A Quantitative Assessment of Organizational Factors Affecting Safety using a System Dynamics Model

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Abstract

The purpose of this study is to develop a system dynamics model for the assessment of the organizational and human factors in a nuclear power plant which contribute to nuclear safety. Previous studies can be classified into two major approaches. One is the engineering approach using tools such as ergonomics and Probability Safety Assessment (PSA). The other is the socio-psychology approach. Both have contributed to find organizational and human factors and to present guidelines to lessen human error in plants. However, since these approaches assume that the relationship among factors is independent they do not explain the interactions among the factors or variables in Nuclear Power Plants. To overcome these restrictions, a system dynamics model, which can show cause and effect relationships among factors and quantify the organizational and human factors, has been developed. Handling variables such as the degree of leadership, the number of employees, and workload in each department, users can simulate various situations in nuclear power plant organization. Through simulation, users can get insights to improve safety in plants and to find managerial tools in both organizational and human factors.

Introduction

While managing Nuclear Power Plants (NPP), it is important to supply power with stability and to continuously keep the highest standards of safety. In order to secure NPP safety, massive investment in R&D (research and development) and equipment has been made for several decades. However, interest in management issues has been relatively neglected. Recently, the IAEA & OECD/NEA have stressed organizational culture, and examine organizational factors that may affect the NPP safety. It is well recognized that considerable accidents or incidents in NPP have been caused by human error. Therefore, models in which human error is quantified have been developed in order to develop strategies to reduce human error and to assess the effects of human factors on plant hardware safety.

Despite these endeavors, there are many restrictions to systemically assess NPP safety, especially in organizational terms. Assessment of safety of NPP hardware is critical. However, considering that NPP safety can be guaranteed not only by technology and hardware, but also by the people who manage it, we need to expand our view of safety to include human resources and managerial organization, not only hardwar[1]e. The purpose of this study is to develop a system dynamics model to assess NPP safety from an organizational perspective by modeling general NPP organization including operations, maintenance, and engineering. The model can give plant managers much insight to develop management strategies to reduce human error and finally to improve NPP safety. To develop a system dynamics model of general NPP organization and to find factors or variables which can affect safety, we conducted interviews with employees and managers and conducted a survey. After understanding the workflow, information path and function of each department in a NPP, we drew a causal loop and a stock and flow diagram which can quantify safety along with the typical steps of the system dynamics model.

Previous research related to human and organization factors in NPP have been mainly conducted in two ways[2]. The engineering approach based on ergonomics and probability contributes to quantify human and organizational factors and to present a logical process of events or accidents. Since this approach researches the level of the individual, there are difficulties in understanding relationships between organization factors and human ones. For example, this approach cannot adequately explain and consider how organizational factors such as human resource management policies such as pay, job security and promotion affect human performance. Especially in the case of the probability method, there are some criticisms that 1) it is static, 2) it breaks down events into success and failure, and 3) it has an assumption of independence among the variables.

The other is the socio-psychological approach. It has been mainly practiced by organizational theorists or psychologists. It has been interested in motivation or the organizational structure's effect on human or organizational performance. The approach has included both the level of the individual and the organization. Since a socio-psychological approach usually utilizes an index evaluation method using a checklist or verifies the significance using statistical methods among selected variables, a socio-psychological approach also has restrictions such as difficulty in operational definition and the assumption of independence among items in a checklist survey. The proposed model in this study can compensate for the restrictions or limitations as stated above. We tried to connect the relationship among hardware, individuals and the organization. The Model can demonstrate how management policies affect

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individual performance such as productivity, quality of work, and most importantly NPP safety[3,4].

Modeling Organizational Factors

Causal Loop Diagram

In order to develop a model, we tried to grasp the structures and functions of plant organization. Most NPPs are commonly composed of major four departments: operations, maintenance, coordination, and engineering. The connection and cooperatio n of each department's functions can make it possible for a plant to eliminate defects which are directly related to safety. First interviews, surveys and observations are conducted in order to select the major factors and to draw an initial causal loop diagram. Figure 1. is a high-level causal loop diagram of plant safety.

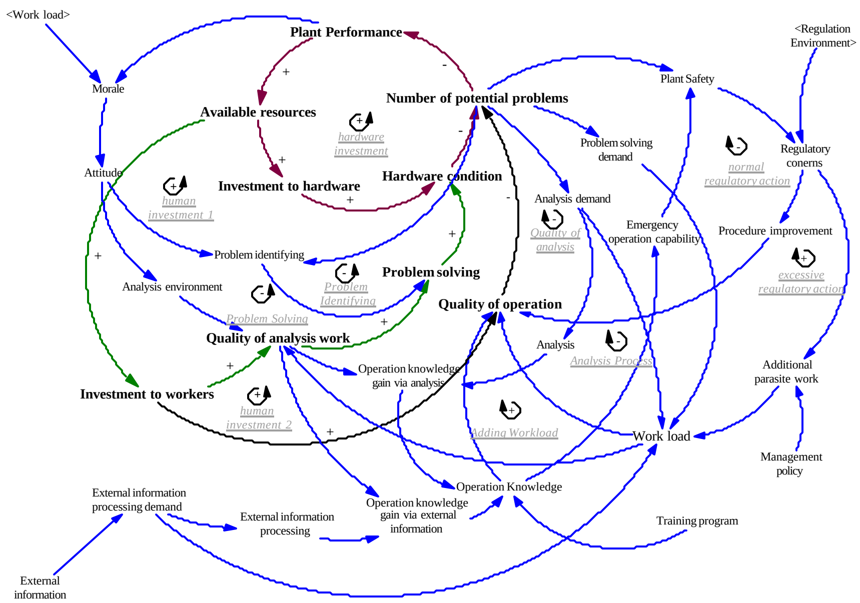

Figure 1. High-Level Causal Loop Diagram

If hardware conditions and the quality of work is high, it may mean that the plant has minimal problems and keeps a high level of safety. When generation capacity or plant performance is sustained, a plant can be profitable. Profits are reinvested in hardware such as equipment improvement, procurement of parts and technical importing. It can then enable a plant to maintain good hardware conditions <hardware investment loop> as shown in Figure 1. Profits or available resources can also be thought of as reinvested human resources. Investment in human resources can improve the quality of work by giving staff chances to get education and training. Although investment in hardware can eliminate defects in old equipment or parts by replacing them, in the end, it is the individual employee who discovers defects, identifies them, and repairs them <human investment loop 1,2>. This fact means that human resources at NPP are also a key factor to maintain safety standards. If NPP safety is low, regulatory concerns will increase. Regulatory concerns positively aid to improve procedures and the quality of operation by offering information and skills which NPPs do not maintain <normal regulatory action loop>. However, the more regulatory concerns produced, the more additional parasite work to satisfy regulatory requirements. Since regulatory concerns may make an increase in total workload for staff to deal with, it can negatively affect the quality of operation. Excessive regulatory concerns may bring about increasing workload <excessive regulatory action loop>.

The operator's training is an important factor to sustain safety or to improve it. Operators can gain knowledge through either the inside or outside path. Inside learning is an activity to analyze problems which happen in the node of <analysis process loop> in Figure 1. The more potential problems there are the greater the need for analysis. Analysis demand affects safety in two directions. One is a positive effect for operators to gain knowledge, and the other is a negative one to increase workload. Workload over optimum quantity can lower the quality of analysis work, <quality of analysis loop>. Both knowledge and workload usually affect the quality of workers. While additional knowledge can improve the quality of operation, an excessive workload can decrease the quality of operation, <adding workload loop>. On the other hand, outside learning can also help staff accumulate knowledge related to their work. Accumulated knowledge inside or outside the plant can contribute to improvement of an emergency operation capability which is the most important factor in emergency cases. Employees seek to discover problems, analyze them and solve problems with adequate procedures and methods. As employees discover more problems, there is a greater workload and greater demand for problem solving <problem solving loop & problem identifying loop>. Finally, the operator's total added workload associated with external information processing demand, additional parasite work and analysis demand must be reconciled in limited time. The amount of allocated time for analyzing problems plays a role in determining the quality of the operator, <analysis process loop>.

Stock and Flow Diagram

After the CLD was developed, a Stock and Flow Diagram (SFD) was added to quantify the model. That is, the task of each department and the attributes of human and organizational behavior were quantified in the SFD. Since the tasks of each department are different, tasks are categorized as presented in <Table 1>. In the model, plant levels are broken into three groups: top managers, middle managers, and employees. Moreover, as the task of each department is different, it needs to be classified into several subcategories presented in the model as a type of subscipt variable in Vensim.

Table 1. Types of Task

Level of Hierarchy		Types of Task
Top managers		Unexpected work, Planning, Administration, Supervision
Middle managers	Operation	Unexpected work, Planning, Administration, Supervision
	Engineering	Unexpected work, Planning, Administration, Supervision
	Maintenance	Unexpected work, Planning, Administration, Supervision
	Coordination	Unexpected work, Planning, Administration, Supervision
Employees	Operation	Normal operation, Emergency Operation, Procedures improvement, Maintenance test, Preventive maintenance test
	Engineering	Unexpected work, Maintenance Engineering, Regulation engineering, Information process, plant improvement
	Maintenance	Repair Maintenance, Preventive Maintenance, Repair Maintenance Administration, Emergency Maintenance, Preventive Maintenance Administration
	Coordination	Unexpected work, Regulation, Planning, Information

Since human performance results from various attributes are commonly coupled with each other, more specific factors were added to the SFD[5-7]. Table 2 shows the factors list affecting attributes such as organizational culture, staff capacity, plant condition, and workload. The Stock and Flow Diagram (SFD) can make it relatively easier to quantify the relations among attributes or factors than the causal loop diagram. As seen in Figure 2, attributes of the plant are composed of various factors which can change the status of other factors. Not only hard data such as the number of staff is reflected in the model, but also soft data such as the lookup function of stress and performance. While hard data can be gotten easily from documents, soft data obtained through interviews with employees, surveys and other research.

Table 2. List of Factors affecting attributes of each level and department

Level of Hierarchy	Attributes			
	Organizational Culture	Staff's Capacity	Plant Condition	Workload
Top Managers	Attitude Leadership Morale	Productivity Quality of work Skill level	Number of Defects Defect generation rate	Spent time to dealt with work Administration

Middle Managers (MM) (Operation,Engineering Maintenance Coordination)	Attitude Supervision Time allocation Number of MM Education Etc.	Spent Time to dispose of task	Parts Etc.	task Maintenance task Etc.
Employees (Operation Engineering Maintenance Coordination)	Attitude Workload Supervision Support from other departments Number of staff Education Etc.			

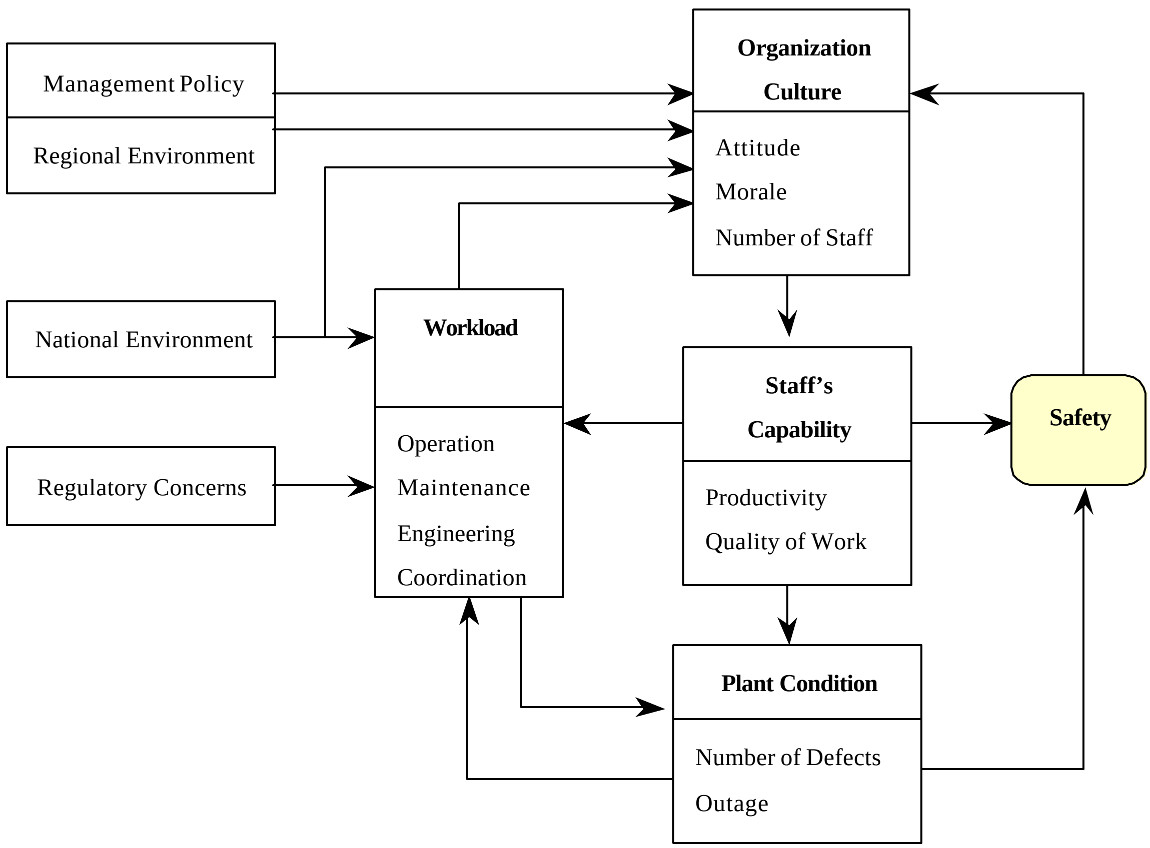

Figure 2. Overview of the relationship among attributes

Plant safety is affected by a staff's capability and plant condition. Safety affects organizational culture which is composed of attitude, morale, and the number of staff. Organizational Culture repeatedly impacts on staff capability. Besides these attributes, management policy, the regional or national environment, and the regulatory concerns can affect organizational culture and workload. However, in this model such an attribute is dealt with as external variables. SFD concerning hardware condition is shown in Figure 3. Since it is impossible for staff to discover all defects, defects can be classified into 1) identified defects and 2) unidentified defects. Defect discovery is also made by human activities through two paths. One is Preventive Maintenance (PM), and the other is unexpected discovery. Whatever the discovery path is, once defects are identified, maintenance staff tries to repair them with support from other departments. Since total defects impact on NPP safety, the quick discovery and elimination of defects is key to ensure safety.

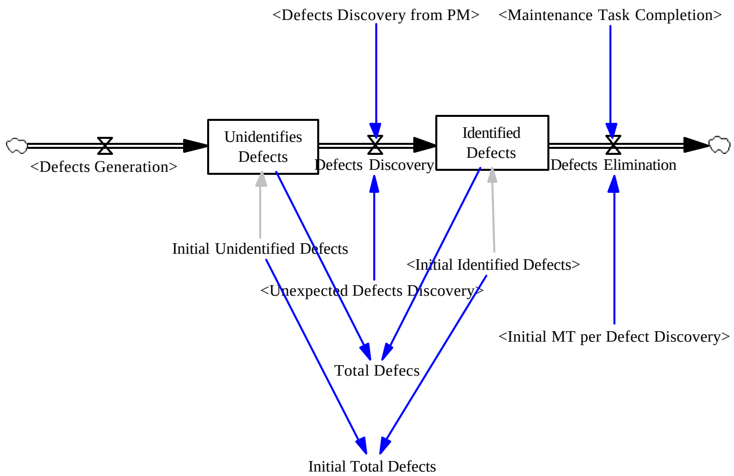

Figure 3. SFD of Defects Sector

Simulation and Results

The CDF (Core Damage Frequency) concept was borrowed from PSA (Probabilistic Safety Assessment) for a clearer definition of safety. In PSA, paths to core damage are logically modeled with the event tree method. Using a PSA model, the CDF is calculated. CDF is computed by the MCS (Minimum CutSet) which is defined as the set with the highest frequency of the core damage event and composed of several basic events. The basic event, which may result in core damage, can be broadly categorized into hardware failures and human errors. Since MCS and basic events contian a massive amount of data, external functions were developed to run the model more efficiently. External functions were defined to multiply the frequency of basic events related to human error by the quality of work and the frequency of basic events related to hardware failure by normalized total defects. The value calculated by the external function is returned to the system dynamics model. Figure 4 depicts the structure of the macro model to calculate safety with external functions. In this model, safety is calculated in the form of a relative fraction of the CDF, which was normalized by operating the original CDF Value. What the relative fraction of the CDF is high means that safety is low. The higher the relative fraction of the CDF, the lower the level of safety.

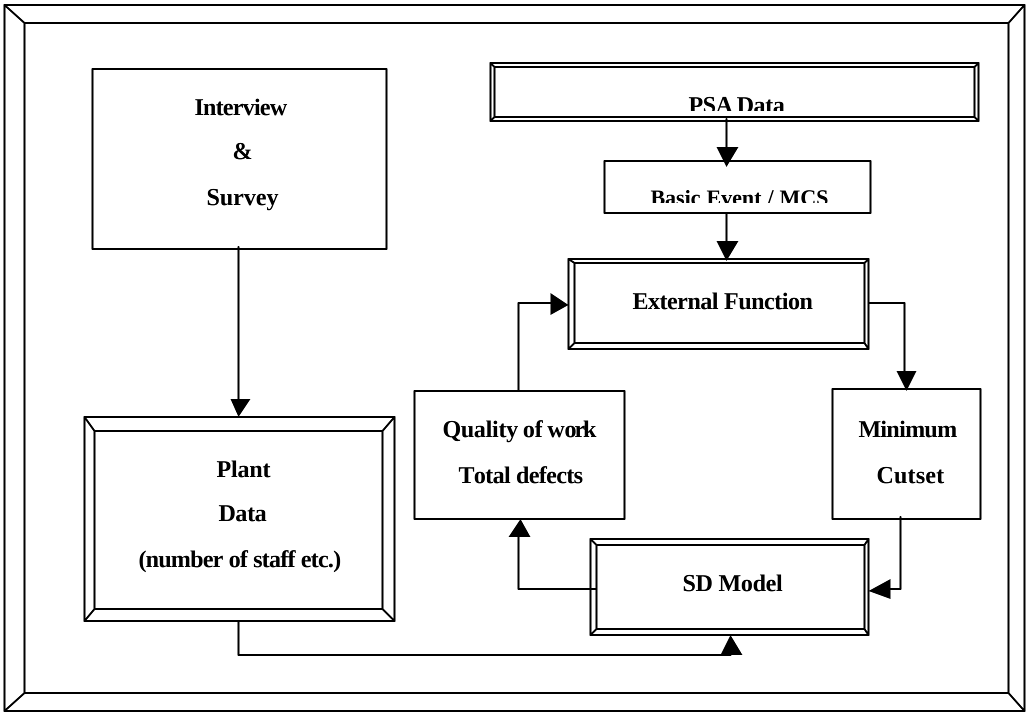

Figure 4. Structure of the macro model

Simulation

Various case studies or sensitivity studies, such as examining the changes in the degree of leadership and the adjustment of the number of employees can be practiced using the model. First of all, the following case studies of both 1) education and training effects and 2) hiring and layoff effects were carried out to comprehend the effects on safety: Before showing simulation results, the simulation conditions of each case study are described in <Table3>.

Table 3. Conditions of Case Studies

Case Study	Data set	Description
Case 1 : Education effects	Routine	Normal Status
	High Edu	Degree of Edu. & Training : +20% of the normal status
	Low Edu	Degree of Edu. & Training : - 20% of the normal status
Case 2 : Layoff effects	Routine	Normal Status
	Pro 20	Hiring : + 20% of normal status at time 120 day

Layoffs 20	Layoff : - 20% of normal status at time 120 day
Time Unit	1800 Days (about 5 years)
Time step	0.25 day

Generally, a site has two plants. In this model, a site with two power plants was also applied. Since each plant has one preventive maintenance time about once per year, a site with two plants is overhauled twice a year. During the overhaul period the plant is usually shut down to refuel and replace old equipment. Therefore, workload per staff usually increases during overhaul periods. Because of the two overhauls, safety levels change periodically. The safety level of the routine dataset showing normal status without any change of variables is presented in <Figure 5>.

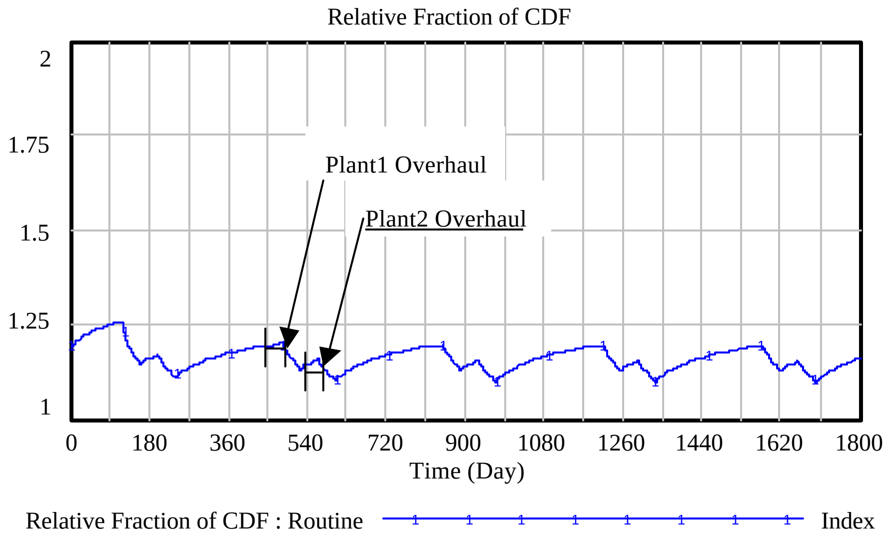

Figure 5. Simulation in Normal Status

First, education and training effects on safety are simulated. Although the degree of education or training is increased, safety is rarely affected. That is, a high degree of education does not ensure a high degree of safety (line 2 : High Edu). On the other hand, a low degree of training can decrease safety (line 3 : Low Edu). Figure 6 shows that a low degree of education or training may result in low performance for an overhaul period, while there is little difference between a low degree of education and a higher one in the normal period. This reveals that managers may not decrease the level of education or training programs even if these seem to be of no significant effect. The effects of hiring and layoffs are also shown in <Figure 7>. Hiring staff does not necessarily ensure the improvement of safety. Even if plants hire new employees, they might not have the skills required to operate or maintain a plant. Time is needed for them to obtain skills. Even if they obtain new skills and accumulate knowledge, the effect on safety is not high (line 2: pro20). If a plant lays staff off, gradually, it impacts on safety. For a period after the laying off of staff, there is little difference between normal status and layoff status. However, as time goes by, safety becomes worse. It may not return to normal status. While layoffs have little effect on safety during normal times, during overhaul time, it has a greater effect on safety by reducing staff capabilities such as productivity and quality of work resulting from the increased workloads.

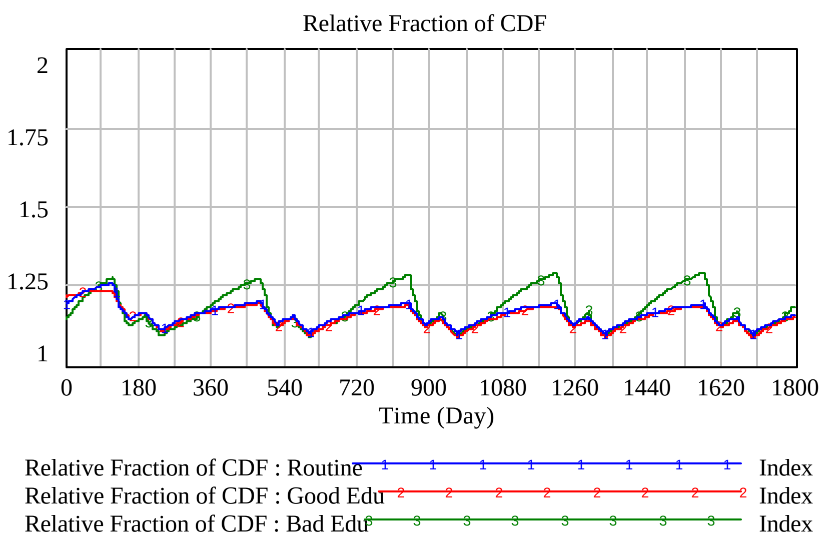

Figure 6. Education and Training Effects on Safety

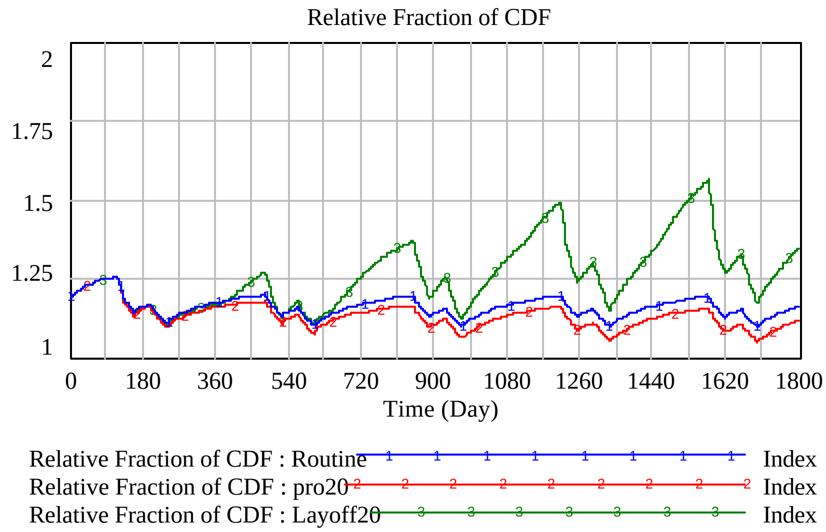

Figure 7. Hiring and Layoff Effects on Safety

Conclusion

Since this model is a general model of plant organization, if specific plant data is reflected in the model, it could be utilized as an individual model on the basis of that specific data. The following are possible areas of the model's application. First, this model can be applied to review NPP safety in t erms of organization. While previous models for assessment are static and only examine the short-term basis, the system dynamics model is dynamic and can be applied on a long-term basis. When considering situations where managers are periodically changed, managers can coherently execute their policies using this model.

Second, this model can make it easy to communicate with employees and managers. While developing a model, employees may discuss gaps of recognition with each other. It may help employees correctly recognize the system status and system structure. Third, the model may help managers and employees correct or expand their understanding of the organizational system in the process of the analysis of variables. Each individual at the NPP may get not only knowledge of the plant, but also correct the reference plant during the process of developing the model. A developed model can be also be applied to high-hazard organizations such as the aviation and chemical industry. It can give managers information about safety through simulation of their management policies. Simulation results give managers insights to help improve safety, performance and support to make better decisions concerning safety.

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