The application of system dynamics modeling to study impact of water resources planning and management in Taiwan

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ABSTRACT:

The demand for water in Southern Taiwan has increased significantly in recent years owing to industrial growth and increasing living standards. However, for financial reasons, only limited expansion of existing surface water facilities is possible in a river basin. Therefore, a suitable strategy is required to consider the fixed costs and operating costs for expansion. On the other hands, the conjunctive use of surface water and groundwater can enhance the reliability of water supplies by providing independent sources, making research on conjunctive use important particularly with regard to fixed and operating costs. Therefore, government authorities have to urgently resolve the tension between water deficit and economic profit, while ensuring sustainable development of water resources. Accordingly, this investigation proposes a process for combining the system dynamics and impact analysis to evaluating water strategy systematically and quantitatively, with reference to water shortage and economic profit as they pertain to the planning and management of regional water resources.

KEYWORDS:

System dynamics, impact analysis, water resources planning and management

1. INTRODUCTION

The primary tasks faced by water resource managers and policy-makers are to find and assess effective solutions for water problems. The conventional systems approach to problems has been to simulate, optimize, or choose a compromise alternative solution based on trade-offs between conflicting objectives. However, system thinking is evolving into concepts that may clarify how to approach complex problems that affect or involve people. Systems analysis tools are applied to facilitate good or creative solutions, rather than to recommend the “best “ solution. System dynamics is one approach to help managers meet the challenges of communicating with stakeholders. A system dynamics model is including the critical feedback structures in the system. Simulating the model shows the effect of the system structure on policy interventions. “Feedback” refers to X affecting Y and Y in turn affecting X, maybe through a chain of causes and effects. Accurate results can only be obtained by studying the feedback of the complete system. Therefore, system dynamics is well-suited to analyzing problems whose behavior is governed by feedback relationships and which have a long-term time horizon. Recently, system dynamics have not been much applied to water resources. Stave proposed building a strategic-level system dynamics model based on the water management system in Las

Vegas, Nevada, with the aim of increasing public understanding of the value of water conservation in Las Vegas. Simonovic utilized system dynamics in the case study of water resources policy analysis for Egypt. Nandalal presented a system dynamics to help stakeholders in two different jurisdictions in a hypothetical water resource system to eliminate a potential water-sharing conflict.

This study addressed two major problems: 1) water deficit, 2) economic profit. The main purpose of the work is to make the appropriate strategy to avoid the serious impact between water deficit and economic profit and also prohibit the time delay of strategy. Although scenario simulation can be employed to obtain the effect of system, it is not easy to reflect the improvement of problem solving. Consequently, this investigation also recommends that the method of impact analysis have to proceed after the work of scenario to alleviate the above difficulty.

2. METHODOLOGY

Figure.1 displays a flow chart of the proposed methodology. The detail is explained by a case study in southern Taiwan as follows.

2.1. Concept Building

The first step is the concept building of problem solving. The problem definition, system description and causal loop drawing of system dynamics belong to this field.

2.1.1. Problem Definition

The problem definition is to find one or more key variables whose behavior over time defines the problem. Figure 2 demonstrates that population on the watershed in southern Taiwan will continue to grow, and that the water supply is limited. Therefore, the only solution is “to make more efficient use” of the water available. Therefore, this study addresses the water supply and demand variables. However, Fig. 2 only presents the difference between water supply and demand over time, and cannot indicate that the scale of the problem is how serious. If decision makers consider the difference to be acceptable by decision makers, then interested problem does not become the pressure to them. Hence, a suitable index was adopted to describe the pressure of our problems.

The the U.S. Army Corps of Engineers proposed the Shortage index (SI) to reflect the water deficit, defined as,

$$SI = \frac{100}{N} \sum_{i=1}^{N} \left(\frac{Sh_i}{T_i} \right)^2 \tag{1}$$

where N = number of periods; Shi = shortage volume during the period i ; Ti = target demand during the period i and $\sum$ is the summation of the indicated values for all periods. Ten days is usually taken as the period of reservoir operation for planning purposes in Taiwan.

Another problem in this study is the economic profit of every suggested strategy. The net benefit is calculated as follows:

Net benefit = benefit - total cost (2)

Where the benefit is the cumulative income of water selling and the total is the sum of the fixed operating costs.

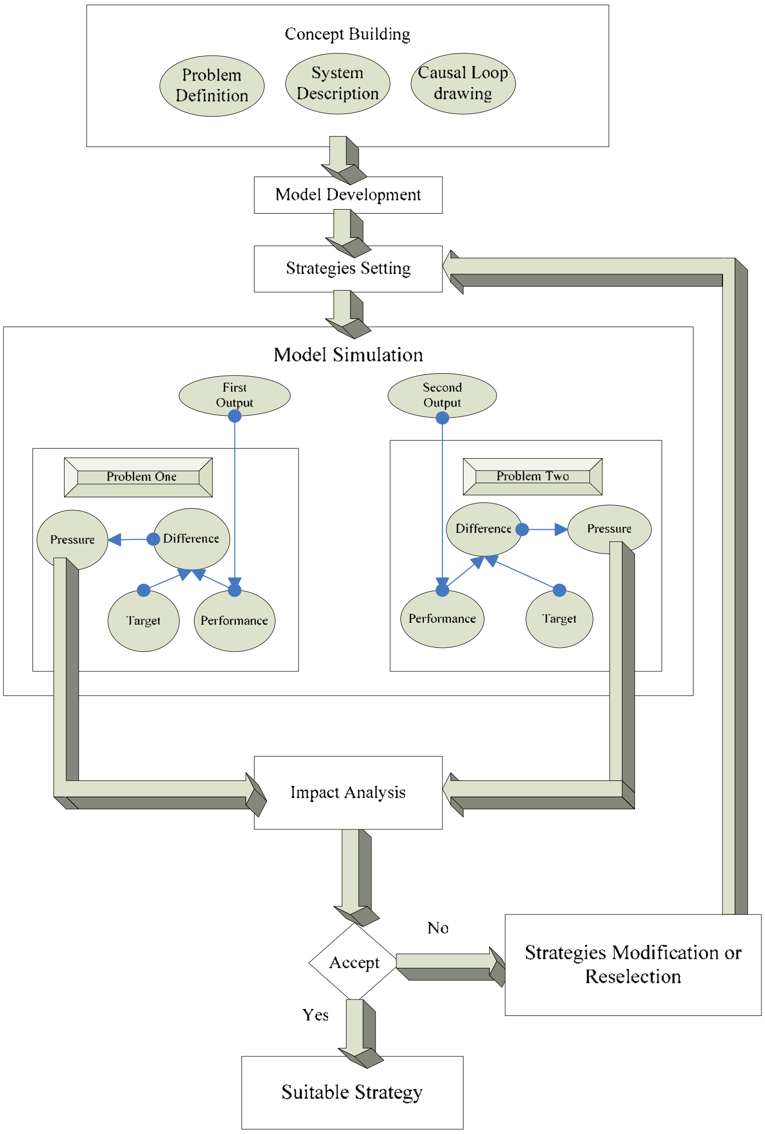

Fig. 1 Flow chart of proposed methodology

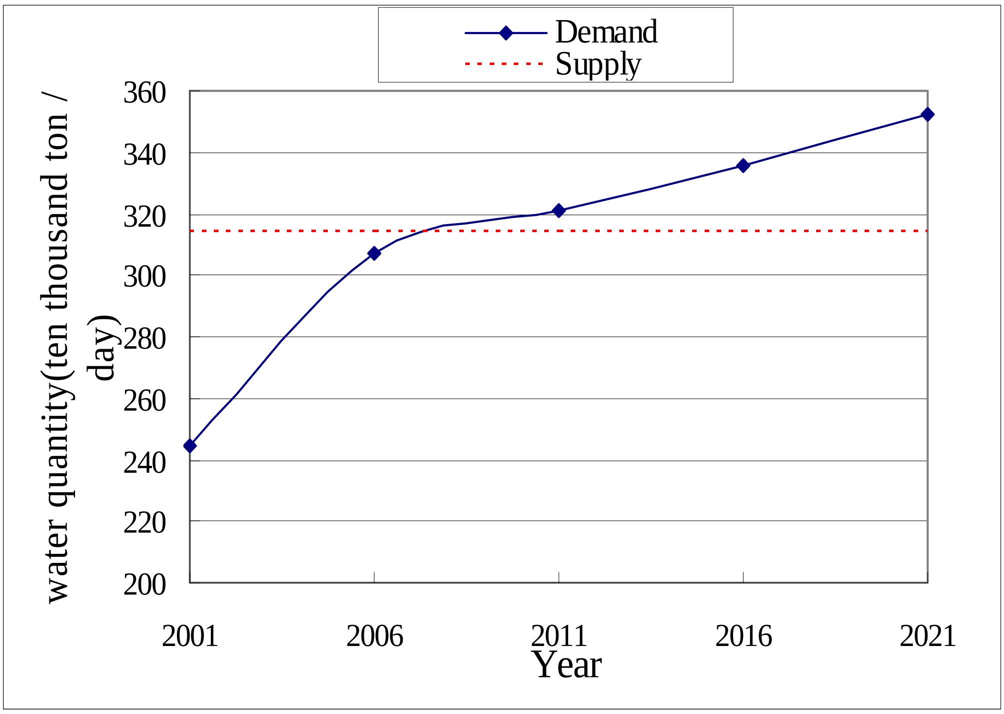

Fig. 2 Water supply and demand situation in Southern Taiwan

2.1.2. System Description

Describing the system means identifying the system structure that appears to be generating the problematic trend and involves extracting the essential elements and connections from the real system that produces the observed or anticipated behavior.

Located in south Taiwan, the study region covers two major watersheds, Tsengwen River and Kaopin River, and two metropolitan areas, Tainan and Kaohsing. While Tainan is supplied by Nanhwa Reservoir with an effective storage capacity of 149.46×10^6 m^3, the water for Kaohsing area is supplied by the Nanhwa Reservoir and Kaopin River Weir. The proposed methodology is demonstrated to find facilities with appropriate capacities and operation procedures to satisfy the future demands in 2021.

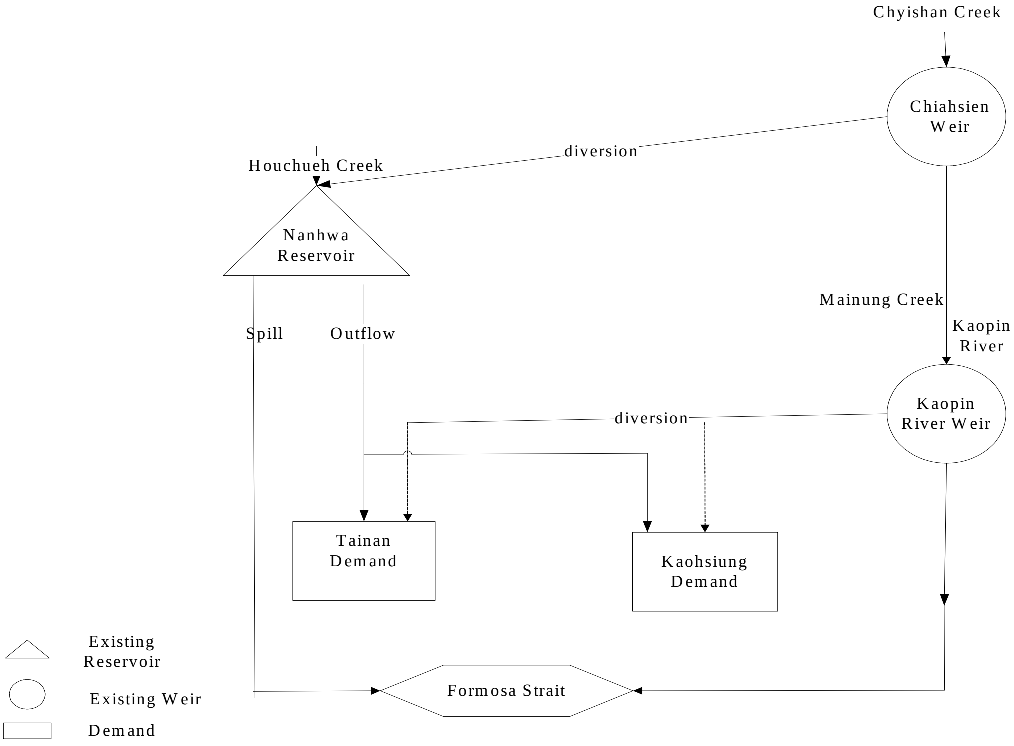

Fig.3 System diagram of the study basin

2.1.3. Causal Loop Drawing

A causal loop diagram provides an understanding of the nature of the impact dynamics and feedback. Considering the priority of supply to water facilities, increasing water demand, shortage index, fixed cost, operating cost and possible strategies, the causal loop diagram is shown in Figure 4. From this loop, the first supply is the weir due to no utility of water storage. If the water supply of weir is not enough to meet the demand, the reservoir is the next provider and the groundwater is the final one. This priority of water supply is proceeding in every time step. The shortage index (SI) is then counted depending on the water deficits in all time steps, when the simulation is completed. If the SI is bigger than our criterion (SI = 1), the strategy is need to start. The planning strategies in this study are the capacity expansion of existing reservoir, water treatment plant and groundwater.

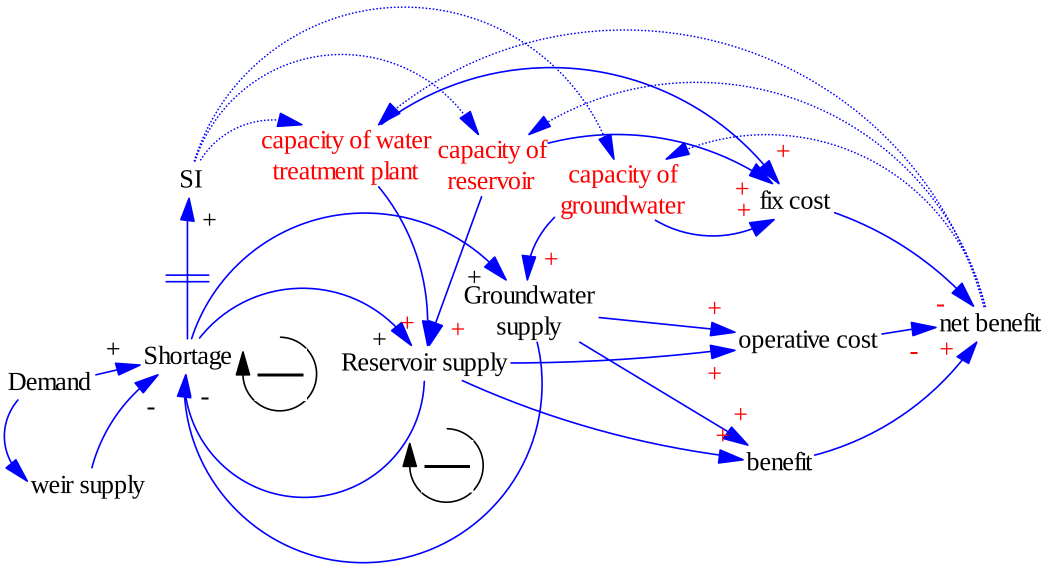

Fig.4 Causal loop diagram

2.2. Model Development

The system dynamic simulation tool adopted in this investigation contains objects for denoting the system structure of concept building, comprising stocks, flows, converters and connectors. Stocks are variables that can accumulate, describing conditions ‘how things are’ or simply the state of the system. Flows, represent actions ‘how things are going’, i.e. variables whose values are measured as rates. A converter transforms input in the form of algebraic relationships and graphs into output. A connector, which is the relationship between other objects, conveys information from one variable to another. Figures 5 and 6 display the system dynamics model in this study.

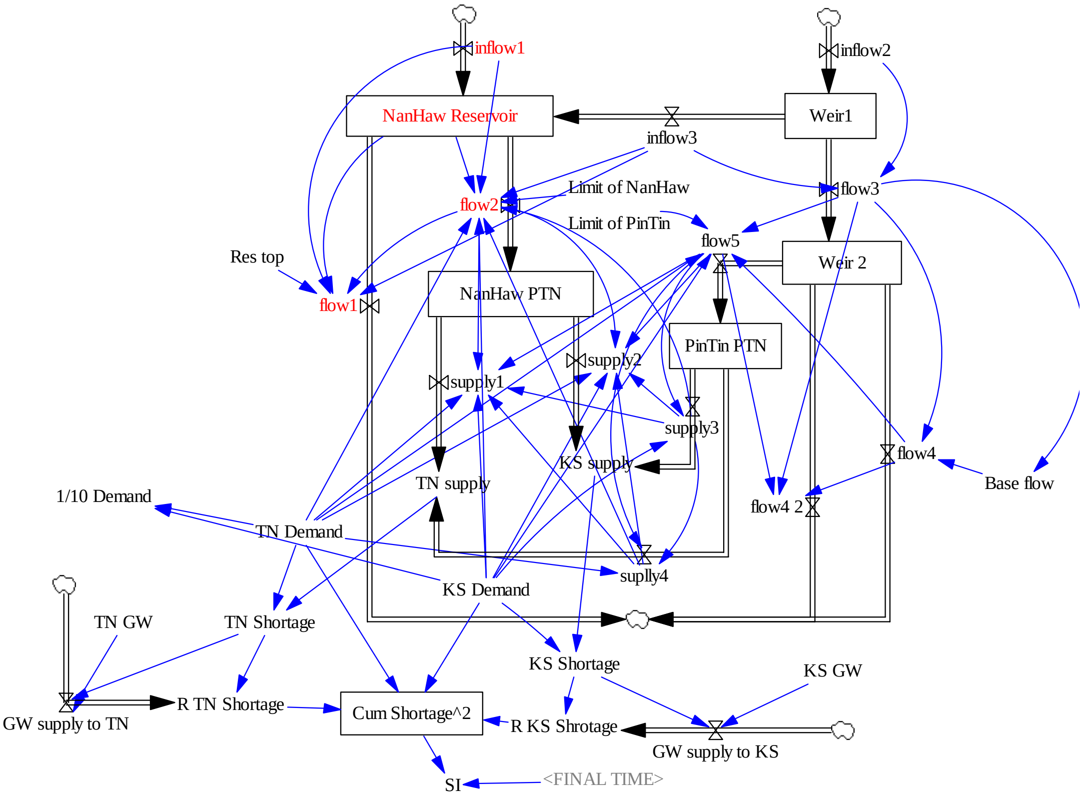

Fig.5 System dynamics model (water quantity)

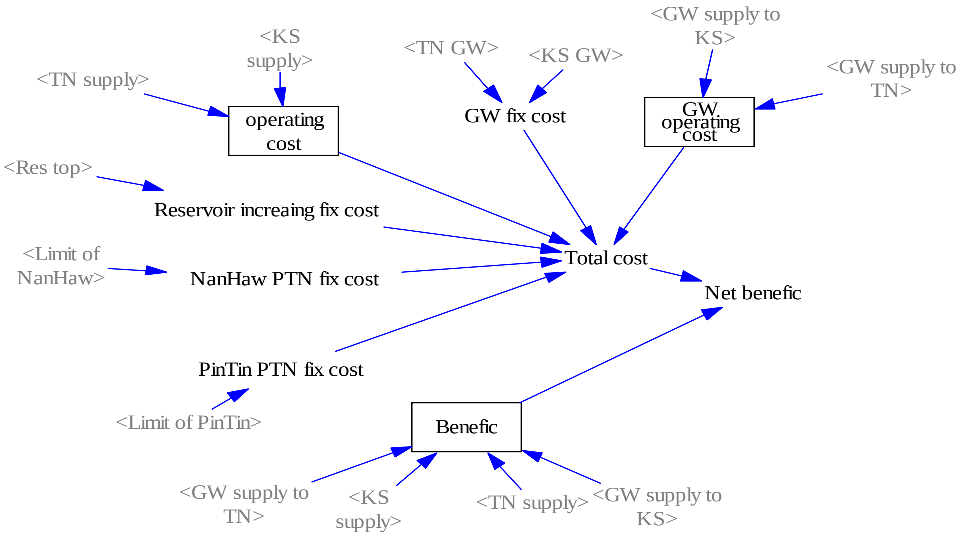

Fig.6 System dynamics model (economic profit)

2.3. Strategy Setting

When the model structure has been validated, it can be used to test the effect of strategy interventions on the problem, by studying the model structure to find policy levers, then simulating the effect of those changes. The strategies of interest are the capacity expansion of existing reservoir, water treatment plant and groundwater.

2.4. Model Simulation

The model was simulated using Vensim PLE version 5.3 software. The model includes several simplifying assumptions. For instance, the future inflow in Nanhwa Reservoir is same as previous data. The price of water selling is assumed to be 11.2 NT/ton. The fixed cost of capacity expansion to a reservoir is 2.6 NT/m^3, to a water treatment plant is 1.0 NT/m^3 and to groundwater is 0.38 NT/ton. The operating cost of capacity expansion to a water treatment plant is 10.955 NT/m^3 and to groundwater is 0.9 NT/m^3. The time of simulation is twenty-one years (2001-2021).

2.5. Impact Analysis

The first difference of water supply and second difference of benefit and cost in every time step are obtained through the work of model simulation so that the shortage index and net income can be calculated to measure the scale of pressure. If the SI is below 2, it reflects the problem of water deficit is slight (“L”) and same with the net benefit is over $220000. If the SI is over 3, it reflects the problem of water deficit is very serious (“H”) and same with the net benefit is below $200000. If the SI ranges between 2 and 3, it reflects the problem of water deficit is serious (“N”) and same with the net benefit ranges between $200000 and 220000. From this work, we can understand the interactive impact of these two problems to every kind of strategies easily and collect several acceptable strategies under the consideration of above classification. Then the characteristic of time delay among those acceptable strategies can be observed by the graph of indicator variables to help decision making.

3. RESULT

Table 1 displays the results of impact analysis using all tested strategies. From this table, we find that the water supply of reservoir is limited by the capacity of water treatment plant when the capacity expansion of reservoir is bigger than 18000. Similarly, if the capacity expansion of water treatment plant is under present capacity in reservoir, it not only improves the water deficit, but also makes it to worsen. Those indicate the important of strategies combination.

Furthermore, only four strategies can be accepted in the proposed definition. Drawing the characteristic of time delay among those acceptable strategies and showing in Figures 7~14. Figures 7~10 display the started time of positive net benefit to these four strategies and the performance of case 3 is the best of all cases. It means that the case3 seem to be a nice choice to abate the interest when the investment is loaned from the bank. Besides, Figures 11-14 shows the differences in shortage variation among the acceptable strategies and there is no obvious different to each other. In conclusion, above mentioned graphs are suitable to facilitate decision making.

4. CONCLUSION

The simulation results reveal that the proposed methodology effectively integrates the system dynamics and impact analysis for systematically and quantitatively evaluating water strategy. The proposed methodology can assist decision-makers in discovering the win-win strategy. In the future, our concern problem have to add the environmental impact because it will also postponed the further development of large water resource projects, if we ignore, the risk of damage due to drought in the dry season is increasing.

Table1 The results of impact factor.

Strategy	**key variables**	**scenario**	**SI**	**Net Benefit (NT)**	**Scale of pressure in problem 1**	**Scale of pressure in problem 2**	**acceptable case**
capacity expansion of water treatment plant	"Limit of NanHaw"	900	6.053	276806	H	L	
		1000	6.637	278530	H	L	
		2000	10.33	279279	H	L	
capacity expansion of existing reservoir	"Res top"	16000	5.324	272728	H	L	
		18000	5.213	268054	H	L	
		25000	5.213	249714	H	L	
groundwater supply(to Tainan)	"TN ground"	100	4.504	251833	H	L	
		200	3.39	232687	H	L	
		300	2.498	216158	N	N	
groundwater supply(to Kaohsing)	"KS ground"	100	4.53	253768	H	L	
		200	3.493	238599	H	L	
		300	2.749	227128	N	L	
groundwater supply(to Kaohsing and Tainan)	"KS ground" / "TN ground"	100/100	3.337	232027	H	L	
		200/200	1.749	197707	L	H	
		300/300	0.7838	168715	L	H	
capacity expansion of water treatment plant +capacity expansion of existing reservoir	"Limit of NanHaw" /"Res top"	1000/18000	3.849	279807	H	L	
		1200/23000	1.586	282066	L	L	Case1
		1300/25000	1.034	282415	L	L	Case2
capacity expansion of water treatment plant +capacity expansion of existing reservoir + groundwater supply(to Kaohsing and Tainan)	"Limit of NanHaw" / "Res top" / "KS ground" / "TN ground"	1000/18000/30/30	3.255	268551	H	L	
		1100/21000/50/50	1.625	264883	L	L	Case3
		1200/23000/20/20	1.357	276023	L	L	Case4

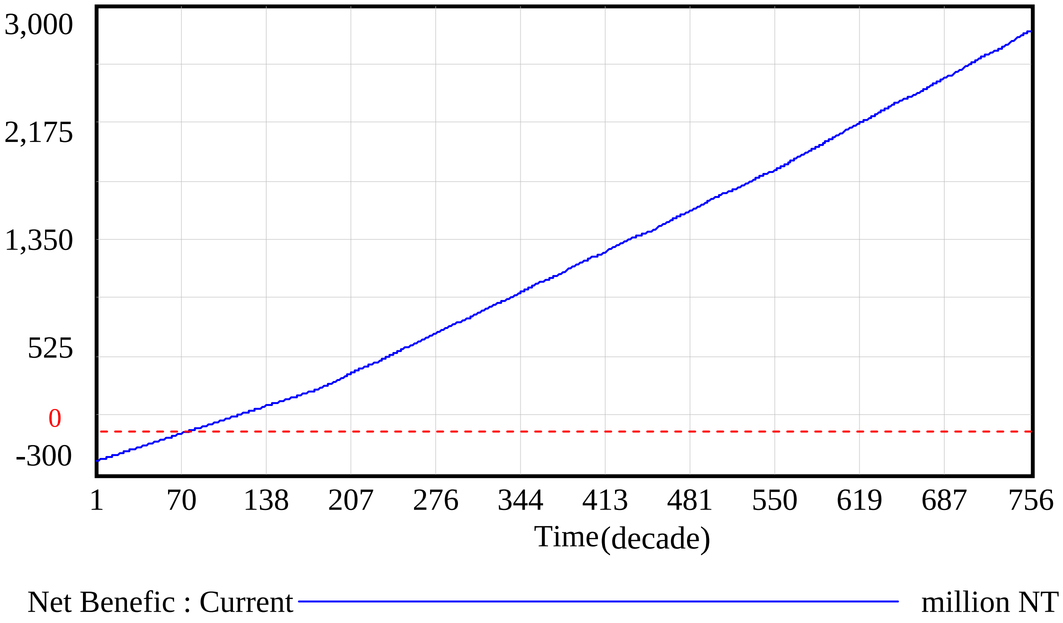

Fig.7 The time delay of net benefit in case1

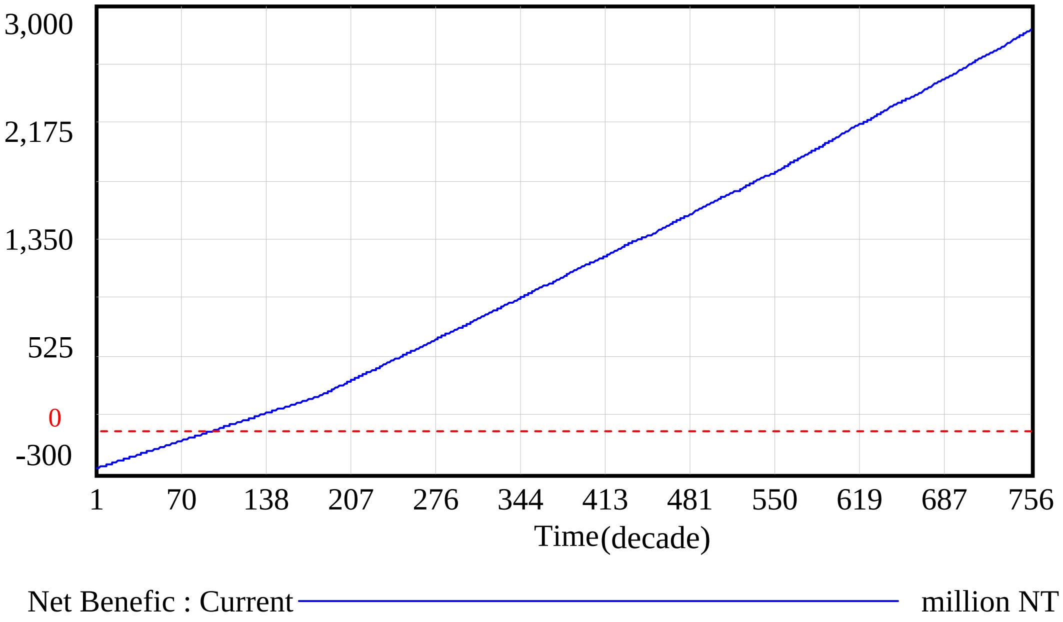

Fig.8 The time delay of net benefit in case2

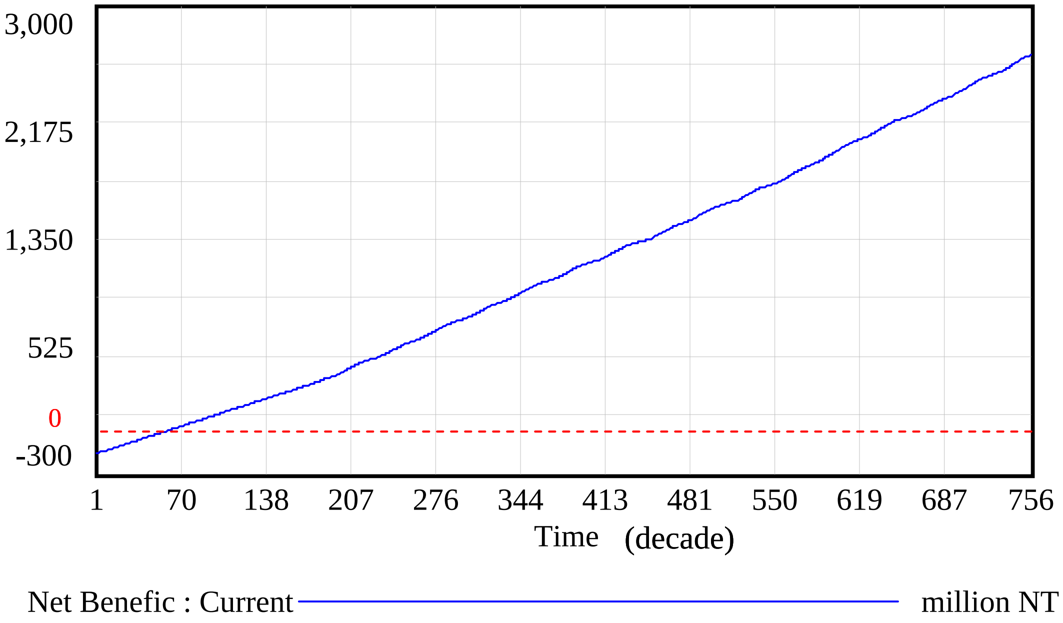

Fig.9 The time delay of net benefit in case3

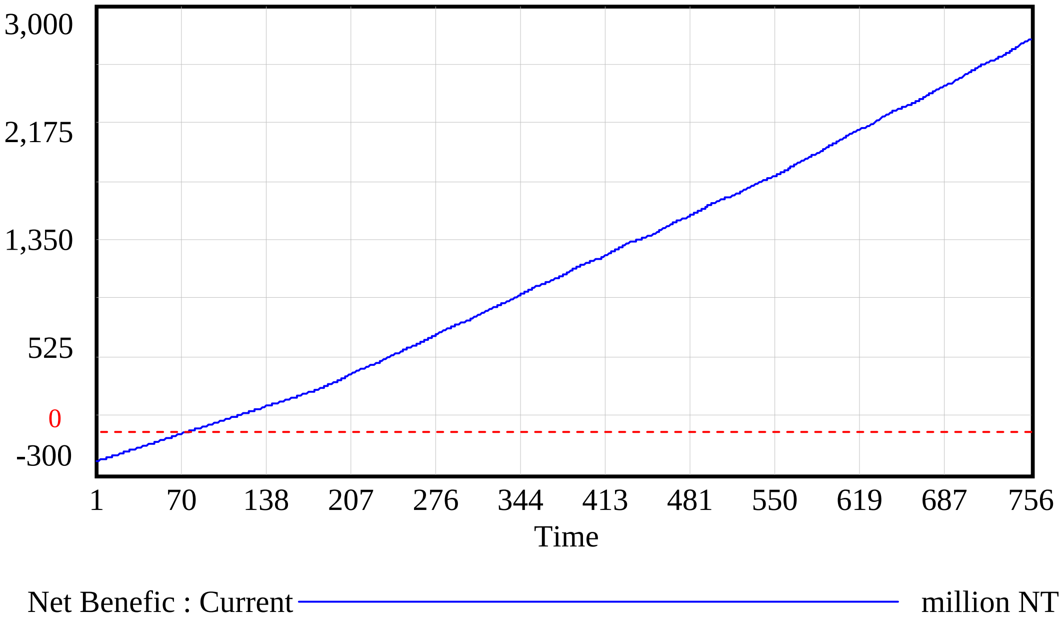

Fig.10 The time delay of net benefit in case4

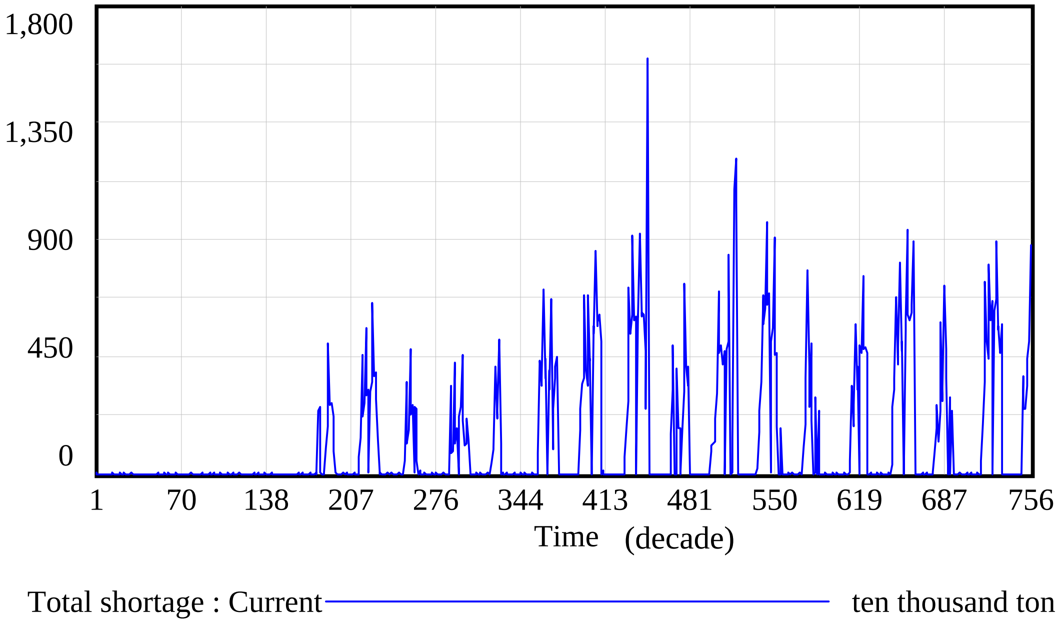

Fig.11 The time delay of shortage in case1

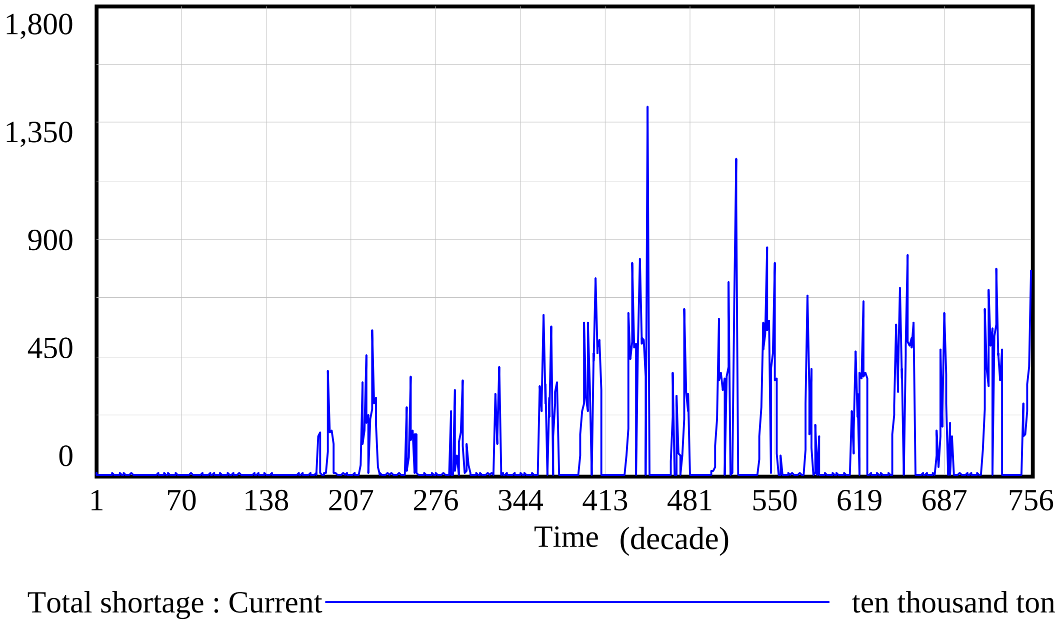

Fig.12 The time delay of shortage in Case2

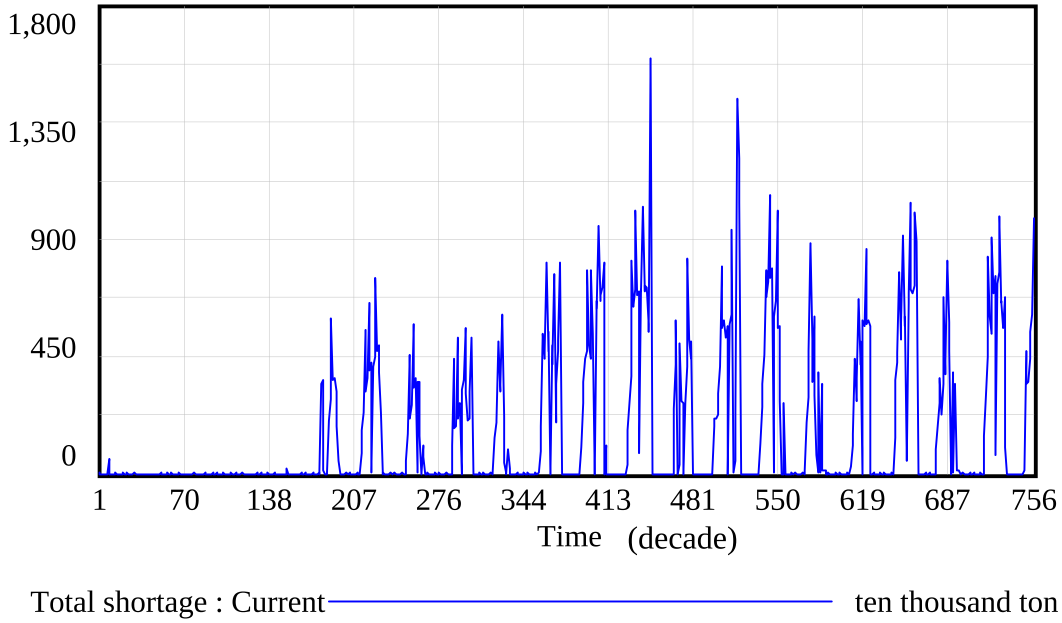

Fig.13 The time delay of shortage in Case3

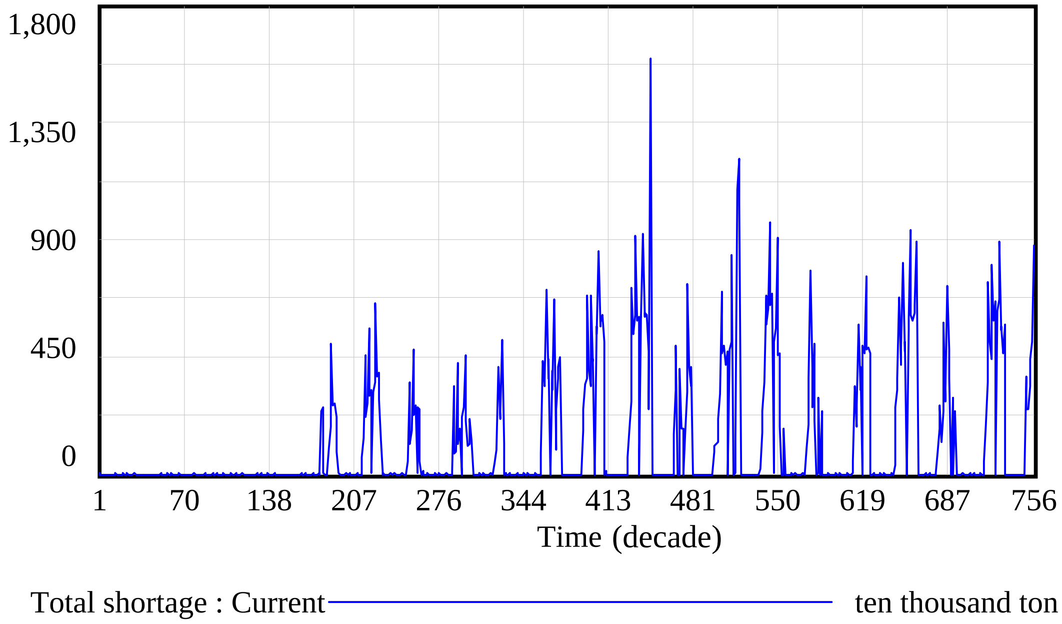

Fig.14 The time delay of shortage in Case4

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