Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 55-29 (2022) 55–60

Functional Analysis of Law of Requisite Variety: Envisioning How Systems Variety Affects Their Resilience Based on FRAM

Takayuki Hirose, Hideki Nomoto, Yasutaka Michiura, Shota Iino *

* *IV&V Research Laboratory, Japan Manned Space Systems (JAMSS), 100-0004 Tokyo, Japan*
e-mail: {hirose.takayuki, nomoto.hideki, yasutaka.michiura, shota.iino}@jamss.co.jp

Abstract:
Resilience Engineering has been attracting its attention since its first introduction in 2006. It has widely been studied both in academic and industrial domains, and the interest is currently directed to relationships between resilience and variety in system controllers (i.e., action variety of systems), based on ideas of Law of Requisite Variety (LoRV) in Cybernetics. However, the relationship between Resilience Engineering and the LoRV is still so conceptual that it is difficult to verify the validity. The purpose of this study is to overcome the gap between the theory and practice. This paper firstly reviews the concept of Resilience Engineering and its relationships with the LoRV. This paper also provides an analysis of a case study by using Functional Resonance Analysis Method (FRAM); this case study is based on a previous research focusing on the variety in terms of actions by people — especially those who are called experts, having investigated the effect of such experts' action variety against variabilities of their surrounding working environment. The analysis result confirmed that the more the action variety increases, the more the experts can be resilient against the variabilities of working environment. Based on the result, this paper concludes with discussions of future prospects of Resilience Engineering.

Keywords: Resilience, Variety, Cybernetics, Envisioned World Problem, Functional Resonance Analysis Method (FRAM).

1. INTRODUCTION

Innovative technological developments and the complications of society have been making artifacts or systems more and more complex, leading to the creation of System of Systems (SoS) (Selberg and Austin, 2008). Specifically, SoS involving human, machine, organization, environmental factors are known as socio-technical systems. Those systems are said to be intractable in the sense that it is difficult to investigate their safety based on cause-effect relationships, and Resilience Engineering (Hollnagel et al., 2006), in this context, has been attracting its attention to ensure their safety.

The resilience was firstly defined as "the intrinsic ability of an organization (system) to maintain or regain a dynamically stable state which allows it to continue operations after a major mishap and/or in the presence of a continuous stress" (Hollnagel et al., 2006). This definition has been discussed and revised since the first introduction (Hollnagel, 2011, 2017; Hollnagel et al., 2021), and it is now regarded as "the ability to succeed under varying conditions, so that the number of intended and acceptable outcomes (in other words, everyday activities that go well) is as high as possible" (Hollnagel et al., 2021). In this context, one of the latest discussions of Resilience Engineering put a focus on how to achieve safety, quality, productivity, and reliability simultaneously (Hollnagel, 2020).

Specifically, Hollnagel (2020) addresses relationships between resilience and variety in system controllers, based on ideas of Cybernetics (Wiener, 1948) or Law of Requisite Variety (LoRV) (Ashby, 1956). The LoRV states that the variety of consequences produced by a system or process (i.e., uncertainties) can only be decreased by increasing the variety in their controllers. Hollnagel (2020) points out that the LoRV is an essential concept to cope with the growing complexity — or variety of socio-technical systems and enhance their resilience.

In terms of the safety/resilience of socio-technical systems, this point of view can actually play a significant role. One primary reason for this is that the operation of those systems often involves complex Standard Operational Procedures (SOPs) designed for sophisticated automations. Specifically, those complicated SOPs can conflict with an actual situation, and those discrepancies demand the operators to perform more "flexibly" to cope with the situation. Such flexibility could result in their deviation from the SOPs for various reasons (Degani and Wiener, 1994), and it is therefore important for the safety of socio-technical systems to investigate the feasibility of what is actually done by human operators in a specific context.

The purpose of this study is to investigate the intersection of the Resilience Engineering and LoRV with a case study. This paper firstly reviews the concept of resilience and its

10.1016/j.ifacol.2022.10.231

relationships with the variety in system controllers, based on ideas of the Law of Requisite Variety (LoRV) (Ashby, 1956). Then, this paper provides an analysis of a case study by using a simulation model based on Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012; Hirose and Sawaragi, 2019); the case study is a revalidation of a previous research (Kirlik, 1998), which investigated the effect of actions by expert-cooks at a restaurant against variabilities existing in their surrounding working environment. Based on the result, this paper concludes with discussions of future prospects of Resilience Engineering.

2. RESILIENCE AND SYSTEM VARIETY

Resilience Engineering was introduced by Hollnagel et al. (2006). The concept of resilience originates from the physics of material science, and then has been applied in other fields such as psychology or ecology. Specifically, Holling (1973) referred to resilience in ecosystem as "a systems' ability to absorb changes, identify next compatible states, and get into the states for their survival." Resilience Engineering adopted this idea and defined their resilience as "the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" (Hollnagel, 2011).

In this context, Hollnagel (2020) points out that essential entities for system operations or management of organizations, including safety, quality, productivity, and reliability, should not be considered independently but simultaneously; a fragmented view of those entities used to be effective when the structure/mechanism of artifacts, including machine, organization, or even society were tractable but is no longer the case with today's complex socio-technical system. It is therefore necessary to understand their dynamics functioning in specific environments involving variabilities and enhance those entities simultaneously rather than one-by-one. In this regard, Hollnagel (2020) suggests that the Law of Requisite Variety (LoRV) (Ashby, 1956) plays an important role to cope with the growing complexity, variety, or uncertainty of socio-technical systems.

The Law of Requisite Variety (LoRV) was presented by Ashby (1956) within the framework of Cybernetics (Wiener, 1948) and formulated as:

$$Min(V_O) = V_D - V_R, \tag{1}$$

where V_O, V_D, V_R represent variety of outcome, disturbance, and responses, respectively. The equation 1 indicates that variety of outcome: V_O can only be decreased by increases in variety of responses: V_R if variety of disturbance: V_D is given and fixed; the opposite approach, i.e., to decrease the variety of disturbance: V_D for the less variety of outcome: V_O is irrational since it requires thorough comprehension and constraints of the environment and target systems to be controlled; only variety of responses: V_R can force down the variety of disturbance: V_D, and in this sense, variety (V_R) can destroy variety (V_O), according to the LoRV. The only way to cope with the growing complexity, variety, or uncertainty of socio-technical systems is, therefore, to develop a model of how variety of V_R bring about positive outcomes; otherwise we will be caught in a vicious circle that has no solution to constrain the infinite variety: V_D (Hollnagel, 2020).

This perspective, i.e., the resilience and variety of actions could play a significant role in the safety of socio-technical systems. Operational procedures of those systems, for example, tend to be complicated due to the introduction of highly sophisticated automations, and it sometimes demands human operators to engage in their tasks in more "effective ways" in a specific context. Their flexibility subsequently results in the deviation from original procedures (Degani and Wiener, 1994) and brings about various consequences. Here, it should be noted that such consequences could include not only negative cases such as accidents but also positive cases or effective operations. One of the most extreme and well-known cases of such positive consequences, for instance, is a successful ditching of an airplane known as the "Miracle on the Hudson," in which the captain skipped several items of the "Engine Dual Failure checklist" and started the Auxiliary Power Unit (APU) early in the accident sequence. The report (NTSB, 2010) concluded that this operation was critical and improved the outcome of the ditching by ensuring the electrical power of the airplane. As suggested in those examples, the safety of socio-techncial systems highly depends on what is actually done by human operators in a specific context, and their feasibility, including the validity of action variety, should therefore be investigated carefully.

The following section will go on to investigate the intersection of the Resilience Engineering and LoRV with a simple but insightful example. The example is an observation of short-order cooks at a restaurant conducted by Kirlik (1998), in which skills of expert cooks, performed in ever-changing environment, were investigated. His observation firstly found that the cooks were responsible for preparing a large number of food orders simultaneously, where task demands were uncertain and arriving dynamically. The observation also found that there were clear differences of strategies to manage cooking steaks on the grill, depending on their level of skills; the more expert they are, the more physical actions were observed and vice versa, as shown in the following sections. He also estimated the varieties shown in Eq. 1 as information entropy (Shannon, 1948) and discussed the result based on the LoRV as well; the result confirmed that the strategy of expert cooks can decrease the V_O by increasing the V_R in Eq. 1. To this end, his research provided an insight that the variety of actions can contribute to the performance of experts in ever-changing environment, and it is quantitatively supported by the LoRV as well; his research can be regarded as a basic approach bridging the Resilience Engineering and LoRV.

The aim of case study in the following section is to revalidate this example from the perspective of Resilience Engineering. Specifically, the validity of such results is generally confirmed only in hindsight after such experiments or observations are actually conducted. This could limit the scope of investigation with ad-hoc insights, as suggested by the *Envisioned World Problem* (Woods and Dekker, 2000), and one possible solution to overcome this problem is to 1) develop a model of such human activities, 2) validate the model behavior in simulated ever-changing environment, and 3) derive systematic knowledge/insights. In this context, a simulation model based on Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012; Hirose and Sawaragi, 2019) can be applied for the validation.

3. METHODOLOGY

3.1 Functional Resonance Analysis Method: General

Functional Resonance Analysis Method (FRAM) is a method to investigate the behavior of socio-technical systems, based on characteristic functional representation of the systems. Each of function in FRAM is defined with six aspects listed in Table 1 and visually represented as hexagons each of whose vertex corresponds to the six aspects. Those aspects enable us to describe complex dependencies among functions in detail, and a target socio-technical system is consequently represented as a network of hexagonal-shaped functions; an example is shown in Fig. 1, illustrating a functional representation of drug dispensing procedure provided by Hollnagel (2004).

Table 1. Six aspects of FRAM function

Aspect	Description
Input	Input/Trigger of a function
Output	Outcome of a function
Precondition	Conditions that must be satisfied before a function is carried out
Resource	Something consumed or required by a function (e.g. fuel, energy, labor force)
Control	Something supervising or regulating a function
Time	Time/Temporal conditions for a function

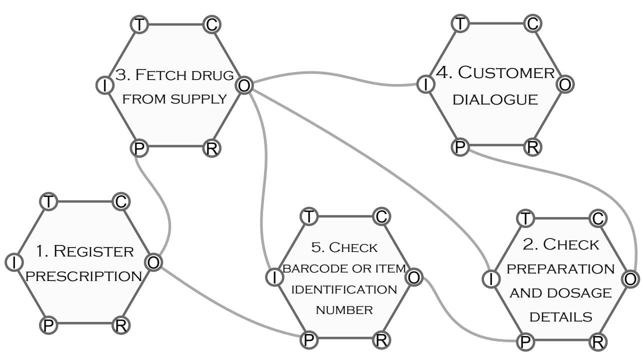


Fig. 1. Example: FRAM representation of drug dispensing procedure (Hollnagel, 2004).

The functional representation based on FRAM provides insights about how a target system actually works rather than what it generally is. Specifically, FRAM explicitly puts focuses on the interaction of variabilities existing in the functions and their surrounding environment as shown in Fig. 2. The variabilities are generally caused by temporal conditions such as availability of resources or social demands, and all of the variabilities interact with each other. Their interaction eventually could result in unexpected outcomes in a specific context, as if they were resonated, and FRAM refers to such effect as the "Functional Resonance." FRAM is, in other words, a method to investigate how a target system actually works in the framework shown in Fig. 2.

3.2 Simulation Model of FRAM

FRAM is a *method-sine-model*, rather than *model-cum-method*, according to (Hollnagel, 2012). This means that the purpose of FRAM is to develop a model of how a target system actually works, and its detailed process should be implemented, depending on the case. In this context, Hirose and Sawaragi (2019) has developed a simulation model of FRAM whose architecture is consistent with the concept shown in Fig. 2. The feature of their model is that the variabilities of socio-technical systems are defined based on Fuzzy CREAM — an extended model of Cognitive Reliability and Error Analysis Method (CREAM) (Hollnagel, 1998), and their interactions among those variabilities are formulated as well.

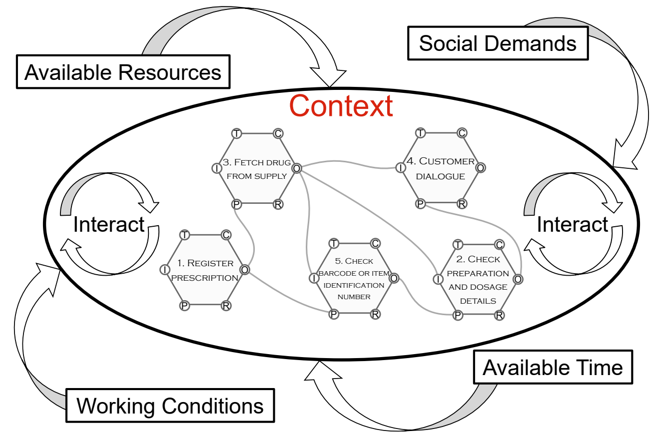


Fig. 2. Schematic illustration of FRAM model.

According to CREAM, the surrounding factors creating the context described in Fig. 2 can collectively be defined as eleven Common Performance Conditions (CPCs) listed in Table 2. They are evaluated with linguistic values such as "Available resource is enough" or "Number of simultaneous goals are too much." Based on the evaluation, another index called "control mode" is identified, representing how human actions are chosen and executed according to their surrounding environment. The control mode is associated with four levels: Strategic, Tactical, Opportunistic, and Scrambled; the situation gets better as it gets toward Strategic, and vice versa.

Table 2. List of CPCs (Hollnagel, 1998, 2004).

ID No.	CPC
1	Available resources
2	Adequacy of training and experience
3	Quality of communication
4	Adequacy of Human-Machine Interface (HMI)
5	Availability of procedures
6	Working conditions
7	Number of simultaneous goals
8	Available time
9	Circadian rhythm
10	Crew collaboration quality
11	Adequacy of organization

Fuzzy CREAM incorporates quantitative and continuous aspects to original CREAM methodology. In Fuzzy CREAM, membership functions of the linguistic CPC states are associated with continuous scores ranging from 0 to 100, and the fuzzy reasoning based on their evaluations provides a control mode as a crisp value called Probability of Action Failure (PAF); the higher CPC scores represents the better state of each CPC, and the the situation gets better as the PAF gets smaller.

Among the proposed Fuzzy CREAM methodologies, Hirose and Sawaragi (2019) adopted "*weighted CREAM model*" (Ung, 2015) and implemented the simulation model of FRAM. The simulation model assumes that a state in each function can be described in terms of the control mode, and the state can change according to the state of their surrounding environment created by CPCs and their weight; the variabilities in each function and the surrounding environment are therefore defined as the change of their continuous control mode (crisp value of PAF) and CPC scores, respectively. The numerical definitions of the variabilities then enable us to formulate the interaction of variabilities, and the simulation model eventually repeats a set of the following processes: 1) variabilities of CPC scores induce that of control mode in each function based on Fuzzy CREAM; 2) the variabilities of functions propagate to their downstream functions and interact with each other according to one of the formulations; 3) the effect of interaction is looped back and changes the scores of surrounding CPCs again according to another formulation. In the end, the change of control mode in each function with respect to the simulation time: $T[-]$ can be obtained as a result of the simulation.

3.3 Application of FRAM simulation

The simulation model of FRAM has been applied to the safety analysis of autonomous driving system as well; Hirose et al. (2020) investigated how the takeover request (TOR) from the autonomous driving system to human drivers can be established in ever-changing environment and found that cognitive functions of human drivers must be maintained even when the autonomous driving system is responsible for the driving; otherwise the TOR could fail in time-critical situations.

In this case, the result of FRAM simulation suggested that the variety of functions required for driving plays an important role in order to cope with variabilities existing in ever-changing surrounding environment. If there are similar dynamics in cooks' strategies observed by Kirlik (1998), the validity of the strategies can also be confirmed with the FRAM simulation; the following case study addresses the issue.

4. FUNCTIONAL ANALYSIS OF LAW OF REQUISITE VARIETY WITH FRAM SIMULATION

4.1 Target of Simulation

The target of this simulation is short-order cooks' strategies confirmed in the observation by Kirlik (1998). According to him, there were three types of strategies observed as shown in the following and Fig. 3:

Strategy 1: Brute Force Strategy
This strategy is to put steaks on the grill in apparently random locations as shown in Fig. 3(a) and try to remember how each steak should be cooked.

Strategy 2: Position Control Strategy
This strategy is to place steaks in an area of the grill associated with how well each steak should be cooked as shown in Fig. 3(b); the cooks can manage the progress by using the location information.

Strategy 3: Position + Velocity Control Strategy
This strategy is not only to decide the areas of steaks on the grill, just like the *Strategy 2* above, but also their initial position is controlled, depending on their goal state: well-done at the far-right side of the grill; medium at the center of the grill; rare toward the left side of the grill. As the time goes on, all steaks are continually slided towards the left side of the grill at an approximately fixed velocity, flipped at the midpoint of their journey across the grill, and picked up at the left edge of the grill as shown in Fig. 3(c).

The *Strategy 3* seems to be the most effective even though it requires physical tasks the most. The additional physical tasks enable the cooks to flexibly modify related parameters such as frequency of the sliding, and the flexibility leads to the variety of actions. The *Strategy 3* was actually employed by the expert cooks, and Kirlik (1998) mathematically showed its validity. The result of his investigation is found to be consistent with the idea of LoRV; this case study is to validate this through the FRAM simulation.

4.2 Simulation Setup

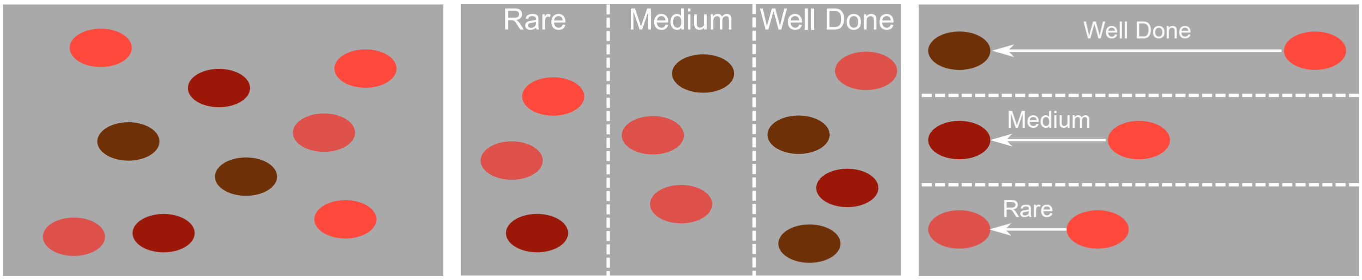
The first step of the FRAM simulation is to represent the *Strategy 1*, *2*, and *3* with FRAM as shown in Fig. 4. Figure 4(a) shows the FRAM representation of the *Strategy 1*. It consists of the basic procedures in a restaurant kitchen as described in the name of FRAM functions, and they are connected through the six aspects of functions; the connections consequently represents, for instance, a loop structure between the two functions: 5. To grill and 6. To check condition of steak, under the time constraints by 7. To manage time to grill. Based on the function network in Fig. 4(a), the FRAM representation of *Strategy 2* and *3* can also be derived as shown in Fig. 4(b) and 4(c); the area distribution in the *Strategy 2* is represented as the red lines providing in Fig. 4(b), and the periodic slides of steaks in the *Strategy 3* are represented as the additional red entities in Fig. 4(c), in addition to the functional structure in Fig. 4(b).

For all of the functions, CPC weight for the obtained functions are then required to be set. The CPC weight is a relative value among a set of CPCs, inherent to a function, and a set of CPC weight values represent sensitivity of a function against those CPCs. They are often evaluated with a methodology of paired comparison process (Saaty, 1990), and the result is shown in Table 3.

Table 3. CPC weight in each function

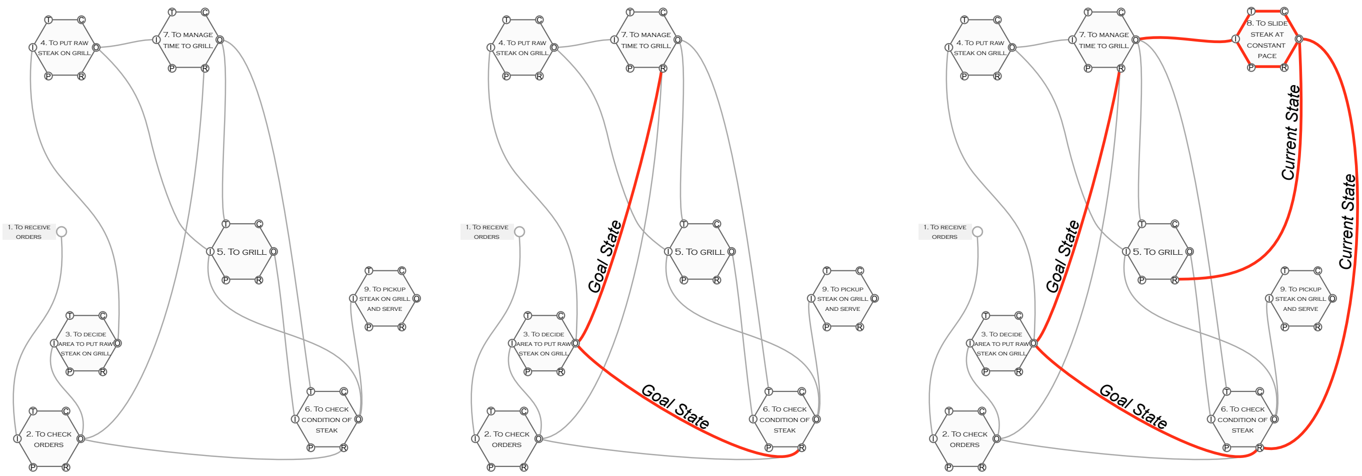
CPC ID in Table 2	Corresponding number of functions shown in Fig. 4								
	1	2	3	4	5	6	7	8	9
1	0.11	0.15	0.27	0.15	0.13	0.12	0.15	0.15	0.16
2	0.044	0.064	0.082	0.039	0.12	0.17	0.062	0.046	0.091
3	0.11	0.085	0.044	0.07	0.064	0.027	0.029	0.022	0.055
4	0.027	0.029	0.022	0.019	0.022	0.04	0.063	0.052	0.023
5	0.023	0.027	0.023	0.021	0.034	0.026	0.018	0.032	0.027
6	0.15	0.14	0.13	0.19	0.10	0.13	0.14	0.14	0.16
7	0.17	0.20	0.18	0.19	0.21	0.20	0.21	0.26	0.18
8	0.17	0.20	0.17	0.23	0.22	0.21	0.24	0.23	0.18
9	0.02	0.013	0.012	0.013	0.017	0.022	0.029	0.034	0.021
10	0.15	0.072	0.047	0.062	0.051	0.029	0.047	0.028	0.085
11	0.021	0.029	0.018	0.016	0.019	0.02	0.016	0.019	0.02

On the basis of the simulation setup, a simulation scenario was prepared as follows:



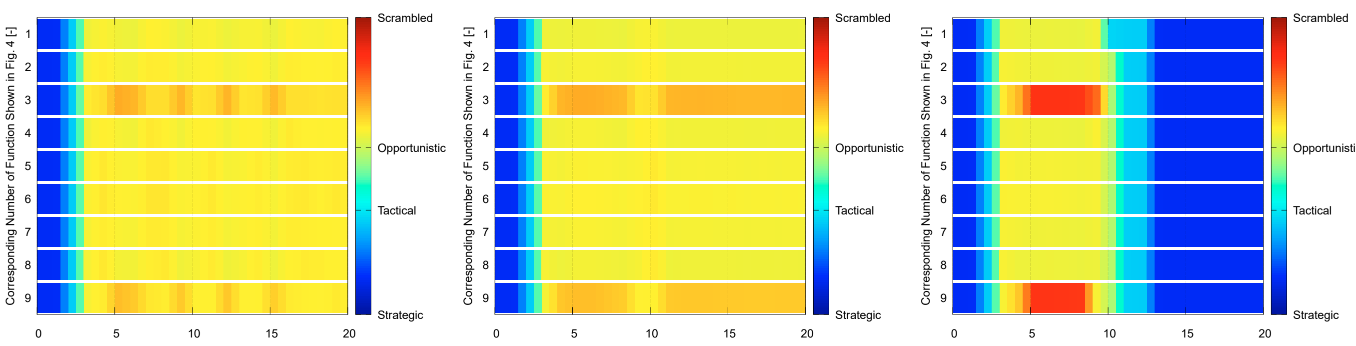
(a) *Brute Force Strategy.* (b) *Position Control Strategy.* (c) *Position + Velocity Control Strategy.*

Fig. 3. Schematic illustration of strategies confirmed in observation by Kirlik (1998).



(a) *Brute Force Strategy.* (b) *Position Control Strategy.* (c) *Position + Velocity Control Strategy.*

Fig. 4. FRAM representation of each strategy shown in Fig. 3.



(a) *Brute Force Strategy.* (b) *Position Control Strategy.* (c) *Position + Velocity Control Strategy.*

Fig. 5. Simulation result: behavior of functions in each strategy against variability in working environment.

<u>Scenario</u>*: one day, cooks at a restaurant were doing their daily work as usual, and everything was going well. They after a while became very busy due to the rush-hour of the restaurant and had to work on multiple tasks simultaneously in parallel. In this context, the cooks were coping with the rush, based on their strategies shown in Fig .3.*

This scenario can be described within the framework shown in Fig. 2, just by setting the CPC scores as follows: the initial state where "*every thing was going well*" can be simulated by setting all CPC scores to 100; its following situation in which "*They after a while became very busy*" can also be simulated by setting the score of CPC: "Number of simultaneous goals" to 0 at simulation time: $T = 0$. These manipulation of parameters will, so to say, "shake" the functions in Fig. 4 and simulate how the different strategies, or functional structures respond to the variability caused by CPCs. The result is shown in Fig. 5

4.3 Simulation Result

Figure 5 illustrates transition of the control mode in each function as heatmaps; the lateral axis shows simulation time: $T[-]$, and the vertical axis corresponds to the ID number of functions shown in Fig. 4. Based on this configuration, each of function becomes blue as it gets toward the strategic — low risk control mode, and vice versa; the result of FRAM simulation is now represented as color gradation pattern of each function.

The effect of the different three strategies is obvious in Fig. 5. According to Fig. 5(a) and 5(b), the control mode in each function remained yellow or orange state: the opportunistic or scrambled — mid/high risk control mode, after the variability of CPC: “Number of simultaneous goals” was caused at the simulation time: $T = 0$; it should also be noted that these unstable patterns continued semi-permanently, confirmed by additional simulations. On the other hand, Fig. 5(c) shows that the control mode in each function can recover from the effect of variability caused at the simulation time: $T = 0$ even though the two functions (i.e., the corresponding function No. 3 & 9) temporally reached the vivid red state: the scrambled — highest risk control mode.

The result suggests that the *Strategy 3* is capable of overcoming the effect of variability, but, it is not the case with *Strategy 1* and *2*. Moreover, the *Strategy 3* involves more action variety than in the case of *Strategy 1* and *2*, and exhibited more resilient behavior in this simulation; this finding is consistent with Kirlik (1998), Ashby (1956), and Hollnagel (2020) as well. Consequently, their insights are now validated also by the FRAM simulation.

4.4 Discussions

The obtained result confirmed that the increase in variety of action, or more specifically, variety in system controllers can enhance the resilience against the variability of ever-changing environment. This supports an idea of Hollnagel (2020) that it is more effective to increase the system variety such as human activities rather than trying to constrain systems including human, organizations, or environment, by imposing, for example, excessive rules, restrictions, or controls to them. Therefore, this perspective is essential for Resilience Engineering.

This might conflict our intuition at first glance since such variety of human or system behavior is generally regarded as a source of instability or errors which could bring about negative rather than positive outcomes; the validity can only be confirmed through practical experiments or observations, and those attempts often result in limited scope of insights with great costs as suggested in the *Envisioned World Problem* (Woods and Dekker, 2000). However, the FRAM simulation indicated a possibility to address the issues without relying on hindsight. Under the growing complexity of socio-technical systems, it shall be more essential to investigate the validity of what is actually done by human operators in a specific context, and the approach presented throughout this paper can be a possible solution to overcome the problem.

5. CONCLUSION

This paper was to investigate and validate the relationships between the resilience and Law of Requisite Variety (LoRV). To address the issue, we carried out a simulation based on FRAM, further investigating the validity of cooks’ strategies confirmed by Kirlik (1998). The result of FRAM simulation showed that the increase in action variety of the cooks can enhance the resilience against the variability of ever-changing environment. The result also suggested that the analysis provided in this paper can contribute to further development of Resilience Engineering.

REFERENCES

Ashby, W.R. (1956). *An Introduction to Cybernetics*. Chapman & Hall Ltd.

Degani, A. and Wiener, E.L. (1994). On the Design of Flight-Deck Procedures. Nasa contractor report, NASA Ames Research Center.

Hirose, T. and Sawaragi, T. (2019). Development of FRAM Model Based on Structure of Complex Adaptive Systems to Visualize Safety of Socio-Technical Systems. *IFAC-PapersOnLine*, 52(19), 13–18.

Hirose, T., Sawaragi, T., Nomoto, H., and Michiura, Y. (2020). Functional safety analysis of SAE conditional driving automation in time-critical situations and proposals for its feasibility. *Cognition, Technology & Work*, 1–19.

Holling, C.S. (1973). RESILIENCE AND STABILITY OF ECOLOGICAL SYSTEMS. *Annual review of ecology and systematics*, 4(1), 1–23.

Hollnagel, E. (1998). *Cognitive reliability and error analysis method (CREAM)*. Elsevier.

Hollnagel, E. (2004). *Barriers and Accident Prevention*. Ashgate Publishing Ltd.

Hollnagel, E. (2011). *Resilience engineering in practice: A guidebook*. Ashgate Publishing, Ltd.

Hollnagel, E. (2012). *FRAM: The Functional Resonance Analysis Method: Modelling Complex Socio-technical Systems*. Ashgate Publishing Ltd.

Hollnagel, E. (2017). *SAFETY-II IN PRACTICE: DEVELOPING THE RESILIENCE POTENTIALS*. Taylor & Francis.

Hollnagel, E. (2020). *Synesis: The Unification of Productivity, Quality, Safety and Reliability*. Routledge.

Hollnagel, E., Leonhardt, J., and Licu, T. (2021). The Systemic Potentials Management: Building a Basis for Resilient Performance. Technical report, European Organization for the Safety of Air Navigation(EUROCONTROL).

Hollnagel, E., Woods, D.D., and Leveson, N. (2006). *Resilience Engineering: Concepts and Precepts*. CRC Press.

Kirlik, A. (1998). The ecological expert: Acting to create information to guide action. In *Proceedings Fourth Annual Symposium on Human Interaction with Complex Systems*, 15–27. IEEE.

NTSB (2010). Loss of Thrust in Both Engines After Encountering a Flock of Birds and Subsequent Ditching on the Hudson River US Airways Flight 1549 Airbus A320-214, N106US Weehawken, New Jersey January 15, 2009. Accident Report AAR-10/03, National Transportation Safety Board.

Saaty, T.L. (1990). How to make a decision: the analytic hierarchy process. *European journal of operational research*, 48(1), 9–26.

Selberg, S.A. and Austin, M.A. (2008). Toward an Evolutionary System of Systems Architecture. In *INCOSE International Symposium*, volume 18, 1065–1078. Wiley Online Library.

Shannon, C.E. (1948). A Mathematical Theory of Communication. *The Bell system technical journal*, 27(3), 379–423.

Ung, S.T. (2015). A weighted CREAM model for maritime human reliability analysis. *Safety Science*, 72, 144–152.

Wiener, N. (1948). *Cybernetics: or Control and Communication in the Animal and the Machine*. Cambridge.

Woods, D.D. and Dekker, S. (2000). Anticipating the effects of technological change: a new era of dynamics for human factors. *Theoretical issues in ergonomics science*, 1(3), 272–282.