Backward Qualitative Simulation of Structural Model for Strategy Planning

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Abstract

In the process of estimating the effectiveness of plans or policies, it is useful to construct a diagrammatic causal model, named the structural model, that represents causality between several factors in the target organization. We have already proposed a method for qualitative simulation that can predict behaviors of a target system modeled with a structural model for the strategy planning. The effectiveness of a supposed plan is estimated by reviewing a predicted behavior of the target as a simulation result. However, trials of the simulation have to be iterated many times in order to find out a better plan, if the model is large and complex.

This paper proposes the backward simulation method that can generate possible initial states of the operable nodes from the desirable behavior of the utility nodes to cope with this problem. Through the comparison with the forward simulation, the efficiency of the method is clarified.

Introduction

The process of estimating the effectiveness of plans or policies introduced into a new strategy in an organization plays an important role for strategy planning. In this process, it is useful to construct a diagrammatic causal model, named the structural model, that represents causality between several factors in the target organization in the form of a directed graph (Warfield 1973). Several effective methods for structural modeling have been proposed, so far, and the computer support for construction and utilization of the structural models has been recognized to be one of the most significant works, as organization becomes large and complex (Axelrod 1976, Montazemi & Conrath 1986, Conrath, Montazemi & Higgins 1987, Zhang, Chen & Bezdek 1989, Zhang et al. 1992).

We have already proposed a method for qualitative simulation that can predict behaviors of a target system modeled with a structural model (Ohkawa & Komoda 1993). In this method, the notion of time scale that is determined based on the time lag for propagating influence from one factor to another factor in the model, is introduced to cope with ambiguities caused by lack of quantitative information. The time scale can help to divide a whole model into several sub-models. In addition, the redundant state transitions in the simulation process can be reduced by using several typical patterns, which specify primitive behaviors in equilibrium for each time scale.

By using the simulation, we can estimate the effectiveness of a supposed plan, by which initial conditions of the simulation are specified, by reviewing a predicted behavior of the target as a simulation result. However, trials of the simulation, in which various initial conditions, namely, various plans are considered, have to be iterated many times in order to find out a better plan, if the model is large and complex.

This paper presents a method of backward simulation of the structural model, which can derive only possible initial plans or policies backwardly from the desirable behavior of the target. In this method, basically, an influence of a utility node of the model is propagated to the other nodes along the directed arcs inversely. The notion of the one-step (forward) simulation is introduced in order to select only meaningful behaviors from possible behaviors derived through the process of backward influence propagations.

The following two sections describe briefly the definitions of the structural model treated in this paper and the overview of the (forward) simulation method respectively. Then the procedure of the backward simulation is presented. Finally, the effectiveness of the backward simulation is verified through some experimental results.

Structural Model

The structural model represents causal relations among several factors in an organization or a system. It takes the form of a directed graph that consists of some nodes and arcs. Each node corresponds to the factor in the system. Each arc expresses the causal relation with the arrow indicating the direction from a cause to an effect. Figure 1 illustrates an example of the structural model. The figure suggests that the existence of reliable executives in a corporation improves

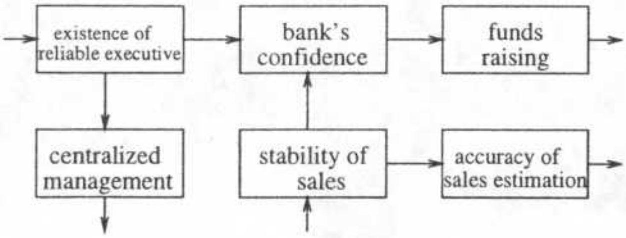

Figure 1: An example of the structural-model.

the bank's confidence, and it brings the funds raising, and so on.

We have defined the following four types of qualitative parameters that specify a state of the structural model. For further details of the definitions, see reference (Ohkawa & Komoda 1993).

Definition 1 (Qualitative status value) Let x be a node and t be a time. $[x(t)]$, the qualitative status value of x at t, is defined as follows:

$$[x(t)] = \begin{cases} \text{H}, & \text{if status value of } x \text{ cannot increase to the higher value than the current value,} \\ \text{M}, & \text{if status value of } x \text{ can both increase and decrease,} \\ \text{L}, & \text{if status value of } x \text{ cannot decrease to the lower value than the current value.} \end{cases}$$

Definition 2 (Change tendency) Let x be a node and t be a time. $[\partial x(t)]$, the change tendency of x at t, is defined as follows:

$$[\partial x(t)] = \begin{cases} \text{I}_+, & \text{if status value of } x \text{ is greatly increasing at } t, \\ \text{I}, & \text{if status value of } x \text{ is increasing at } t, \\ \text{S}, & \text{if status value of } x \text{ is steady at } t, \\ \text{D}, & \text{if status value of } x \text{ is decreasing at } t, \\ \text{D}_+, & \text{if status value of } x \text{ is greatly decreasing at } t. \end{cases}$$

Definition 3 (Direction of influence) Let x be a cause node and y be an effect node. $D(x, y)$, the direction of influence from x to y, is defined as follows:

$$D(x,y) = \begin{cases} +, & \text{if the status value of } y \text{ increases in proportion as the status value of } x \text{ increases,} \\ -, & \text{if the status value of } y \text{ decreases in proportion as the status value of } x \text{ increases.} \end{cases}$$

Definition 4 (Propagation speed) Let x be a cause node and y be an effect node. $V(x, y)$, the propagation speed from x to y, is defined as follows:

$$V(x,y) = \begin{cases} V_0, & \text{if the change of the status value of } x \text{ causes instantaneously the change of the status value of } y, \\ V_n, & \text{if the time order (e.g. hours, days, weeks, months, years, etc) for propagating influence from } x \text{ to } y \text{ is longer than the time order such that } V(x,y) = V_{n-1}. \end{cases}$$

Qualitative Simulation Using Typical Patterns

The goal of qualitative simulation of a structural model is to derive model's behaviors that are triggered by changing states of several nodes in the model. This method is based on the following two assumptions.

- Behaviors of slower sub-models can be ignored when focusing on a faster sub-model.
- A faster sub-model is regarded as being in equilibrium, whenever evaluating other slower sub-models.

The simulation of each sub-model is performed in order of time scale. The result of each simulation, which is obtained in equilibrium, is propagated to the slower system, so that the behaviors of the whole system are derived.

The propagation of influence between nodes in a sub-model is determined based on the change tendency of the cause node that is the source of the influence and the qualitative status value of the effect node that is influenced by the cause node according to the propagation rules summarized in Table 1 in case of $D(x, y) = +$. If $D(x, y) = -$, the table in which 'I' and 'D' in the column of $[\partial x(t)]$ are exchanged is used instead of Table 1. If more than one influences are propagated to a node, the sum of the change tendencies of the cause nodes is treated as the influence to the effect node. The sum of the change tendencies is calculated according to Table 2. The symbol '?' in the table indicates an unknown value, which means the change tendency cannot be determined uniquely. If the unknown value is obtained, all possible values must be considered. The behavior of a node is specified with a sequence of the change tendencies in the node.

If the state transitions according to the propagation rules are in equilibrium, in other words, if the repetition of the same state transitions is observed, the repetition part of the state transition is evaluated qualitatively with a typical pattern for each node using Table 3.

Let TS_i be a sub-model in a certain time scale, and if each sequence of change tendencies that specifies the behavior of each node in TS_i is terminated by a typical pattern, the sub-model TS_i is regarded as been in equilibrium. In this case, the influence is propagated from the sub-model TS_i to TS_{i+1}, which is a

Table 1: Propagation from x to y ($[y(t)], [\partial y(t)]$).

$[\partial x(t)]$ \ $[y(t-1)]$	M	H	L
S	(M, S)	(H, S)	(L, S)
I	(M, I)	(H, S)	(M, I)
D	(M, D)	(M, D)	(L, S)
I_+	(M, I_+)	(H, S)	(M, I_+)
D_+	(M, D_+)	(M, D_+)	(L, S)

Table 2: Summation of the change tendency.

+	S	I	D	I_+	D_+
S	S	I	D	I_+	D_+
I	I	I	?	I_+	D
D	D	?	D	I	D_+
I_+	I_+	I_+	I	I_+	?
D_+	D_+	D	D_+	?	D_+

sub-model with slower time scale than TS_i. This type of influence propagation is achieved based on the sum of change tendencies and the initial value of the qualitative status values according to the rules shown in Table 4, where $[x(TS_i)]$, $[\partial x(TS_i)]$ indicate the initial value of qualitative status value of node x in time-scale TS_i and the final state of node x in TS_i respectively. Each element of the table represents the influence to TS_{i+1}, namely, a pair of the initial value of qualitative status value of node x in TS_{i+1} and the initial value of change tendencies for node x in TS_{i+1}. The final state of a node is estimated from the combination of the sum of a series of change tendencies and the typical pattern of the node in equilibrium using Table 5.

After propagating influences from a fast sub-model TS_i to a slow sub-model TS_{i+1}, the propagation of influence in TS_{i+1} is performed similarly. As a result of simulation, the sequence of change tendencies of every nodes that is terminated by a typical pattern for

Table 3: Identification of the typical pattern.

Change tendency of repetition part	Typical pattern
S only appear	S^*
I or I_+ appear, neither D nor D_+	I^*
D or D_+ appear, neither I nor I_+	D^*
I and D appear, neither I_+ nor D_+	$(ID)^*$, $(DI)^*$
I_+ and D_+ appear	$(ID)^*$, $(DI)^*$
I_+ and D appear, D_+ not appear	I^*
D_+ and I appear, I_+ not appear	D^*

Table 4: Propagation from TS_i to TS_{i+1}.

$[\partial x(TS_i)]$ \ $[x(TS_i)]$	M	H	L
S	(M, S)	(H, S)	(L, S)
I	(M, I)	(H, S)	(M, I)
D	(M, D)	(M, D)	(L, S)
I_+	(H, I_+)	(H, S)	(H, I_+)
D_+	(L, D_+)	(L, D_+)	(L, S)

Table 5: Calculation of the final state.

	S^*	I^*	D^*	$(ID)^*$, $(DI)^*$
S	S	I_+	D_+	S
I, I_+	I	I_+	D_+	I
D, D_+	D	I_+	D_+	D

every sub-model is obtained. For detailed arguments on the simulation procedure, see reference (Ohkawa & Komoda 1993).

Backward Simulation

Overview

The backward simulation is considered as a process of deriving possible initial states of the target structural model from a behavior of a utility node (Axelrod 1976), in which we have interested particularly. The initial state of the model is specified with the qualitative status value and the change tendency of every node at $t = 0$ and the change tendencies of operable nodes at $t = 1$, which correspond to actions of a plan. In other words, the backward simulation aims at enumerating possible change tendencies of operable nodes at $t = 1$ based on the states of all node at $t = 0$ and sequence of change tendencies of utility nodes given as input.

In the backward simulation method, firstly, change tendencies of all nodes in a sub-model TS_i are calculated by the influence propagation with utility nodes as starting points. If the states of all nodes are clarified in TS_i, the results are propagated to the next slower model TS_{i+1} using the manner similar to the normal (forward) simulation methods. The state transitions that cannot follow given behaviors of the utility nodes are discarded in this process, and the survived state transitions give the possible solution, namely the change tendencies of operable nodes at $t = 1$.

Backward influence propagation in a sub-model

Basic propagation rule The backward propagation rules in a sub-model can be defined on the basis

Table 6: Backward propagation from y to x $[\partial x(t)]$ / $[y(t)]$.

$[\partial y(t)]$ \ $[y(t-1)]$	M	H	L
S	S/M	S/H, I/H	S/L, D/L
I	I/M	—	I/M
D	D/M	D/M	—

Table 7: Backward propagation from z to x, y ($[\partial x(t)], [\partial y(t)]$) / $[z(t)]$ (no special order in parentheses).

$[\partial z(t)]$ \ $[z(t-1)]$	M	H	L
S	(S, S)/M (I, D)/M	(S, S)/H (I, ?)/H	(S, S)/L (D, ?)/L
I	(I, ?)/M	—	(I, ?)/M
D	(D, ?)/M	(D, ?)/M	—

of the normal propagation rules shown in Table 1. Table 6 summarizes the backward propagation rules for $D(x, y) = +$. In case of $D(x, y) = -$, 'I' and 'D' for $[\partial x(t)]$ are swapped.

If more than one influences are propagated to a nodes, Table 7, which is generated by interpreting the rule of summation (Table 2) inversely, is applied.

Propagation considering operable node The backward propagation rules shown in Table 6 and 7 can be applied to neither the nodes connected with an operable node nor the operable node itself, because the change tendency of the operable node is determined by the plan as well as the influence propagation. For example, the change tendency of an operable node at $t = 1$ can be regarded as an action of a plan, and if the operable node is not influenced from other nodes, the change tendency of the node at $t > 1$ keeps 'S'. Table 8 shows the rules for backward propagation considering the operable node for each position of them as shown in Figure 2. The initial value of $flag(x)$ is 0. If the result of propagation is given as '?', all possible values are assumed.

One-step simulation If behaviors derived by the backward propagation rules cannot appear in the normal simulation process because of feedback loops in the model, these inconsistent behaviors must be removed. We introduce a mechanism of one-step (forward) simulation in order to find out inconsistent behaviors.

The results of backward propagation at time t are verified by the one-step simulation using the result of backward propagation at $t - 1$ and the change tendency of operable node derived at t. If a result of the

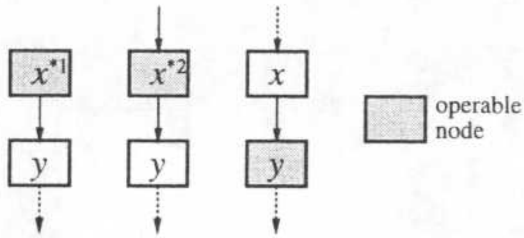

Figure 2: Positions of the operable node.

backward propagation is consistent with the one-step simulation, it is accepted.

Typical pattern identification

The result of (forward) simulation is described in the form of a sequence of the change tendencies including a typical pattern for each node (e.g. ISI(ID)* for node x_1, SSSID* for x_2, etc). The description is divided into two parts, the transitional part (such as ISI for x_1 and SSSI for x_2) and the equilibrium part (such as (ID)* for x_1 and D* for x_2). The typical pattern in the equilibrium part is identified easily by the forward simulation based on the final state of the transitional part. By comparing the typical pattern derived by the forward simulation with the given behavior, the consistency of the state transition is verified.

Procedure of backward simulation

The direction of influence, the propagation speed, the qualitative status value at $t = 0$ and the change tendency at $t = 0$ are given as initial states of the target model. In addition, the change tendencies for some utility nodes are given. Under these preparations, the procedure of the backward qualitative simulation of the structural model is shown as follows.

Step 1: Divide a given structural model into several sub-models $TS_0 \cdots TS_l$ based on the time scale. Suppose current sub-model $TS = TS_0$ and current time $t = 1$.

Step 2: Propagate influences backwardly from the change tendencies of the utility node at t in sub-model TS according to the rule shown in Table 6 and 7, until the change tendency at $t = 1$ for every node in TS has been determined. If the change tendency cannot be determined uniquely, enumerate all possible behaviors and store a condition to be required for each behavior.

Step 3: Execute the one-step simulation based on the result of backward propagation at $t - 1$ and the change tendencies of operable nodes at t. If the result of the one-step simulation matches the behavior derived in Step 2, save them.

Step 4: If $t = t_{max}$ where t_{max} indicates the last time of the transitional part, identify the typical pattern

Table 8: Backward propagation from y to x $[\partial x(t)]$ / $[y(t)]$ with operation node.

Operable node	Condition	Result of propagation	Post process
x^{*1}	$t=1$	$[\partial x(t)]=[\partial y(t)]$	
	$t>1,\ flag(x)=0,\ [\partial x(t-1)]=[\partial y(t)]$	$[\partial x(t)]=[\partial y(t)]$	
	$t>1,\ flag(x)=0,\ [\partial x(t-1)]\neq[\partial y(t)]$	$[\partial x(t)]=$ S	$flag(x)=1$
	$t>1,\ flag(x)=1$	$[\partial x(t)]=$ S	
x^{*2}	$t=1$	$[\partial x(t)]=[\partial y(t)]$	
	$t>1,\ flag(x)=0,\ [\partial x(t-1)]=[\partial y(t)]$	$[\partial x(t)]=[\partial y(t)]$	
	$t>1,\ flag(x)=0,\ [\partial x(t-1)]\neq[\partial y(t)]$	$[\partial x(t)]=[\partial y(t)]$	$flag(x)=1$
	$t>1,\ flag(x)=1$	$[\partial x(t)]=[\partial y(t)]$	
y	$flag(y)=0$	$[\partial x(t)]=?$	
	$flag(y)=1$	$[\partial x(t)]=[\partial y(t)]$	

*1: In case that no influence is propagated to node x.
*2: In case that node x is influenced from other node.

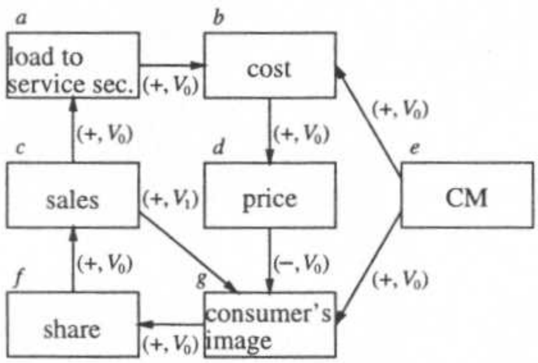

Figure 3: An example of simulation model (model 1).

of the equilibrium part for each node using the forward simulation. If derived patterns are consistent with given behaviors, consider them as possible state transitions. If $t < t_{max}$, increase t and go Step 2.

Step 5: If $TS = TS_l$, output the sequences of the change tendencies of all nodes for each sub-model as the result, and terminate the simulation.

Step 6: Propagate the last state in the current sub-model $TS(= TS_i)$ to the succeeding sub-model TS_{i+1} according to the rules defined in Table 4. Suppose $TS = TS_{i+1}$, go Step 2.

An example of backward simulation

The procedure of the backward qualitative simulation has been implemented on the workstation (SUN SPARCstation2) using the C language. We show an example of application of the method to a structural model about consumer's image shown in Figure 3. In this model, the nodes 'price' and 'CM' are operable nodes and the node 'sales' is a utility node.

Table 9: Simulation results.

No.	Initial state		Condition
	price	CM	
1	D	I	
2	I	I	$E(d,g) < E(e,g)$
3	S	I	
4	D	D	$E(d,g) > E(e,g)$
5	D	–	
6	–	I	$E(d,g) < E(e,g)$
7	–	D	$E(d,g) > E(e,g)$ and $E(a,b) < E(e,b)$

The backward simulation was executed under the condition that the initial values of the change tendency and the qualitative status value of every node are 'S' and 'M' respectively and the behavior of 'sales' are (behavior of TS_0, behavior of TS_1)= (SII(DI)*,II*). As a result, seven kinds of initial states of the operable nodes were calculated in about 0.5 second. The simulation results are summarized in Table 9. In the table, $E(x,y)$ means the degree of influence from node x to y, and '–' indicates the "don't care" state. For example, the result of No.3 suggests that the strategy of keeping the price and improving the CM produces soaring sales under any condition.

Discussion

The efficiency of the backward simulation is evaluated by comparing the number of trials and the total execution time to derive the initial states of the operable nodes with the forward simulation, where all possible combinations of the states of operable nodes are considered.

Table 10: Comparison with forward simulation.

Model	# of state	Backward		Forward	
		# of exec.	Time (ms)	# of exec.	Time (ms)
model 1	7	1	531	10	2,380
model 2	43	1	97,412	131	1,183,884

We evaluated the performance of the methods using two structural models, the same model as shown in Figure 3 consisting of 7 nodes and 9 arcs (model 1) and the more large model about the same theme consisting of 14 nodes and 20 arcs where factors such as 'capital investment' and 'labor cost' had been additionally considered (model 2 shown in Figure 4). The operable nodes of the model 1 are 'price' and 'CM'. The model 2 has two additional operable nodes ('extending branch' and 'office automation') including them. The utility nodes is 'sales' for both models.

The result of comparison is shown in Table 10. '# of state' indicates the number of initial states derived by the backward simulation, and '# of exec.' means the number of trials to obtain all possible solutions. 'Time' means the total execution time.

This result tells the following effectiveness of the backward simulation.

- Performance of the backward simulation for the relatively large scale model is more than 10 times as high as the one of the forward simulation from the view point of the total execution time.
- Difference of the efficiency between both of methods widens as the target model becomes large.

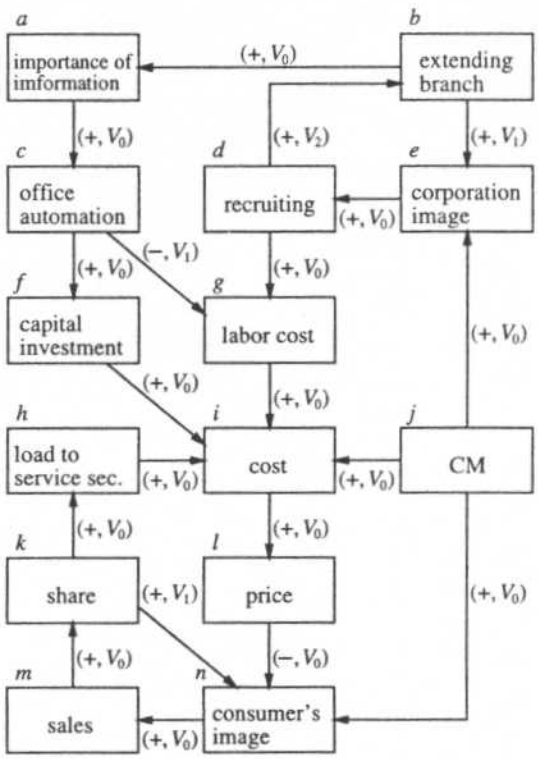

Figure 4: Simulation model (model 2).

Conclusion

This paper reported the backward simulation method that can generate possible initial states of the operable nodes from the desirable behavior of the utility nodes. Through the comparison with the forward simulation, the efficiency of the method was clarified.

On the other hand, the backward simulation never supersedes the forward simulation completely. The combination of both of them is more useful for the strategy planning. For example, after clarifying an essential factor that is inferred from the results of the backward simulation, we can evaluate the effect of the essential factor in detail using the forward simulation. We have developed the GUI based system SPLEQS (Strategy PLan Evaluation system base on Qualitative Simulation) that integrates both of the method and other features, such as the edit of the structural models, the visualization of the simulation results with graphs (Hata, Ohkawa & Komoda 1994), the automatic scenario generating (Hiramatsu et al. 1995), etc.

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