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Development of FRAM Model Based on Structure of Complex Adaptive Systems to Visualize Safety of Socio-Technical Systems

Takayuki Hirose*, Tetsuo Sawaragi*

* *Department of Mechanical Engineering and Science, Kyoto University, Kyoto, Japan*
(e-mail: hirose.takayuki.27v@kyoto-u.jp, sawaragi@me.kyoto-u.ac.jp)

Abstract: FRAM: Functional Resonance Analysis Method is an effective way to know about the safety of complex Socio-Technical Systems. However, it is a method rather than model and required to be extended for its practical usage. According to this, in this paper, a latest version of FRAM simulator based on our developed model is presented. The model simulates a process in which variabilities exiting in a working environment induce variability of FRAM functions that emerge out of the dynamic interactions among the functions as well as with the environment. Moreover, the model simulates a process where a specific context composed of variabilities existing in a working environment "shakes" FRAM functions, while the context is "shaken" by those functions vice versa, which is a typical dynamics specific to complex adaptive systems. This is implemented by integrating FRAM and Fuzzy CREAM which is an extended model of CREAM: Cognitive Reliability and Error Analysis Method with fuzzy reasoning. It enables to parameterize the variabilities, define the context, and formulate their interactions quantitatively, whose result is given as a dynamical change of state in each FRAM function.

Keywords: Functional Resonance Analysis Method (FRAM), safety, Socio-Technical Systems, complex adaptive systems.

1. INTRODUCTION

Technological developments and complications of society have been making systems more and more complex. Especially, systems whose operation involves human factors, technical factors, organizational factors, and working environment are called Socio-Technical Systems. Typical examples of those systems are operations of airliners, railways, or nuclear power plant, and their safety is one of the most critical issues of the society.

It is difficult to understand the safety of Socio-Technical Systems with traditional approaches such as why-because analysis because of their complexity. For example, it is difficult to find out the "root cause" of an accident. Also, it is difficult to know why operations are going well. Therefore, the safety of Socio-Technical Systems must be investigated not only based upon the conventional cause-effect relationships but also upon the idea of emergence, which is characterized by the "systemic" accident model.

FRAM: Functional Resonance Analysis Method (Hollnagel (2004)) is a new approach to overcome this problem. It was introduced to investigate the effect of variabilities (e.g. fluctuations of working environment or task performance) existing in Socio-Technical Systems and their interactions; their non-linear interactions could sometimes resonate and bring about unexpected outcomes which cannot be predicted by simple summation of each of their effects. Therefore, FRAM is an effective way to know the safety emerging from non-linear interaction of variabilities. However, FRAM is a method rather than model, according to E. Hollnalgel who is the advocate of FRAM, and it should be further elaborated for its practical usage.

We have been building a model of FRAM and developing a simulator based on it (Hirose et al. (2017)), whose latest model is shown in this paper. The model was built to represent a process in which variabilities exiting in a working environment induce variability of task performances in FRAM functions emerging out of interactions among functions as well as the environment. In other words, the model simulates a process where a specific context composed of variabilities existing in a working environment "shakes" FRAM functions, while the context is also "shaken" by those functions, which is a typical dynamics specific to complex adaptive systems. The model was implemented by integrating FRAM and Fuzzy CREAM which is an extended model of CREAM: Cognitive Reliability and Error Analysis Method (Hollnagel (1998)) with fuzzy reasoning. It enables to parameterize the variabilities, define the context, and formulate their interactions quantitatively. Moreover, the model makes it possible to simulate the safety of Socio-Technical Systems based on the idea of complex adaptive systems, whose result is given as a dynamical change of state in each FRAM function.

2. FUNCTIONAL RESONANCE ANALYSIS METHOD

FRAM: Functional Resonance Analysis Method is an effective way to understand about the safety of Socio-Technical Systems; they are usually operated with involving human factors, technical factors, working environment, and

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organization factors, making it difficult to predict their behavior with traditional approaches such as why-because analysis. FRAM was proposed to overcome the challenge based on the systemic perspective; each component of a Socio-Technical System potentially works with some variabilities, and their global behavior emerges from interactions of those variabilities. It should be noted that the word: variability corresponds to fluctuations of task performance of human/machines or working environment such as availability of resource or time in this context.

FRAM starts with defining functions with six aspects. Functions in FRAM are regarded as "what has to be done to achieve a specific goal"; each item described in manuals or checklists is typical examples. Also, the six aspects are shown in Table 1, connecting the FRAM functions and representing a target system as a network of them, which is called as an instance.

Table 1. Six aspects of FRAM function

Aspect	Description
Input	Input/Trigger of a FRAM function
Output	Outcome of a FRAM function
Precondition	Conditions that must be satisfied before a FRAM function is carried out
Resource	What is consumed by a FRAM function (e.g. fuel, energy, labor force)
Control	What supervises or restricts a FRAM function
Time	Time constraints for a FRAM function

Figure 1 illustrates an example of instances, representing a normal procedure to start a car. For example, "Starting a car", which is the goal of this procedure, is triggered by releasing the foot brake; that is why a FRAM function: "Releasing foot brake" is required, whose output is connected with input of "Starting a car". Also, several conditions must be satisfied before starting a car; that is why FRAM functions: "Fastening seatbelt", "Shifting from park to drive", and "Releasing parking brake" are necessary, and their output are connected with precondition of "Starting a car". FRAM functions and their connections are identified in this way; it should be noted that FRAM functions can be described at any abstraction levels, depending on cases, and massive FRAM functions are not required even in the case of large complex systems such as nuclear power plants.

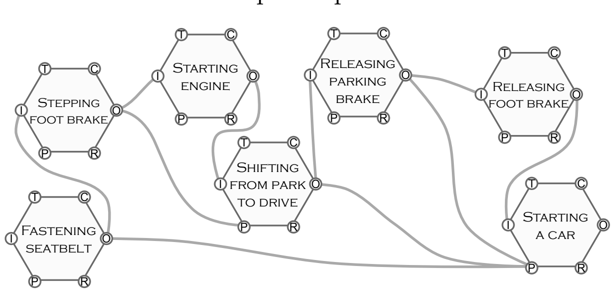


Fig. 1. Example of instance: procedure to start a car

Variability of FRAM functions are generally induced by variabilities exiting in a working environment. It is ideal that Socio-Technical Systems are operated in accurately executing predetermined operational procedures. However, there may exist variabilities of working environment in the real world caused by the temporal conditions such as available resources (e.g. time), interfering the expected operations. They force the operators to perform their tasks in a more efficient way to cope with the situation (e.g. deviations from SOPs: Standard Operation Procedures) while they are also required to execute them precisely. This kind of dilemma is called ETTO: Efficiency and Thoroughness Trade-Off (Hollnagel (2004)), and ETTO usually results in the deviation of task performance from work as imagined, causing the variability of FRAM functions.

FRAM investigates the effect of such variabilities exiting in an instance. The variability of a FRAM function interacts with that of other FRAM functions, and their interactions could cause unexpected or severe outcomes in a specific context, which cannot be explained with simple cause-effect relationships. This kind of non-linear phenomena is called functional resonance in Hollnagel (2004), and FRAM is to simulate it. Moreover, FRAM is characteristic compared to the other safety analysis method in the sense that it aims to know what will happen when variabilities come together rather than analyzing events (e.g. accidents) based on decomposition and causality.

However, FRAM is a method rather than model, implying that there is no systematic procedure of FRAM, and it needs to be implemented for its practical use; That is why we have been building a model of FRAM and developing the simulator by introducing numerical definition of FRAM entities (e.g. variabilities of working environment or FRAM functions).

3. A NEW MODEL OF FRAM

3.1 Definition of Variabilities with Fuzzy CREAM

The first thing to build a FRAM model is to define variabilities numerically, and Fuzzy CREAM, which is an extended model of CREAM: Cognitive Reliability and Error Analysis Method (Hollnagel (1998)) with fuzzy reasoning, makes it possible.

CREAM is a safety analysis method to investigate how things or events are going well under a certain situation. The situation is represented by factors called CPCs: Common Performance Conditions, and eleven CPCs such as "Availability resource", "Quality of communication", and "Number of simultaneous goals to be attained" have already been defined (Hollnagel (1998), Hollnagel (2004)). Also, an index which represents how things or events are going well is prepared in CREAM. The index is called Control Mode, which has four values: Strategic, Tactical, Opportunistic, Scrambled; the safer the Control Mode gets toward Strategic, and vice versa. Moreover, each Control Mode is related to the interval of PAF: Probability of Action Failure; the lower the PAF is, the safer the situation is as shown in Table 2; the goal of CREAM is to identify Control Mode and PAF based on evaluation of CPCs.

CREAM was extended with fuzzy reasoning, since entities of CREAM such as states of CPCs, Control Mode, and PAF are too discrete to deal with. It is generally called Fuzzy CREAM in which membership functions corresponding to linguistic state of CPCs are introduced with their support sets of CPC score; this is also the

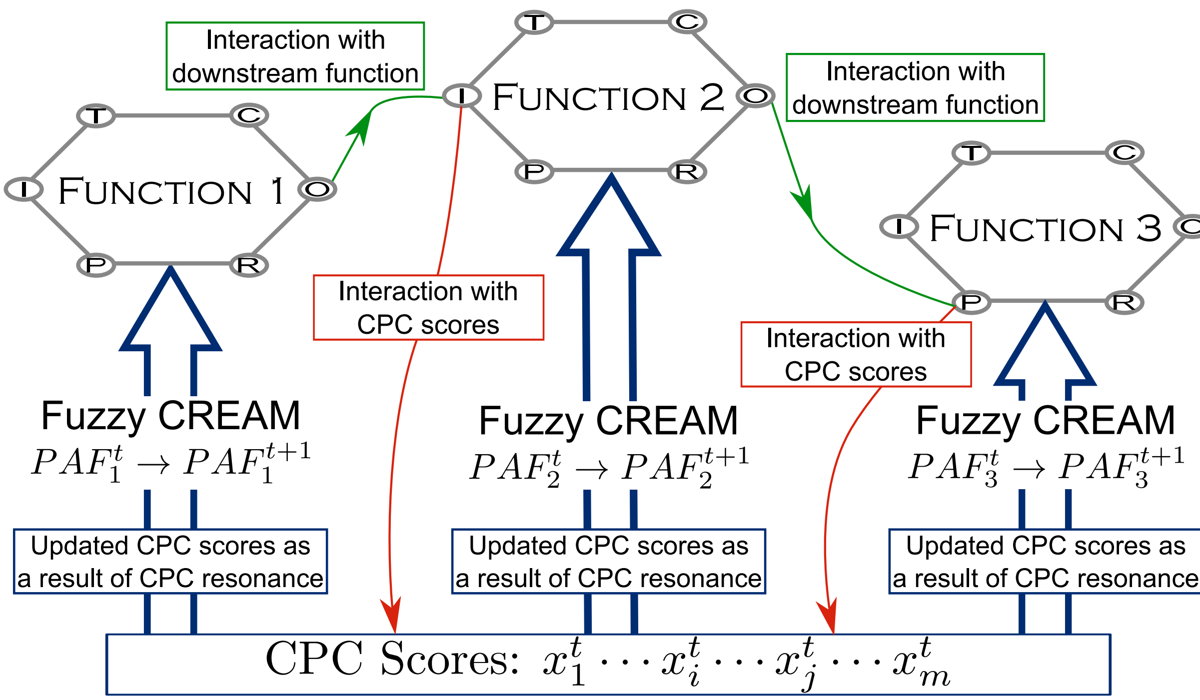


Fig. 2. Overview of the latest FRAM model

Table 2. PAF intervals with respect to Control Modes

Control Mode	Intervals of probability of action failures
Strategic	$0.50 \times 10^{-5} < p < 0.010$
Tactical	$0.10 \times 10^{-2} < p < 0.10$
Opportunistic	$0.010 < p < 0.50$
Scrambled	$0.10 < p < 1.00$

case with Control Mode whose support set is logarithm of PAF. The membership functions vary from 0 to 1.00 and represent degree of matching between a linguistic state of CPC/Control Mode and its support set; CPC score is a continuous value varying from 0 to 100 to represent the state of a CPC; the higher the CPC score is, the better the CPC status is. In addition, linguistic fuzzy rules: IF-THEN rules between combinations of CPC status and a specific Control Mode is built. The following is an example of the rule:

$$IF\ S_1 = Compatible\ AND\ S_2 = Efficient\ AND \cdots AND\ S_m = \cdots\ THEN\ C = Strategic$$

where S_i denotes the linguistic state of the i-th CPC, m is the total number of CPCs, and C represents the Control Mode ($1 \leq i \leq m$). With above items, conclusion fuzzy set of Control Mode is obtained by calculating how the antecedent matches to consequent in those If-Then rules; it represents "continuous" Control Mode, and crisp value of PAF also can be obtained by calculating its center of gravity: defuzzification process. It should be noted that there are several models of Fuzzy CREAM, and *weighted CREAM model* (Ung (2015)) is adapted in this research.

The Fuzzy CREAM model is applied to each FRAM function. This is because we assumed that Fuzzy CREAM corresponds to the process in which the variabilities are caused; variabilities existing in a working environment can be regarded as fluctuation of CPC scores, and variability of each FRAM function can be regarded as fluctuation of "continuous" Control Mode or crisp value of PAF in our model. Therefore, our FRAM model is implemented as a network of the Fuzzy CREAM models driving in each FRAM function, and how they are connected, which is our originality, is shown in the next.

3.2 Connecting Fuzzy CREAM Models Through FRAM Functions

The FRAM model is implemented by connecting Fuzzy CREAM models, and its overview is shown in Fig. 2. In this model, all functions are supposed to share one set of CPC scores; those scores are kept on updating by the effect of variability coming from upstream FRAM functions; they can be also changed manually to trigger or intervene the simulation process. At the same time, Control Mode or crisp value of PAF in each function is also kept on updating based on the change of those CPC scores in this model.

The CPC scores are updated once after they are changed by the effect of variabilities or manually, according to dependency among CPCs. The dependency has been already described by Hollnagel (1998) as shown in Table 3, and CPCs in the left column change their own state depending on the state of CPCs in the right column; if a CPC status in the right column is better than that in the left, it improves the state of CPC in the left column, and vice versa. This is formulated as following:

$$x_i^{t+1} = x_i^t + \frac{\sum_{j=1}^{k}(x_j^t - x_i^t)}{k} \quad (1)$$

where x_i^{t+1} is an updated score of the i-th CPC in the left column of Table 3, and x_i^t is its original score; x_j^t is the score of the j-th CPCs in the right column of Table 3;

k is the number of surrounding CPCs listed in the right column of Table 3; its example is shown in Fig. 3.

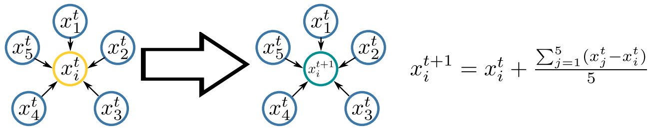


Fig. 3. Schematic diagram of CPC dependency

Table 3. Dependency among CPCs

CPC	Depends on the following CPCs
Working Conditions	Adequacy of organization, Adequacy of HMI, Circadian rhythm, Availability of resource, Available time, Adequacy of training and experience
Number of Simultaneous Goals	Working conditions, Adequacy of HMI, Availability of procedures/plans
Available Time	Working conditions, Adequacy of HMI, Availability of procedures/plans, Number of simultaneous goals, Adequacy of training and experience, Circadian rhythm
Crew Collaboration Quality	Adequacy of organization, Circadian rhythm, Quality of Communication

Crisp value of PAF in each function is updated by Fuzzy CREAM with the updated CPC scores, and they interact with each other; note that the PAF is output as a result at this time. The interaction is formulated as following:

$$PAF_{down}^{t+1} = PAF_{down}^{t} + \frac{\sum_{j=1}^{l}(PAF_{up,j}^{t+1} - PAF_{up,j}^{t})}{l} \quad (2)$$

where PAF_{up}^t and PAF_{up}^{t+1} respectively refer to crisp value of PAF in a upstream function before and after the PAF is updated by the Fuzzy CREAM process; this is also the case with PAF_{down}^t and PAF_{down}^{t+1}. Also, l is the number of functions surrounding a certain downstream function; an example of its schematic diagram is shown in Fig. 4.

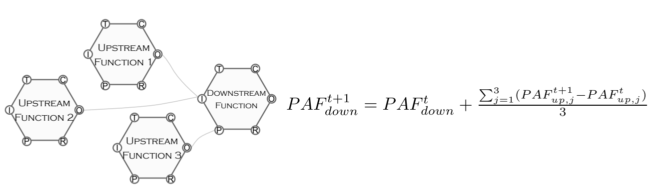


Fig. 4. Schematic diagram of interaction among functions

The effect of interaction among functions is looped back to the set of CPC scores; fluctuation of CPC scores changes crisp values of PAF in each function, and CPC scores themselves are also affected by its effect. This is formulated as following:

$$x_i^{t+1} = \frac{PAF_{down}^{t}}{PAF_{down}^{t+1}} \times x_i^t \quad (3)$$

where x_i^{t+1} and x_i^t are the updated and original scores of the i-th CPC, respectively; equation 3 represents that CPC scores decrease if the PAF in the function increases, and vice versa.

All functions repeat the above processes simultaneously; the processes go on automatically after they are triggered by manual. As a result, a crisp value of PAF in each function is sequentially obtained, playing a role as quantitative criteria to interpret the qualitative safety of Socio-Technical Systems.

This model can be explained from another perspective as shown in Fig. 5. A specific working environment or context can be regarded as a space spanned by a vector whose components are CPC scores, and an instance are included in the context; the context and instance mutually "shakes" each other in response to the other, and their mutual interaction results in dynamical change of the safety of each function, as if it is a complex adaptive system. In addition, the safety of each function or instance can be abstracted into the safety of one function which is called super function here. Since the vector of CPC scores is developed by the mutual interaction between context and instance, it also seems to represent a context where a goal as an entire instance (e.g. preparing breakfast, driving a car, or landing an airplane) is achieved. That is why multiple functions of an instance can be abstracted into one function by applying Fuzzy CREAM to the super function existing out of the context; this process just keeps on representing the state of super function, and there is no interaction with other entities in this model. Therefore, the model is expected to simulate complexity of Socio-Technical Systems, and the result can be more simplified by the abstraction process than our old models.

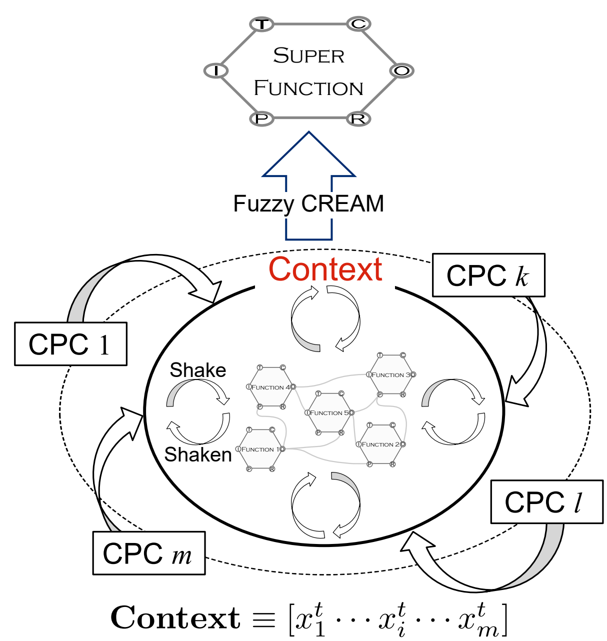


Fig. 5. Another perspective of the FRAM model

4. CASE STUDY

4.1 Target of Simulation

The target of this simulation is drug dispensing procedure carried out by pharmacists. This is one of the most well-known examples of FRAM since it was introduced in the first book of FRAM (Hollnagel (2004)). However, it does not provide more than conceptual explanation of the procedure with FRAM, and there are few additional findings about its safety. That is why this example was chosen to demonstrate the FRAM model in this paper.

4.2 Initial Setting of Simulation

The first step of initial setting is to identify an instance representing drug dispensing procedure; FRAM functions and their relationships are usually defined as explained in Fig. 1. However, the instance has already been provided in Hollnagel (2004) in this case, and we used it in this simulation. The instance of drug dispensing procedure is shown in Fig. 6; it should be noted that there are ID number of functions in Fig. 6 for convenience, and they do not have special meaning such as the order of execution.

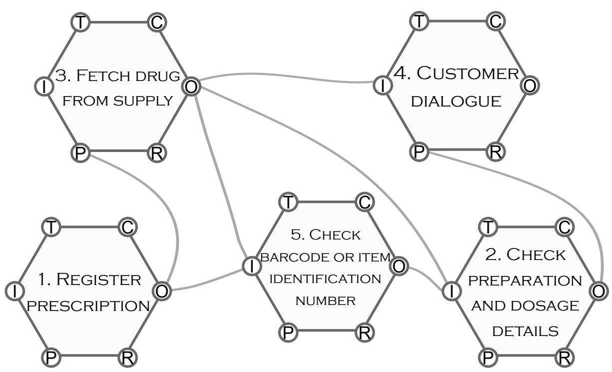


Fig. 6. Instance of drug dispensing procedure

The next step is to define weight of CPCs in each function. The weight of CPC is a kind of sensitivity of functions against each CPC. In this simulation, they were determined by the following procedure for the sake of simplicity and shown in Table 4; the ID No. 0 corresponds to the super function of the instance.

1. Identifying CPCs which are the most significant on the function and letting it be 100.
2. Evaluating relative weight of other CPCs based on the above evaluation.

It should be noted that the weight of each function is normalized by their sum in the simulation process.

Table 4. CPC weight in each function

CPC	ID No. of functions in Fig. 6					
	0	1	2	3	4	5
Availability of resource	10	100	100	100	80	100
Adequacy of training and experience	50	60	60	30	30	70
Quality of communication	90	20	5	5	100	5
Adequacy of HMI	100	5	5	30	5	100
Access to procedures	30	60	10	10	10	30
Working condition	60	40	20	10	40	10
Number of simultaneous goals	80	60	70	70	50	50
Available time	80	80	70	70	50	50
Circadian rhythm	20	10	10	5	5	5
Crew collaboration	30	10	5	10	5	5
Adequacy of organization	10	5	5	5	5	5

In the end of initial setting, simulation scenarios need to be set and converted into manual change of parameters such as CPC scores or dependency among functions. The scenario was set as shown below in this simulation.

Scenario: a pharmacist was dealing with a daily task represented in Fig. 6, and everything was going well as usual. However, his colleague asked him an extra task, and the number of waiting patients had also been increasing little by little; he suddenly got too busy to carry out his tasks as expected in the end.

This is converted into the following operations, referred to it as *Variability 1*, *Variability 2*, and *Variability 3*. It should be noted that all CPC scores are supposed 100, which is the best condition, at the beginning of this simulation.

Variability 1: CPC score: "Number of simultaneous goals" is set to 0, which is the worst condition of the CPC, at simulation time: $T = 0$
Variability 2: the simulation process is paused once after *Variability 1* degrading the safety, and 5. Check barcode or item identification number is eliminated from the instance to simulate the FRAM function of the procedure is failed to carry out
Variability 3: the simulation process is paused once after *Variability 2*, and 5. Check barcode or item identification number is revived again to simulate a case in which the pharmacist overcomes the pressure of work

Based on these items: *Variability 1, 2*, and *3*, the following three cases are examined in this simulation.

Case 1: the single effect of *Variability 1*, simulating a situation in which the pharmacist did not miss the check even though *Variability 1* interfered his task
Case 2: the combined effect of *Variability 1* and *2*
Case 3: the combined effect of *Variability 1, 2*, and *3*

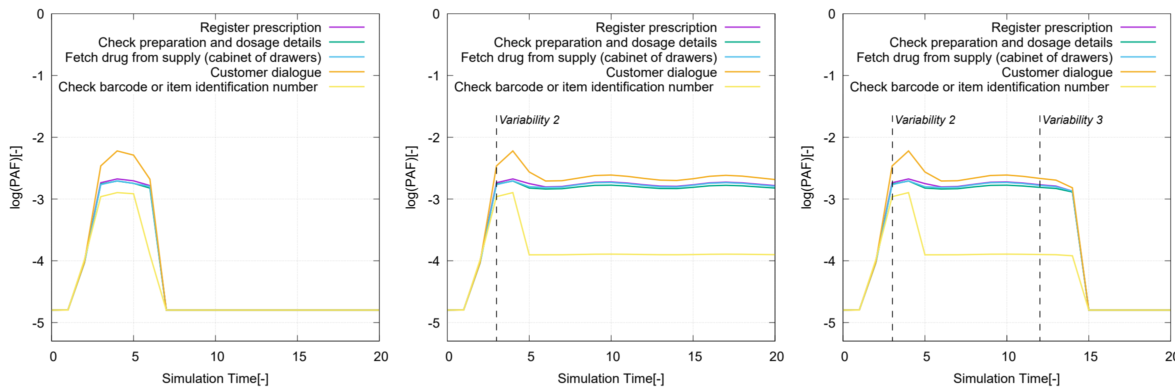
4.3 Result

The result of simulation is shown in Fig. 7 and Fig. 8. The former and latter shows the dynamical transition pattern of $log(PAF)$ in each function with respect to the each case, and the latter illustrates the abstracted transition patterns of the former result: transition pattern of super function. Also, the horizontal axis and the vertical axis represent the simulation time and $log(PAF)$ in each function, respectively; the $log(PAF)$ can also be regarded as degree of danger/instability of functions here.

The simulation result of case 1 is shown in Fig. 7(a) and Fig. 8(a). Figure 7(a) shows $log(PAF)$ of all functions increased as a result of *Variability 1*, and they went back to the original state automatically; the same trend is shown in Fig. 8(a). Therefore, the instance can be regarded as resilient against *Variability 1* if it sustains the original state shown in Fig. 6.

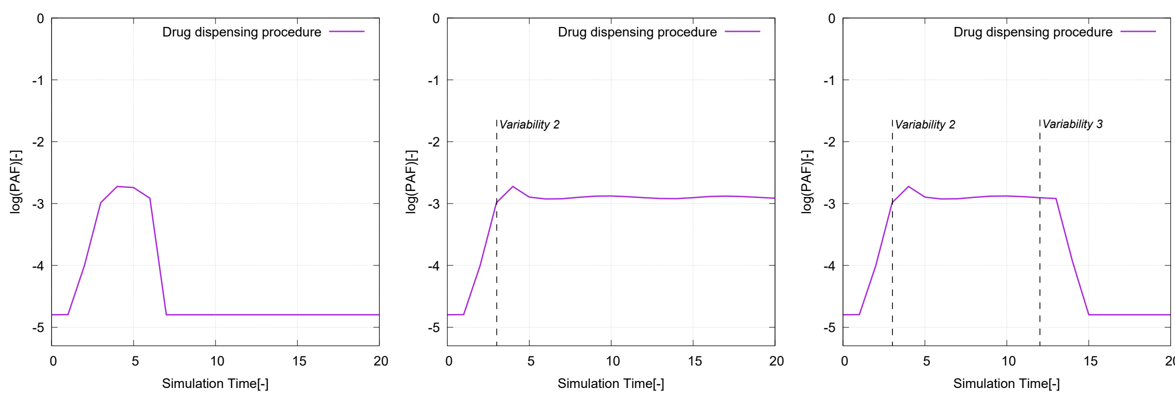
The simulation result of case 2 is shown in Fig. 7(b) and Fig. 8(b). Figure 7(b) shows $log(PAF)$ of all functions increased as a result of *Variability 1*, and almost all of them remained high whose Control Mode corresponds to "Opportunistic" after *Variability 2*; the similar trend is shown in Fig. 8(b). This suggests that the safety in each function cannot go back to their original state if the procedure is missed to carry out in such an upset situation.

The simulation result of case 3 is shown in Fig. 7(c) and Fig. 8(c). In this case, the same transition pattern was obtained until *Variability 3*, and they recovered to the original state after that; the super function also shows



(a) Simulation result of case 1 (b) Simulation result of case 2 (c) Simulation result of case 3

Fig. 7. Result of each case: transition patterns of $log(PAF)$ in each function



(a) Simulation result of case 1 (b) Simulation result of case 2 (c) Simulation result of case 3

Fig. 8. Abstracted transition patterns of $log(PAF)$ shown in Fig. 7: transition pattern of super function

the similar trend. This implies the effect of *Variability 3* enabled the instance to recover its own safety.

Therefore, those results can be concluded that the FRAM function: 5. CHECK BARCODE OR ITEM IDENTIFICATION NUMBER is capable of absorbing the effect of the variability, and it cannot be skipped in drug dispensing — even if in an upset situation.

4.4 Discussions

The result of this simulation provided us with an insight that feasibility of procedures could fluctuate in a specific context, depending on their design. Feasibility of procedures in a specific context is regarded as important especially when highly automated systems (e.g. autopilot of airplanes or auto driving of cars) are introduced. This is because automations could make original procedures rather complex and bring about confusion of operators in spite of their original purpose: reducing workloads and improving task performance of humans; this causes conflicts between humans and machines, which is referred to as dissonances in Vanderhaegen (2017), resulting in deviations from SOPs. Therefore, it is one of the most critical issues about the safety of Socio-Technical Systems to validate the feasibility of procedures in a specific context. Our approach is to investigate it based on Socio-Technical framework, and more specifically, ETTO principle, and the model can be effective for the validation or design of SOPs as a stress test tool of procedures carried out in a specific context.

5. CONCLUSION

FRAM is an effective way to understand about the safety of Socio-Technical Systems. However, it needs additional elaboration for its practical usage; the latest model was shown, and the safety of drug dispensing procedure in a specific context was examined in this paper. The result provided us with an insight that feasibility of procedures could vary in a specific context, depending on their design. This is one of the most essential issues to think of the safety of Socio-Technical Systems — especially the safety of automation, and our model could contribute to them.

REFERENCES

Hirose T, Sawaragi T, Horiguchi Y, Nakanishi H (2017) Safety Analysis for Resilient Complex Socio-Technical Systems with an Extended Functional Resonance Analysis Method. Int J Astronaut Aeronautical Eng 2:012.

Hollnagel, E. (1998). Cognitive Reliability and Error Analysis Method-CREAM. Oxford: Elsevier Science.

Hollnagel, E. (2004). Barriers and Accident Prevention, Aldershot, UK: Ashgate

Ung, S-T. (2015). A Weighted CREAM model for maritime human reliability analysis, Safety Science, 72, pp.144-152.

Vanderhaegen, F. (2017). Towards increased systems resilience: New challenges based on dissonance control for human reliability in Cyber-Physical&Human Systems. Annual Reviews in Control, 44, 316-322.