# Analysis of interdisciplinary safety assessment for nuclear accident using system dynamics (SD) method: In memory of admirable Dr. Jay W. Forrester at MIT Sloan School of Management (Died at 98)

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## 1. Introduction

As one of complex algorithms for the descriptions of nature, system dynamics (SD) has been broadly applied to our society. Even the ambiguous problems such as the probabilistic characteristics in industrial features could be analyzed in the aspect of integrity of the structures. The nuclear system analysis for multiple failure accident (MFA) is focused in this study of the nuclear power plants (NPPs) following the nuclear regulation and standard strengthening after the Fukushima nuclear accident. In the applications of nuclear MFAs by gas cooled reactor and liquid metal reactor as well as light water reactor, newly imagined scenarios are discussed.

It is designed to construct the much more improved nuclear system analysis method following the nuclear regulation and standard strengthening after the Fukushima nuclear accident and to study safety and risk analysis for natural disaster with the internal system trouble and human factor. Since the Fukushima nuclear accident was happened by the combinational reasons for the core meting accident, it is analyzed for the scenario and consequence in the MFAs of NPPs where the mechanical systems of the NPPs and the human factors are considered for the interested scenarios.

Even though, in Fukushima case, the earthquake was the initiation to make the accident, there are multiple kinds of the factors to make the results. In Table I, there is the list of the accident sequence by time [1]. The sequences are described by the loss of coolants and recovery of the external coolants. There are some aspects of internal system, natural disaster and human factors. Therefore, it is analyzed for aspect of internal system as follows,

1. To apply the Design Basis Accident (DBA) to the MFAs
2. To study the effect by natural disaster
3. To study the response to the multiple failure accidents of the multiple plants in each site
4. To develop SD computer program method for quantitative analysis
5. To suggest for the post-accident treatment

In the human factor and natural disaster,

1. To make applications for the conventional risk analysis in human factor
2. To study and analyze the past events in geology, metrology, and sea water-related cases
3. To study the human factor and natural disaster in each nation
4. To study the international cooperation

In some previous works, Prasad et al. worked for a hypothetical severe core damage accident in pressurized heavy water reactor (PHWR) in which the multiple failure of the core cooling system could be the collapse of pressure tubes and calandria tubes and eventually relocate inside the calandria vessel with a debris bed [2]. In addition, Rangel et al. worked that as the definition of accident explained other events the independence assumption underlying the three first Poisson models is violated [3].

## 2. Methods and Results

### *2.1. Strategy for multiple failure accident (MFA)*

In the analysis, there are factors for the MFA in Fig. 1 where three categories for the modeling. The natural disaster, internal facility, and human factor ae classified for the analysis. The natural disaster has common phenomena in which the earthquake is one of most important examples. The internal facility has some equipment in the NPPs. The human factors are composed of the social matters including human behaviors. It is considered that there were some preventions of core damage due to multiple failures as follows [4],

- Common cause related loss of safety functions
- Some measures to prevent core damage
- Opening of a safety-relief valve with mobile battery and/or compressor
- Injection of the water into reactor pressure vessel (RPV) with mobile pumping unit
- Supplying the power from ground power unit (GPU) during SBO

Furthermore, the natural disaster has produced the turmoil in Fukushima site from 2011 East-Japan earthquake event. Hence, it is necessary to consider the unexpected natural disasters like the flood, volcano, or even meteoroid. It is difficult to imagine exactly about the scale of the natural damage. Pau Gunter mentioned that a natural disaster can make the on-site emergency generators fail the operations and in U.S. Nuclear Regulatory Commission (NRC) report, Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants, where the core damage was estimated to begin in approximately 1 hour in the event of station blackout at the Surry and Peach Bottom NPPs for the case of the safety injection systems failures, where he insisted that the plant ageing, inspection/maintenance cost, safety margin, and defense-in-depth should be considered for the natural disaster related nuclear accident [5].

*2.2. System dynamics (SD) algorithm*

The SD was created at MIT Sloan school by Prof. Emeritus Jay Wright Forrester, beginning in the 1950s [6] where a lots of tasks like risk management, safety assessment, climate change issue, public health, and economic matters have been studied. The method is based on the non-linear complex algorithm incorporated with the random number generations. The skills are including the stock, flows, and feedback of the event where the event values are accumulated, weighting, and backward direction of event, respectively [7]. In considering of the memorial Dr. Jay W. Forrester, there is a biography of him in Table 2 [8-11].

Fig. 2 shows the algorithm of the SD procedures where the understanding of the problem is the first step of the modeling. The dotted lines are connected the first step of the circle. In the number 4, 5, 6, and 7, the connection is to the number 1. This means the method is affected by the progressed procedure with backward steps. Otherwise, the number 2 is connected to the number 4 where the progress is related to the number 4. In the SD method, the procedure is very flexible and non-linear progress trend which focuses on the goal of the modeling in the designed topic. In addition, the linear modeling does not describe the complex algorithm where the feedback algorithm of the event flows. However, SD can make the arbitrary event flows. From Fig. 3(a) to Fig. 3(d), the modeling is shown where MFA, Disaster, Internal Facility, and Human Factor are described respectively.

## 3. Results

In the simulations, there are several models in this study where MFA is composed of the natural disaster, modifies internal facility, and human factor as major parts. The modified internal facility shows the feedback loop in the Labors combined arrow line. That is, the Modified Internal Facility is affected by the workers' loop containing Labors. In Fig. 4, the simulation results are shown. Three variables of the Natural Disaster, Modified Internal Facility, and Human Factor are normalized as 1.0 in the maximum value. Each basic event has the random number based quantification which is decided by the expert judgment as the expert designed random number generations. For instance, in Table III, the Earthquake value has the random number of 0 or 1 where if the random number between 0 and 1 is lower than 0.3, the value is 0. Otherwise, it is 1. Consequently, the basic elements have the values and they are calculated by arithmetic operations as addition, subtraction, multiplication, or division. If there is any mathematical equation made by the operator, it could be used. The value increased gradually which means that the MFA possibility could be increased as the time goes on in Fig. 4 (d). The quantity is compared as the relative value and there is no unit. During the 60 years' period of the proposed NPP life time, the difference between initial and final values, 2.412 (= 2.05/0.85) which means the initial value is 2.412 times lower than that of the final value.

## 4. Conclusions

Using the Fukushima disaster, the MFA has been focused on for the severe accident prevention. It is performed for the improvement of safety in nuclear power plant. The expected protocol of the nuclear accident prevention related MFA could be accomplished. The constructions for the nuclear safety analysis program in NPPs are needed. The feedback logic in SD could show how the future event effects on the previous event with quantity values in which the dynamical quantifications are possible to give the numeric values to operators. Therefore, the operator could prepare for the unexpected disaster as the relative quantity. That is, today's value can be compared with yesterday's value. Hence, the disaster possibility could be counted by the operator where the human factor, natural disaster, and plant systems are related each other. It is needed to make the safety improvement strategy in MFA-related systems. The SD based modeling could be a regulation of the nuclear related protocols.

It could be analyzed for international co-work related to the International Atomic Energy Agency (IAEA). The NPPs have similar systems in the worldwide market. So, the preparations for the MFA could be done by cooperation about multinational tasks where the IAEA has a role of the management of the cooperation. The regular meeting and conference can improve the quality of constructing the MFA regulations. Additionally, another study of close cooperation for natural disaster is necessary. Especially, the earthquake and volcano around the Pacific-Rim region should be investigated for the exact and rapid information exchange. There are many NPPs and the increasing rates are higher where the Japan and China are closely located. Lastly, Fig. 5 shows the farewell to Dr. J. Forrester. It is the centennial birth in this 2018 and celebrated for his great works.

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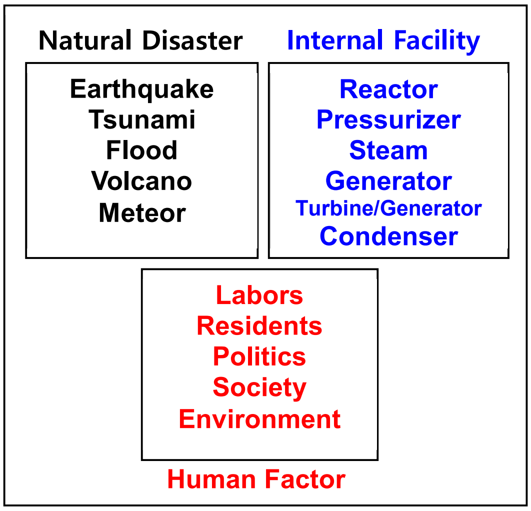



**Fig. 1.** Factors for Multiple Failure Accident (MFA).

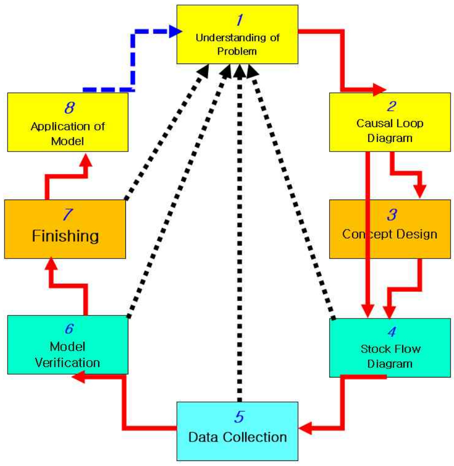
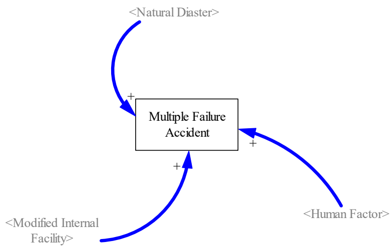
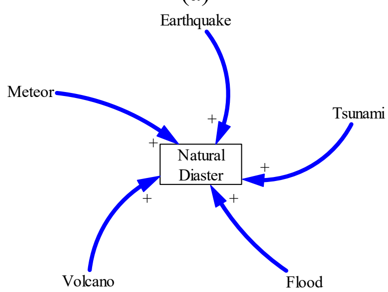


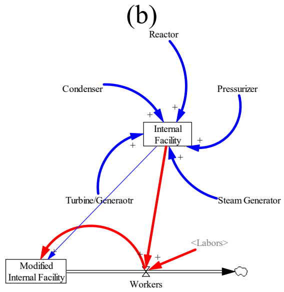

**Fig. 2.** Modeling for System Dynamics (SD).




(a)




(b)

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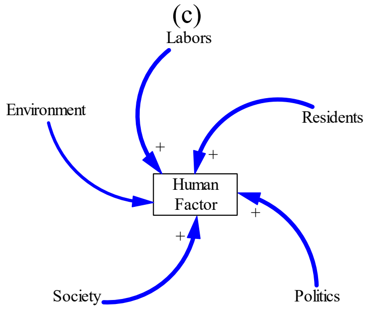
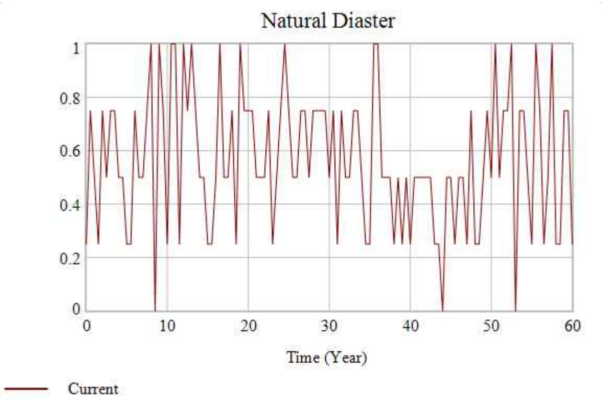
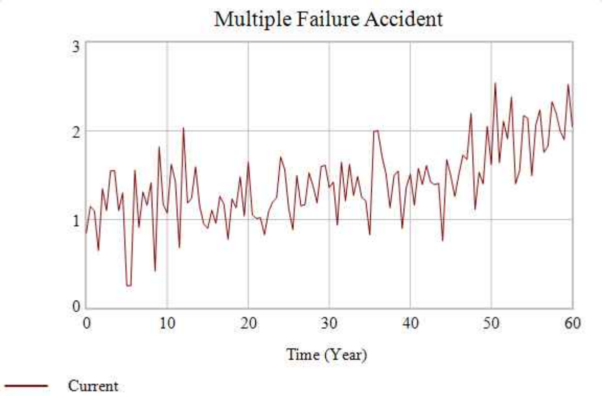



(d)

**Fig. 3.** System dynamics (SD) modeling, (a) Multiple Failure Accident (MFA), (b) Natural Disaster, (c) Internal Facility, and (d) Human Factor.




(a)




(b)

**Fig. 4.** Results for Multiple Failure Accident (MFA) (a) Natural Disaster and (b) Multiple Failure Accident (MFA).


**Fig. 5.** Farewell to Dr. Jay W. Forrester.

**Table I.** Accident sequence by time

| Sequence | Unit#1 | Unit#2 | Unit#3 |
|---|---|---|---|
| Loss of AC power | + 51 min | + 54 min | + 52 min |
| Loss of cooling | + 1 hour | + 70 hour | + 36 hour |
| Water level down to top of fuel | + 3 hours | + 74 hours | + 42 hours |
| Core damage starts | + 4 hours | + 77 hours | + 44 hours |
| Reactor pressure vessel damage | +11 hours | Uncertain | Uncertain |
| Fire pumps with fresh water | + 15 hours | - | + 43 hours |
| Hydrogen explosion (not confirmed for unit 2) | + 25 hours | + 87 hours | + 68 hours |
| Fire pumps with seawater | + 28 hours | + 77 hours | + 46 hours |
| Off-site electrical supply | | + 11-15 days | |
| Fresh water cooling | | + 14-15 days | |

**Table II.** Biography of Dr. J. Forrester

| Year | Content |
|---|---|
| 1918 | Born (Anselmo, Nebraska; July 14) |
| 1939 | *B.S. Electrical Eng.*, Univ. of Nebraska-Lincoln |
| 1945 | *S.M. Electrical Eng.*, MIT |
| 1954 | D.Eng.(Honor) Univ. of Nebraska |
| 1956 | Professor of MIT Sloan school |
| 1967 | National Academy of Engineering |
| 1969 | D.Sc.(Honor) Boston Univ. |
| 1971 | D.Eng.(Honor) Newark College of Eng. |
| 1972 | Medal of Honor, IEEE |
| 1973 | D.Eng.(Honor) Union College |
| 1974 | D.Eng.(Honor) Univ. of Notre Dame |
| 1979 | Doc. of Political Sci.(Honor) Univ. of Mannheim, Germany |
| 1987 | Honorary Prof., Shanghai Inst. of Tech., China |
| 1988 | Doc. of Humane Letters(Honor), SUNY |
| 1989 | Retired |
| 1990 | DPhil, Univ. of Bergen, Norway |
| 2016 | Died (Nov. 16) |

**Table III.** List of basic elements

| Parameter | Value |
|---|---|
| Earthquake | if then else(random 0 1 () < 0.3, 0, 1) |
| Tsunami | if then else(random 0 1 () < 0.4, 0, 1) |
| Flood | if then else(random 0 1 () < 0.3, 0, 1) |
| Volcano | if then else(random 0 1 () < 0.7, 0, 1) |
| Meteor | if then else(random 0 1 () < 0.9, 0, 1) |
| Reactor | if then else(random 0 1 () < 0.3, 0, 1) |
| Pressurizer | if then else(random 0 1 () < 0.2, 0, 1) |
| Steam Generator | if then else(random 0 1 () < 0.2, 0, 1) |
| Turbine/Generator | if then else(random 0 1 () < 0.1, 0, 1) |
| Condenser | if then else(random 0 1 () < 0.2, 0, 1) |
| Labors | if then else(random 0 1 () < 0.7, 0, 1) |
| Residents | if then else(random 0 1 () < 0.5, 0, 1) |
| Politics | if then else(random 0 1 () < 0.6, 0, 1) |
| Society | if then else(random 0 1 () < 0.4, 0, 1) |
| Environment | if then else(random 0 1 () < 0.3, 0, 1) |