A Basic Model for Material Flow Simulation of a Closed Nuclear Fuel Cycle

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1. Introduction

As described earlier in Lee's paper [1], KINAC is developing a physical model of a nuclear fuel cycle. The system dynamics was selected as a key modeling methodology from the previous literature study to analyze a general nuclear fuel cycle, including enrichment, reprocessing as well as nuclear reactors.

Because the complete design of a fuel cycle cannot be considered during modeling, KINAC studied the best way to construct adaptive workflows which make the rapid update on the prior model after some clear evidence of a subject nuclear fuel cycle was revealed.

To do this, a simple and basic stock-flow model was assumed and key elemental variables are defined. From this study, several principles and key considerations in modeling were derived such as outlet rate's effects on inventory change or effects on WIP (work in process) quantity.

2. Methods and Results

The entire system of nuclear fuel cycle of a country is very complex. Thus bottom-up approach or simulation with all information in detail cannot be an option. Top-down approach with known information and applying a tiered schematic are important if the information is restricted and evidence collection is impossible.

As shown in Fig.1, facilities or buildings can be level 1 elements in a nuclear fuel cycle system. And a closer look at the facilities or buildings gives us the process level information, that is to say, tier 2 level information.

In this way, level 3, level 4 and level 5 information can be defined in tiered approaches. The decision of further analysis into lower tier information is dependent on the result of a statistical test. It means the uncertainty of information is sufficiently low enough to meet the goal of an investigation, there is no need to do further analysis.

2.1 Rules in Real Factories

There are several rules in real world modeling. Material flow in a real nuclear fuel cycle is similar to the behavior of the variables in a factory. For example, a fuel fabrication facility is working on exactly the same way as a typical factory is. Reprocessing facility can also be regarded as one of a chemical process plant. Thus a nuclear fuel cycle can be a pseudo-factory system dealing with nuclear material.

At this point of view, KINAC selected system dynamics (SD) software to study the material balance or material flow in a nuclear fuel cycle. Even without SD tools, the balance equations can be solved with spreadsheets, MATLAB, or any kind of simulation tools. However, the advantage of using SD software is accessibility to the important mechanisms and behaviors of materials, because it is based on the simple concept of stock-flow diagram, and graphical interpretation of a model.

To analyze the nuclear fuel cycle as a simple factory or stock-flow system, several tendencies must be considered at first. They are:

1. Most variables in real factories are positive numbers.

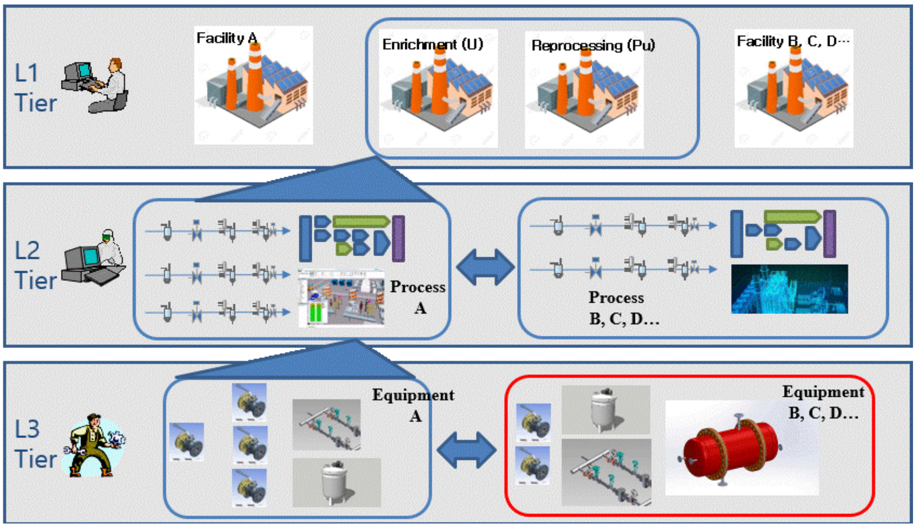


Fig. 1. A Tiered Graph for Material Flow Analysis in a Nuclear Fuel Cycle.

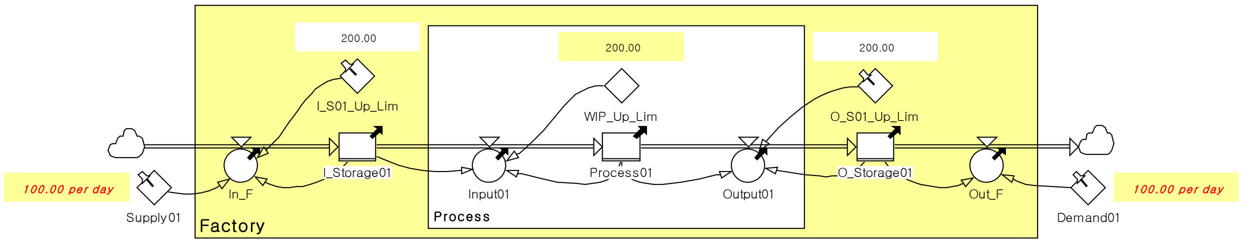


Fig. 2. A simple Material Flow Model of common element in Manufacturing Factory (Powersim SW).

2. Outflow rate (material flow rate of outlet position) is generally constant.
3. In addition to Rule No. 2, outflow rate is zero when the stock is below a certain level.
4. Inflow rate is generally constant.
5. In addition to Rule No. 4, inflow of a material stop when the stock reaches a certain level.

From these rules, variables such as WIP capacity, maximum stock level, and minimum stock level should be considered at each process. Of course the rules from No. 2 to 5 have exceptions in case of batch processes or specialized controls for the product quality.

2.2 Common Stock-Flow Model

Fig. 2 shows the common and elemental stock-flow model in KINAC's nuclear fuel cycle studies. There must be many differences in the detailed processes, whether the type of them is continuous or batched, and product amount is managed by item counting or bulk measuring. However, generally speaking, they can be simplified as shown in Fig.2.

It is assumed that the facility is composed by only one process, which is perfectly automated by machines, and only one type of raw material flows from start to finish, which means one raw material is converted into one complete product. Thus, working efficiency or proficiency of human resources is not considered in this model. The demand quantity of this product is 100 units per day, and the first (and only) material is supplied by 100 units per day from suppliers (All the units are omitted from now on, it can be kg, or liter).

The variables in this model means;

- Supply01: 100 per day, from the material supplier
- In_F: the rate of material provision
- I_Storage01: storage of material before process
- I_S01_Up_Lim: upper limit of storage capacity
- Input01: the rate of material input to process
- Process01: WIP (work in process)
- Output01: the rate of product output from process
- O_Storage01: storage of product after process
- O_S01_Up_Lim: upper limit of storage capacity
- Out_F: the rate of product provision to demand
- Demand01: 100 per day, sold to customers

Figures in Fig. 2, such as squares, circles, and diamonds are types of variables, and arrows represent the relations as a function. The actual relations are as follows, which the above tendencies are considered.

(1) In_F = IF (I_Storage01 >= I_S01_Up_Lim, 0, MIN (Supply01 * 1<<day>>, I_S01_Up_Lim - I_Storage01)) / 1<<day>>
(2) Input01 = IF (I_Storage01 > 0, MIN (WIP_Up_Lim - Process01, I_Storage01), 0) / 1<<day>>
(3) Output01 = IF (O_Storage01 <= O_S01_Up_Lim, MIN (Process01, O_S01_Up_Lim - O_Storage01), 0) / 1<<day>>
(4) Out_F = IF (O_Storage01 < Demand01 * 1<<day>>, 0, Demand01 * 1<<day>>) /1<<day>>

*. The expression '1<<day>>' is inevitable in rate variables because the Powersim requires a definition in time duration. And for the Level variables, the 'Reservoir' option was used.

These relations are exactly same as the functions in Powersim, thus, readers can test the models, equations, and the entire simulation if you use the same tool. As you can see in these equations, 'in and out' rate is determined by comparing the storage level and upper limit of storage capacity. MIN function was used so that we can prevent the storage level exceeds the upper limit of capacity.

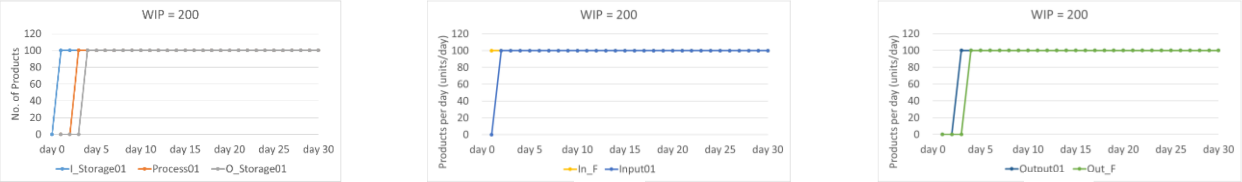
All the modeling and simulation on this common and simplified factory is carried out by Powersim Studio 10.

2.3 Simulation and Results

Fig. 3, 4, and 5 shows the results from various simulations. The time step is 1 day, and total period is 30 days. The start time is 0 days. The upper limits of each material or product storage were assumed as 200 products.

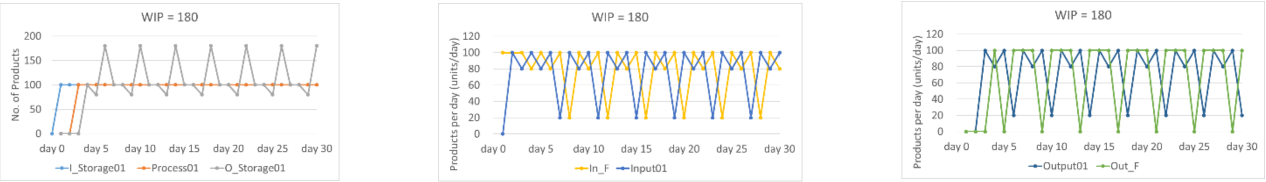
Because the input of raw material and output of product demand per day is same, we can easily expect that this system is a steady state over time. Then what impact can be drawn if we lower the upper limit of the WIP capacity below 200 products per day?

As you can see in Fig.3, if the WIP capacity is 200 (i.e. WIP_Up_Lim = 200), nothing happens. The lead time



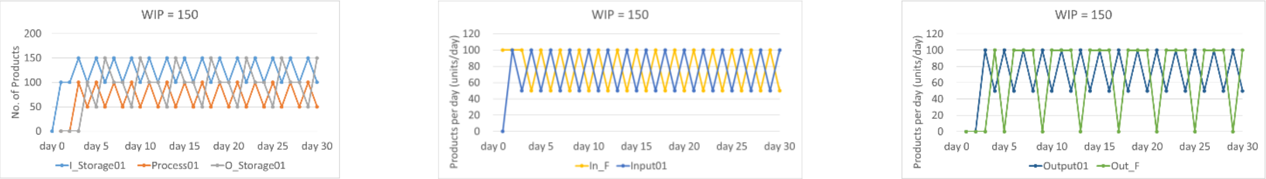
(a) (b) (c)

Fig. 3. Inventory changes (a) and in-out rate change (b, c) over time when WIP capacity is 200.



(a) (b) (c)

Fig. 4. Inventory changes (a) and in-out rate change (b, c) over time when WIP capacity is 180.



(a) (b) (c)

Fig. 5. Inventory changes (a) and in-out rate change (b, c) over time when WIP capacity is 150.

between storages are same, and no bottleneck exists. When the WIP capacity is decreased in 180, some periodic behaviors showed up as shown in Fig.4. This is caused by the MIN function, which the input variables of Input01 on day 3 is 80 products per day, not 100 products per day. On day 3, the difference between the upper limit of WIP capacity and the current WIP level is 180-100 = 80, and this is lower than the inlet storage level, 100 products on day 3.

When we decrease the WIP limit in 150, the periodic behaviors are deeper. Comparing the each storage level and inlet rate between 180 and 150, we can easily find that raw material storage and WIP level are changed into periodic when WIP capacity is 150.

3. Conclusions

When the WIP capacity is over 200, no periodic behaviors are shown (Results are omitted). Because the ‘in and out’ rate of material in this factory is fixed at 100 per day, the capacity over 200 units makes always 100 per day rates by the MIN function.

There are several findings similar to this behavior by this simple simulation. Even we introduce many ideal assumptions to make the model as simple as possible, it is not easy to guess all the characteristics of variables, though we are experts in the nuclear industry or nuclear engineering.

For example, the ‘Out_F’ variable is a little different from the other rate variables such as In_F, Input01, Output01, there is no difference between WIP capacity of 180 and 150 as shown in c by Fig. 4 and 5. This cannot be expected easily before simulation.

In this simple study, the relations among variables such as stock capacity and flow rate are studied. The further study of the more complex model, including job process effects, various material effects, and safety stock effects will be carried out in near future.

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REFERENCES

[1] J. Lee, A Literature Study on Simulation Methods with respect to Denuclearization, KRS Spring Conference, Busan, May 9th, 2019.