mental State could be the internal operations of the robot intelligence, Circumstances could be the situations around the robot, and the Identity could be something to be by the robot.

In conditional perceptions, the If-Then statement is used for the conditional selections. The procedures are as follows,

If A Then B Else,
If C Then D Else,
If E Then F Else, …
:
:
(1)

Using this algorithm, E33, K11, and K55 are applied for the conditional selections. Each step has a random number of generations which are roles of the selective quantities. So, the conditions are variable by judgment's decision where the mean and standard deviation are used for the selective statistics. The random numbers are distributed uniformly from 0.0 to 1.0. The notation is in Table 1 as follows,

If Then Else (random 0 1 () < 0.3, G, H) (2)

If the random number between 0.0 and 1.0 is below 0.3, the value is G. Otherwise, and it is H. This kind of mathematical calculation can be justified for the unexpected perceptions with mean and variance values. Therefore, the calculations are meaningful for forecasting matters. Especially, the robot's behavior should be related to the combinations of Story supported by Evidence and Knowledge. This consequently goes to the Verdict Category with relative dimensionless values. These methods are tested by the following two cases in the next sections.

Complex values are obtained by combination with randomized sampling and the dynamical calculation because the basic events are decided by the operator intentionally. However, random sampling can give unexpected forecasting, and the time-based periodic calculations could describe the real situation when the future is unclearly estimated.

B. The Accident Dynamics Simulator paired with the Information, Decision, and Action in a Crew context cognitive model (ADS-IDAC)

There is an applicable model by Dr. Kevin A. C. [16] in which the Accident Dynamics Simulator paired with the Information, Decision, and Action in a Crew context cognitive model (ADS-IDAC) [17-23] shows the cognitive applications in the human error events, particularly knowledge-driven errors of commission of NPPs. This modeling is applied for this study in the case of an accident situation. There are ten cases of the Evidence as Average Temperature, Reactor Power, RCS Pressure, RCS Loop Flowrate, Pressurizer Water Level, Containment Pressure, SG Water Level, Feed Water Flowrate, Main Stream Flowrate, and SG Pressure. Relevant World Knowledge1 has six cases of Alertness and Attention, Stress, Task and Time Loading, Situation Perception and Awareness of Roles, Confidence and Motivation, and Knowledge and Skills. In addition, Relevant World Knowledge2 has five cases of Work Practices and Tools, Cohesiveness Coordination and Leadership, Latent Hardware Software and Human Failure, Physical Access Lighting Temperature, etc., and Physical Limitations. Story and Verdict Category is the same as the cases of Cognitive story representation.

In the modeling of the Verdict Category, the robot is divided into four cases in which the Actions could be the motions of the robot in the accident site, Mental State could be the analytic strategy of the robot intelligence, Circumstances could be the situations in the accident site, and the Identity could be the normal situation such as the non-accident state. In the quantifications of the variables E33, K11, and K55, the quantities are made following the case in the section of Cognitive story representation, which is made by expert judgment based on the robotics in the NPPs.

C. The Cognitive skill for plant operations

In the control room modeling, the human-centered design is needed to cope with the complex industrial systems that should be applied to the plant operations [24]. Mumaw et al. [25] studied the cognitive skill for the NPP operations where decision-making, problem-solving, inference-making, and knowledge usage are concerned. There are four cases of Detection and Monitoring, Situation Assessment, Planning, and Execution. Relevant World Knowledge1 has four cases of Cognitive Skill1, Perceptual Skill1, Procedure1, and Motor Skill1, which are similar to Relevant World Knowledge2.

In the modeling of the Verdict Category, the robot is divided into four cases in which the Actions could be the motions of the robot in the normal operations, Mental State could be the plant operation of the robot intelligence, Circumstances could be the situations in the normal operations, and the Identity could be the normal situation such as the non-accident state. In the quantifications of the variables E33, K11, and K55, the quantities are made following the case in the section of Cognitive story representation, which is made by expert judgment based on the robotics in the NPPs.

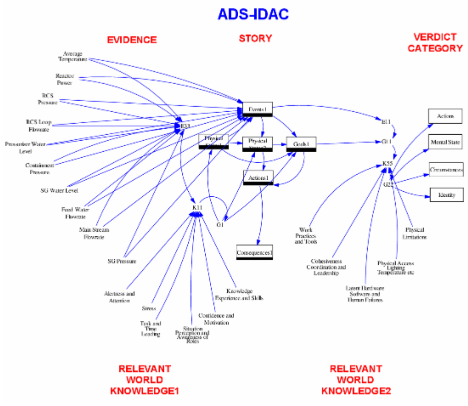
III. RESULTS

There are some results for the simulations in which the randomly sampled modeling of a modified configuration of interfaces connected evidence with world knowledge and evolving story are quantified in Fig. 3. The based calculations are IF-THEN sentences such as,

If A Then B Else, … (3)

The time step is 0.25, which means that the calculations are done every four times a day for 30 days a month. The values are relatively quantified where the dynamical configurations are shown by the periodic manners. The higher values are much more activated in each variable. For two cases of nuclear power, the ADS-IDAC and cognitive operations [26-34] are investigated. Fig. 4 is the ADS-IDAC modeling and simulation results of (a) Model, (b) Actions1, (c) Consequences 1, (d) Actions, (e) Mental State, (f) Circumstances, and (g) Identity. There are two peaks in the 21^{st} and 21.75^{th} sequences in graph Fig. 4 (b). The cumulative values are in Fig. 4 (c). From Fig. 4 (d) to Fig. 4 (g), the frequencies of the robotics are shown. The relative values are the impact or importance of the robotics' behaviors. Otherwise, Fig. 5 shows the cognitive operation modeling and simulation results. There are several peaks, with one big peak in 13.25th sequences. The big peak is in the 25.75th sequence as (e) Mental State, (f) Circumstances, and (g) Identity.

In the ADS-IDAC, the robot actions are presented as two peaks. This means that alternative behaviors could be occurred by the robot. The actions of the robots reflect the situations of the plant site. For example, the radioactive leak by accident should produce robot behavior.



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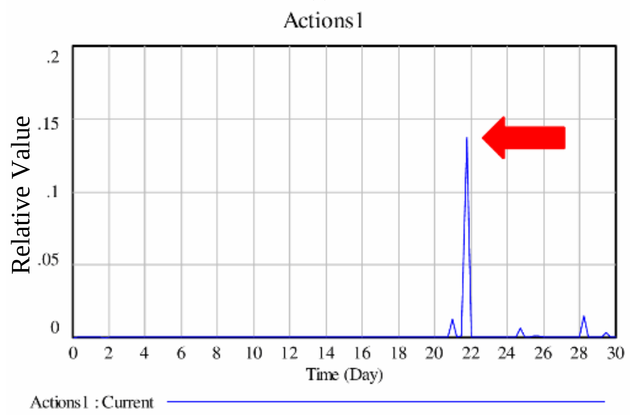

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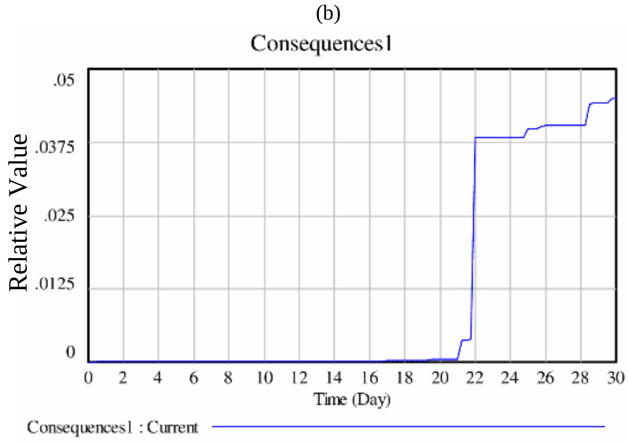

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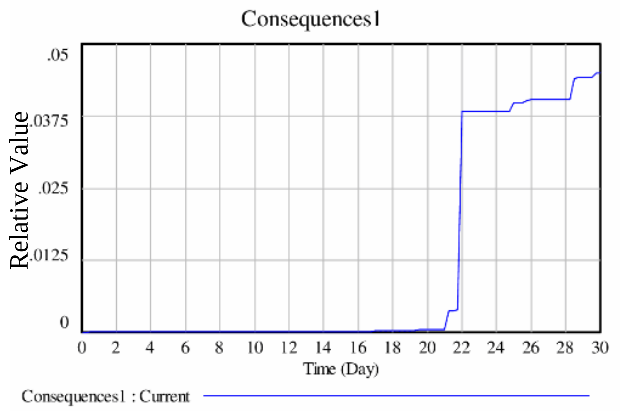

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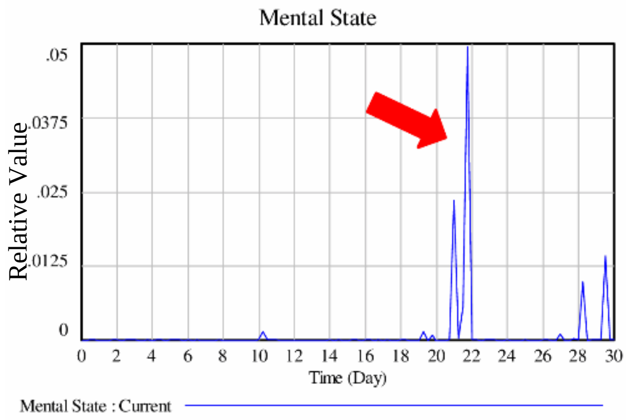

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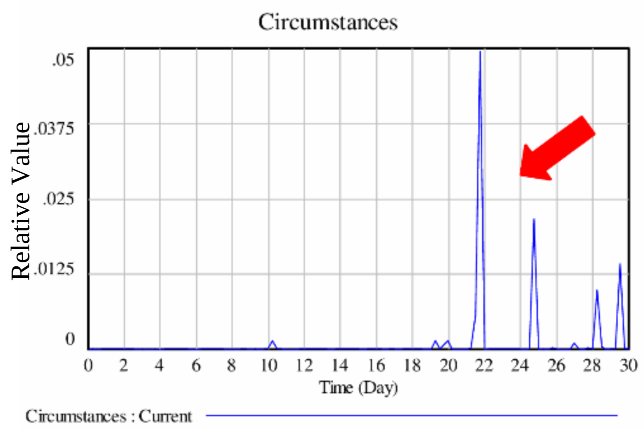

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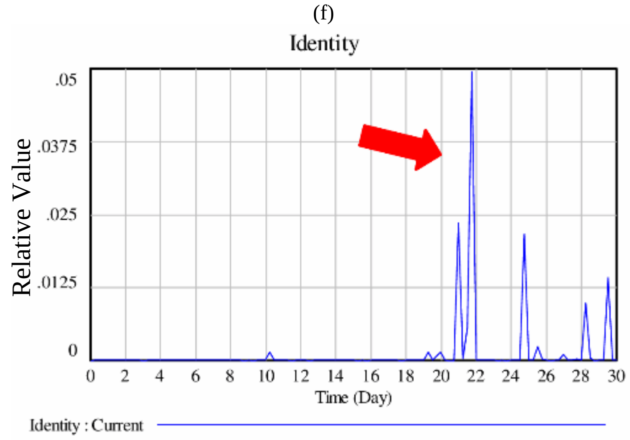
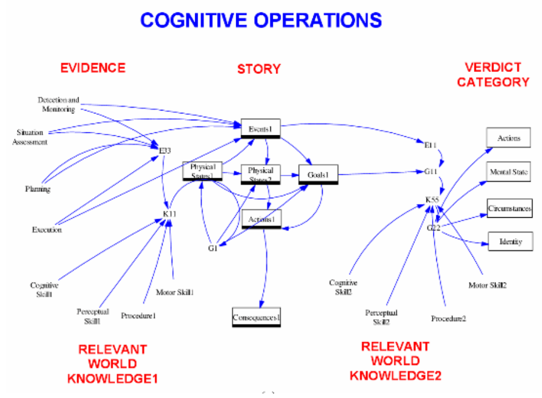


(g)

Fig. 4. ADS-IDAC modeling and simulation results (a) Model, (b) Actions1, (c) Consequences 1, (d) Actions, (e) Mental State, (f) Circumstances, and (g) Identity.



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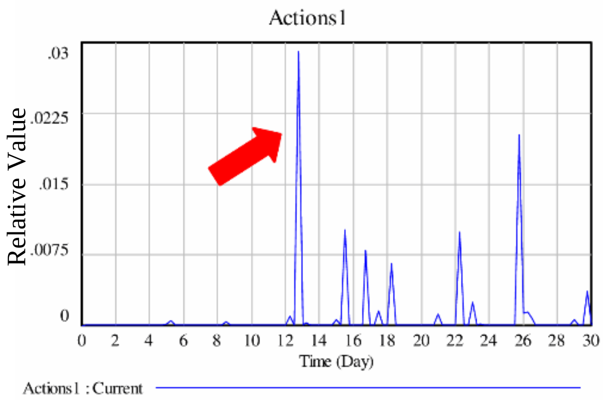

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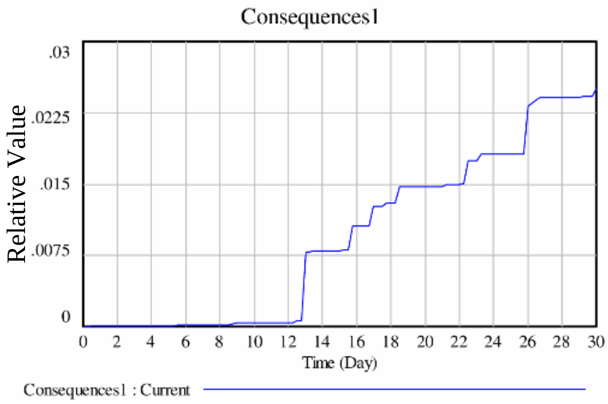

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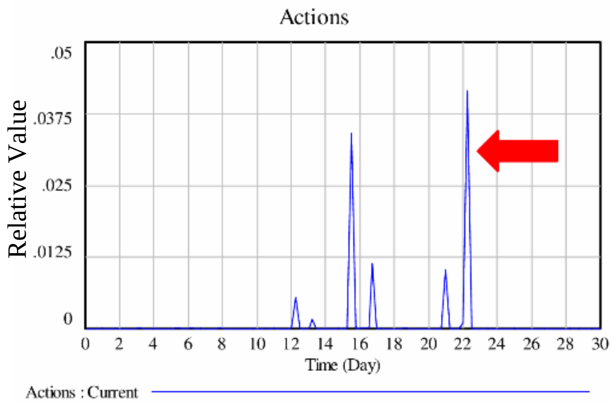

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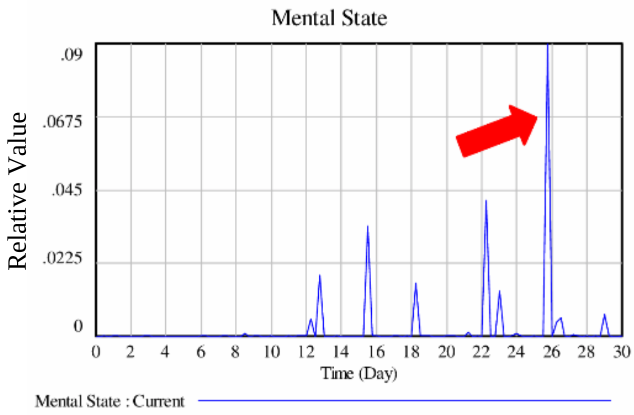

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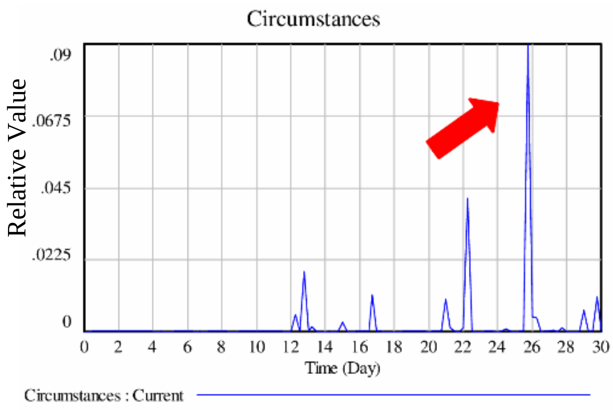

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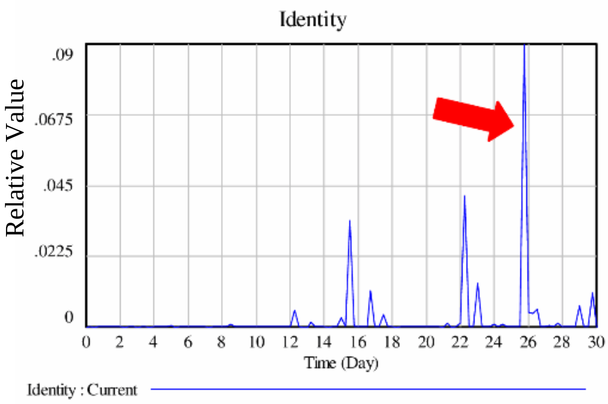

(g)

Fig. 5. Cognitive operation modeling and simulation results (a) Model, (b) Action1, (c) Consequenc-es1, (d) Actions, (e) Mental State, (f) Circumstances, and (g) Identity.

So, the accident situation is related to actions through the cognitive systems. In the operation case, a variety of signals are shown in which the operations of the plant could show several kinds of actions to be done by the robot. Fig. 6 shows the procedure of nuclear cognitive architecture.

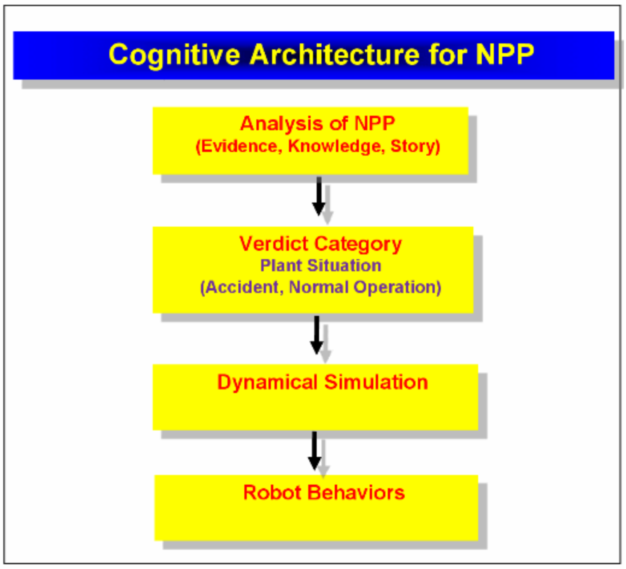

Fig. 6. The procedure of nuclear cognitive architecture.

IV. Conclusions

As a major topic in this work, the artificial brain of the robot is analyzed where several concepts are quantified for the cleared results and compared each other for the activations in the simulations. Therefore, the computerized calculations can show the exceptions of the robot's wrong behaviors, including the intentions of the robotic machine. It is expected the robot behavior could be corrected and modified following the simulations. Using the study results, several variables related to the task could be modified with an emphasis on the interesting factors in the accident or normal operations. There are some important points of this study as follows,

- A nuclear accident is investigated by the designed modeling.
- A much more tractable intelligence system is suggested.
- The actions of robots are quantified by the designed artificial brain.
- The cognitive actions are modeled in the system.

In this work, the intelligence of robotics has been simulated by the designed tasks. The realistic strategy of robotics can be obtained the Evidence and Relevant World Knowledge. In addition, the Story could be modified for the accident and normal operation states in this study. Hence, this simulation can forecast the robot behavior, which can expect the possibility of the robot. The applications of the nuclear accident are imagined by the Evidence and Relevant World Knowledge. But, it is possible to add the other kinds of options such as Creative Minds or Emotional Matters [35-40] because the decision could be made up by not only the realistic matter but the non-reasonable minds. The emotion of the operator could make a mistake in the regulated test. So, it is needed to consider the emotion. In addition, creative ability is also possible to be considered for decision-making related to cognitions.

Designed Verdict Category is variable by the expected results in the humanoid's behaviors where the AI's characteristics are analyzed. The AI is managed by the combinational tasks by the Story, which could be the accidents scenarios of NPPs. By the way, there is a tendency to prepare for the expected situations in advance. However, the complex happenings could be imagined, like the Fukushima case where the earthquake was combined with human error and system failure. These three portions had affected the status of the plant system. Eventually, the final destination was the core melting which proceeded the radioactive material dispersions to the environment through the collapsed plant facility. In the human brain, it is not easy to control and react to the safety system fast because a human has the skills to treat the tasks linearly following the regulations. That is, it is difficult for a human to control for multi-cause and multi-task-based accidents. Additionally, there are many limitations for humans to process incoming information in the very complex facility in NPPs. This robot intelligence system can control the complex tasks of many difficult matters.

The developed algorithm of this paper could be applied to the other kinds of complex industrial systems like airplane operations and safety systems, spacecraft systems, and even financial stock market estimations. The limitation of the human brain could be compensated with the artificial robot intelligence systems. Especially, the data mining technology could be improved by the cognitive architectural technology. The future events are connected with past and current situations. So, this kind of complex algorithm can be solved by the cognitive architecture where the economic and safety improvements would be accomplished. Some other AI algorithms like the fuzzy set theory for linguistic stuff and the neural networking for brain neural systems can be studied for future work.

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