DEVELOPMENT OF LCC EVALUATION SYSTEM FOR CIVIL ENGINEERING INFRASTRUCRES

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ABSTRACT**:** This paper introduces a systematic method for LCC(Life Cycle Cost) evaluation of civil engineering infrastructures. LCC evaluation requires a series of modeling, that is, modeling of functionality of target structures, maintenance activities, uncertain events caused by various conditions of target structures and its environment, incurring costs and so on. Authors are developing a LCC evaluation system which encompasses all of those aspects so that can be a practical tool in real managemental situation. This paper introduces a framework of LCC evaluation system and the idea of each sub-part that constitutes the framework.

This paper especially focuses on two parts of the system, i.e., modeling of functionality of structures and maintenance activity. Regarding functionality modeling, authors point out that civil engineering infrastructures can be categorized into two types from the point of view of LCC modeling, that is, self-deteriorating structures and structures exposed to uncertain natural hazards. Based on the categorization, two types of models are introduced for expressing functionality of structures, Markov model and hazard-fragility model, and then described is how they are applied in LCC modeling.

For LCC evaluation, maintenance activity is necessary part to be modeled as well. This paper also describes how maintenance activity is built in the two types of models mentioned above. In Markov modeling, maintenance activity is regarded as a transition process from worse states to better states, while in hazard-fragility modeling, maintenance activity is expressed as change of fragility curve.

Finally computer software system being developed by authors is introduced. This system consists of multiple parts, that is, modeling of structures, maintenance activity, events caused by various conditions of infrastructures and costs associated with all stages of LCC modeling. Each part is briefly described with its features, and then this paper concludes with introducing future development of the system being planned by authors.

KEYWORDS: LCC evaluation, Markov deterioration model, Hazard-Fragility model, Maintenance, Risk, Decision making

1. INTRODUCTION

Many civil engineering infrastructures in Japan have a long service life, resulting in higher costs for maintenance and retrofitting than for constructing new facilities. Public investment is under severe downward pressure, however, and maintenance activity must be cost-effective, reasonable and transparent.

Authors believe that it is important to develop a systematic and concrete method of LCC evaluation in order to make maintenance activity more reasonable and transparent.

This paper introduces a LCC evaluation system of civil engineering infrastructures being developed by Taisei Corporation, that should be a powerful tool for strategic planning of maintenance activity. The system consists of multiple parts, each of which models various components required for LCC evaluation. This paper describes general idea of the whole system and feature of each component.

The second chapter describes the framework of the whole LCC evaluation method. Next two chapters deal with modeling of structures and maintenance activities, that is, the third chapter explains how civil engineering infrastructures are modeled in LCC evaluation system, and the fourth chapter how maintenance activities are modeled and combined with structure models. The fifth chapter mentions how to model events and accompanying costs caused by conditions of structures and maintenance activities. Finally the computer software system being developed by authors are introduced and then this paper concludes with mentioning our future plan of system development.

2. FRAMEWORK OF LCC EVALUATION SYSTEM

LCC evaluation needs to consider various aspects of target structures during their lifetime. Therefore, LCC evaluation inherently requires multiple steps of modeling. LCC evaluation system being developed by authors consists of a series of modeling each of which calculates various quantities.

Fig.1 shows basic framework of our LCC evaluation system. The first step is modeling functionality of target structures. This step basically models how service level of the structures in their lifetime can change depending on their conditions, e.g. effects of deterioration or uncertain future hazardous disasters, etc.

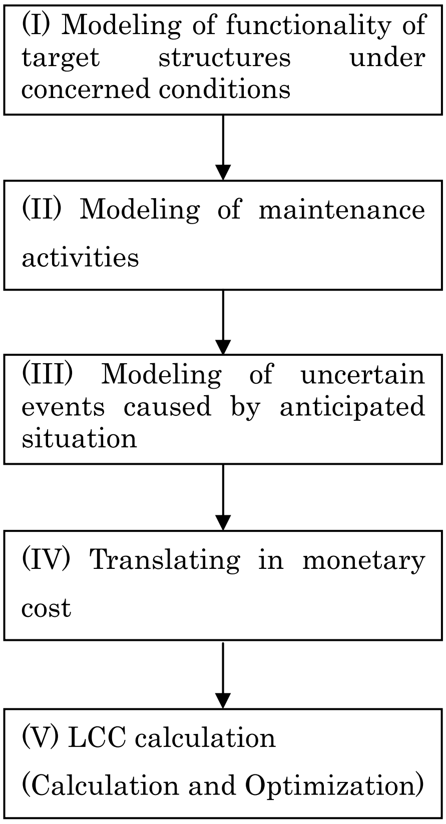


Fig.1 Steps that constitute LCC evaluation system

The second step is modeling of maintenance activities. This step includes modeling of maintenance type, that is, what kind of maintenance activities are carried out, effects of maintenance, that is, how well service level of structures is recovered after the maintenance.

The third step models uncertain events that may happen on conditions of structures, e.g. any accidents caused by deterioration of insufficiently maintained structures, or any catastrophic damages caused by unforeseen disasters, etc.

The fourth step is translation of all phenomena described above into monetary terms. In this step, all quantities are evaluated with monetary cost. Here, it must be noticed that it is important to consider not only anticipated real cost but risk cost which is uncertain to happen. For example, considering maintenance activity of deteriorating structures, any real cost cannot happen if any maintenance activity is not carried out, which can mislead to the conclusion that no maintenance is cost-effective in spite of increasing risk of potential accidents triggered by poor maintenance. To avoid this misleading, anticipated but uncertain accidents and accompanying costs have to be considered as risk cost in LCC modeling, which enables trade-off analysis between maintenance cost and risk cost caused by lack of maintenance.

The last step is LCC calculation part. Authors consider this step not only as a part for LCC calculation but also a part which analyzes calculation results. The most important mission of LCC evaluation is to supply rich information that helps decision makers to reach an optimal solution of managemental activity. Therefore this part should include capability of sensitivity analysis, uncertainty analysis or optimization to help engineers to make an adequate decision.

In the next three chapters, each step of LCC evaluation system is described in sequence, and in the final chapter, LCC evaluation system is introduced.

3. Modeling of functionality of target structures

There are many types of civil engineering infrastructures, each of which has unique features. But authors consider that they can be roughly categorized into two types from the point of view of LCC evaluation, that is, self-deteriorating structures and load-resistant structures. Basic idea of those features is shown in Fig.2 and Fig.3.

Fig.2 shows behavior of self-deteriorating structures. Service level of structures is supposed to decline with time because of deterioration but the declining rate is uncertain. Therefore we need to express the declining curve probabilistically.

On the other hand, Fig.3 shows feature of load-resistant structures. This type of figure is familiar in reliability engineering arena. Since both of load(demand) and strength(supply) of structures are inherently uncertain, both of them need to be expressed probabilistically, that forms a basis of fragility estimation.

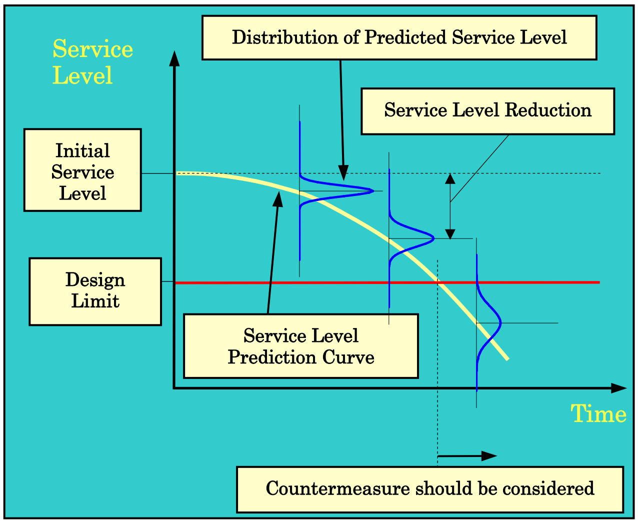


Fig.2 Behavior of self-deteriorating structures

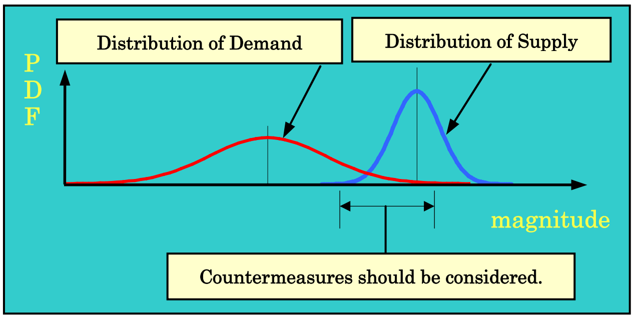


Fig.3 Behavior of load-resistant structures

In the next two clauses, it is shown how they are modeled in our LCC evaluation system.

3.1 Markov deterioration model

For self-deteriorating structures, Markov modeling approach is applied. Markov model describes the system by its states and the possible transitions between these states. A simple example of application of Markov model to deteriorating civil engineering structures is schematically shown in Fig.4. In Fig.4, state of a target structure is supposed to be classified into three states, i.e., “good” condition, “not good” condition and “bad” condition, and transition process is simply limited to from “good” to “not bad” and from “not bad” to “bad”. Behavior of the system(structure) is controlled with transition probabilities.

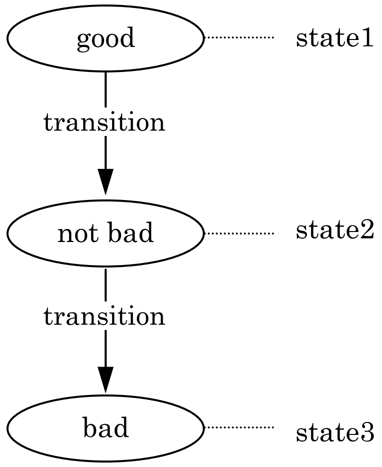


Fig.4 The idea of Markov deterioration model

Mathematically, Markov model is expressed with state probability vector and transition probability matrix. Transition probability p_{ij} that the process is in state i at time n-1 and it will be in state j at time n is expressed as follows.

$$p_{ij} = P\{X_n = j \mid X_{n-1} = i\} \qquad (1)$$

To define the Markov process X_n, it is necessary to assess the transition probabilities between all possible condition state pairs. When there are K states, transition probabilities are expressed in matrix form,

$$\mathbf{P} = \begin{pmatrix} p_{11} \cdots p_{1K} \\ \vdots \ \ddots \ \vdots \\ p_{K1} \cdots p_{KK} \end{pmatrix} \qquad (2)$$

Leting $\mathbf{q}=(q1,q2,,,,qK)$ denote the state probability vector at initial time step, any state probability at time=n is expressed in the matrix form,

$$\mathbf{q}_n = (q1,\cdots,qK)\begin{pmatrix} p_{11} \cdots p_{1K} \\ \vdots \ \ddots \ \vdots \\ p_{K1} \cdots p_{KK} \end{pmatrix}^{n-1} \qquad (3)$$

$$= \mathbf{q}\mathbf{P}^{n-1}$$

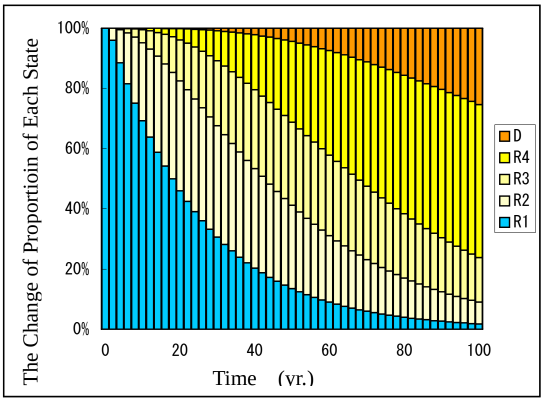


Fig.5 Change of proportion of each state under constant transition probability

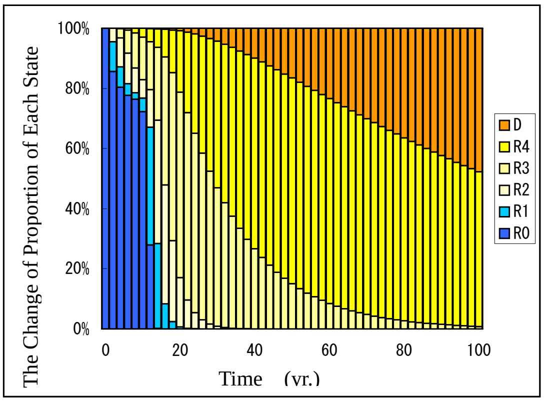


Fig.6 Change of proportion of each state under varying transition probability

This equation means the probability of a process being in any state can be calculated by multiplication of transition probability matrices and initial state probability vector.

Fig.5 and Fig.6 show examples of change of state probability vector(proportion of each state) with time, where each color indicates each state. Fig.5 is a calculation result with constant transition probabilities, where lifetime of any state distributes exponentially. Fig.6 is a result with varying transition probability, which shows more irregular behavior than Fig.5. This type of model is useful to express deterioration of a material having a clear average lifetime.

3.2 Hazard-fragility model

For load-resistant structures, hazard-fragility model is applied. In hazard-fragility model, uncertain load(demand) is expressed with hazard model and strength(supply) of target structures with fragility model. Hazard-fragility model is very popular especially in seismic risk analysis. Fig.7 and Fig.8 show typical examples of hazard curve and fragility curve in seismic risk analysis. Both of them show change of probability with maximum input acceleration of an earthquake and they are utilized to calculate the expected loss caused by earthquakes.

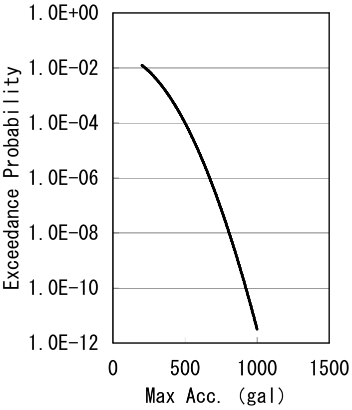


Fig.7 An example of hazard curve

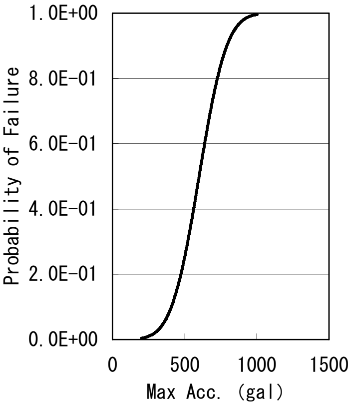


Fig.8 An example of fragility curve

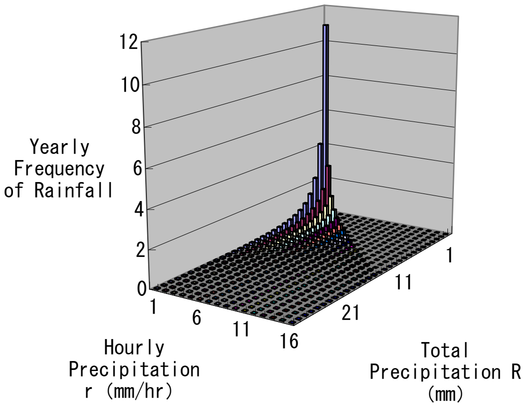


Fig.9 An example of two-dimensional hazard curve

Authors are trying to apply this method to other phenomena than earthquakes and to expand the application range. Fig.9 shows one of our trials to expand the capability of hazard curve. This example is a two dimensional hazard-curve for expressing precipitation hazard which is characterized with two parameters.

4. Modeling of maintenance activities

In order for LCC evaluation to be reasonable and transparent, it is very important to model maintenance activity. In our LCC evaluation system, maintenance activity model is built into both of Markov deterioration model and hazard-fragility model.

In Markov deterioration model, maintenance activity is expressed with a transition from a worse state to a better state. This process is schematically shown in Fig.10. It should be noticed that the transition by maintenance activity is not probabilistic but deterministic if the maintenance is scheduled beforehand.

Mathematically, the maintenance matrix can be expressed with matrix like transition probability matrix. However, transition probabilities in the maintenance matrix must be 1 or 0 because

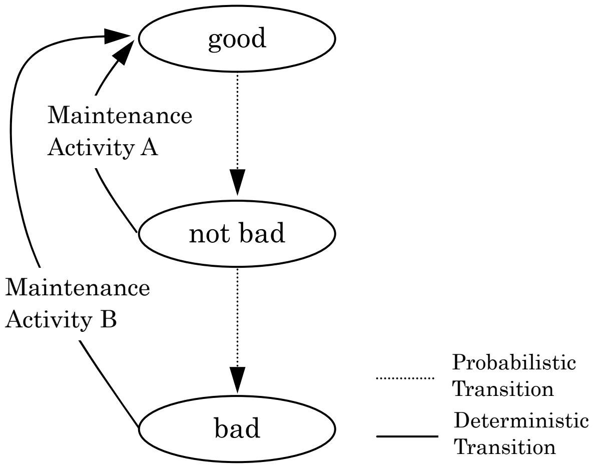


Fig.10 Modeling of maintenance in Markov deterioration model

maintenance activity is deterministically defined as long as it is planned in advance.

In hazard-fragility model, maintenance activity can be expressed with change of fragility curve. Fig.11 shows a simple example. In Fig.11, the original fragility curve shifts to the right after maintenance activity. Shift distance between the original fragility curve and after maintenance means the effect of the maintenance and should depend on type of maintenance.

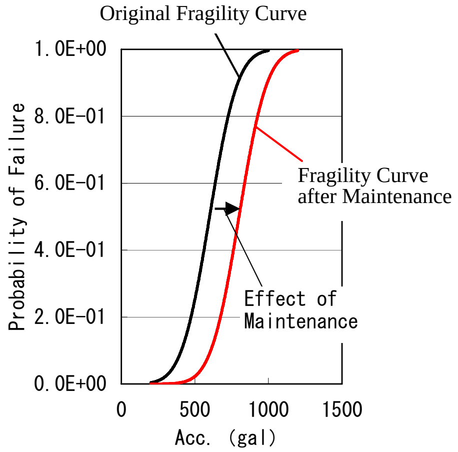


Fig.11 Representation of maintenance in fragility curve

5. Consequent events modeling and translation into monetary terms

For LCC evaluation, after modeling structures or maintenance, it is needed to consider all events that would happen as a result of all phenomena modeled earlier. Any damages or losses that is not modeled in structure modeling or maintenance modeling should be included here. In our system, this events modeling is integrated with both of Markov deterioration model and hazard-fragility model.

Fig.12 shows a simple idea of consequent events modeling in Markov deterioration model. In this Markov process, some consequent events are supposed to be caused by “bad” condition of the structure, which might cause some losses as well. These events are usually uncertain, being defined as risk cost, that is, occurrence probability times estimated loss.

Fig.13 shows the same idea for hazard-fragility model. In this case, some events are anticipated to happen because of collapse of the structure.

Although only simple idea is illustrated in Fig.12 and Fig.13, in real modeling, consequent events are usually complicated and modeled with event tree, where many possible events are considered, sorted out without losing the essence of the problem and logically organized.

After finishing events modeling, all items, including the structure condition, maintenance activity and consequent events are translated into monetary terms, which forms basis for LCC evaluation.

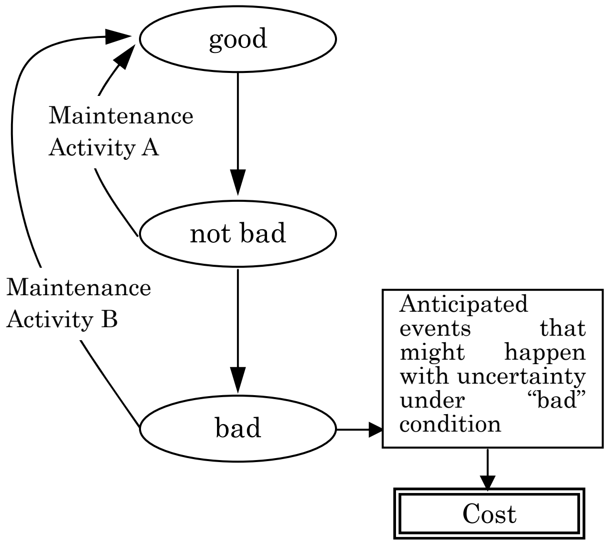


Fig.12 Modeling of consequent events in Markov deterioration

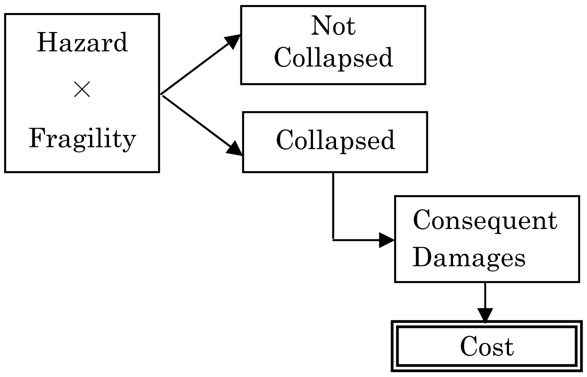


Fig.13 Modeling of consequent events in hazard-fragility model

6. LCC evaluation system

This chapter briefly introduces our LCC evaluation system currently under development. As mentioned in the second chapter, our LCC evaluation system consists of (1)structure model, (2)maintenance model, (3)consequent events model, (4)translation to monetary terms and (5)LCC calculation and optimization.

Microsoft Excel is highly utilized as a platform of the system, and almost all user interfaces, e.g. parameter setting mode, definition mode of deterioration curve, hazard curve or fragility curve, or event tree modeling mode, etc., are developed with Excel VBA. Core calculation part of LCC evaluation is programmed with C++ and the executable program is called from Excel VBA. Fig.14 to Fig.18 show screen snapshots of LCC evaluation system.

Since LCC evaluation requires many steps of modelings, many cumbersome preparative calculations are required before starting core calculation. Our objective of the software development is to make calculation as easy as possible, and to help engineers to concentrate on strategic planning, not just calculations. This system have been used and tested in a couple of projects by authors, and it appeared to be very useful and practical tool that can give rich and prompt information for making a right decision in practical situation.

Authors are planning to continue further development in the future in order to make the system more capable and more convenient. As the next step of the development, several important points can be listed as follows.

(1)Data Analysis capability for defining deterioration curve or hazard and fragility curves

(2)Modeling capability of network system

(3)More enhanced capability of analysis and optimization of LCC calculation results.

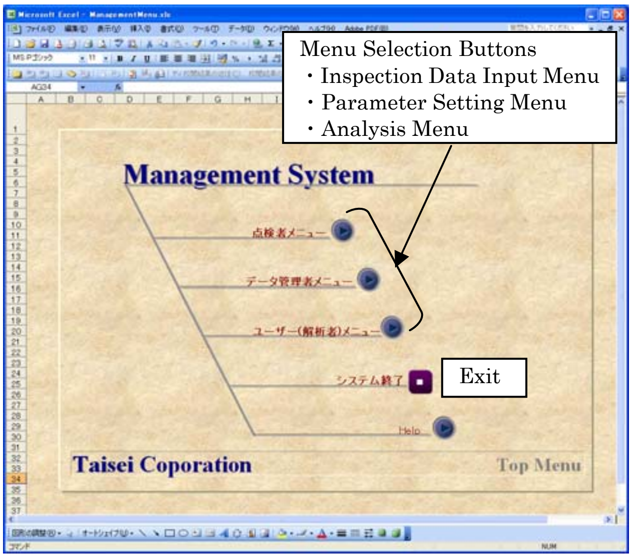


Fig.14 Top view of LCC evaluation system

From this top menu, users jump to each menu as need. Buttons are for "Inspection Data Input menu", "Parameter setting menu", "Analysis Menu" and "Exit".

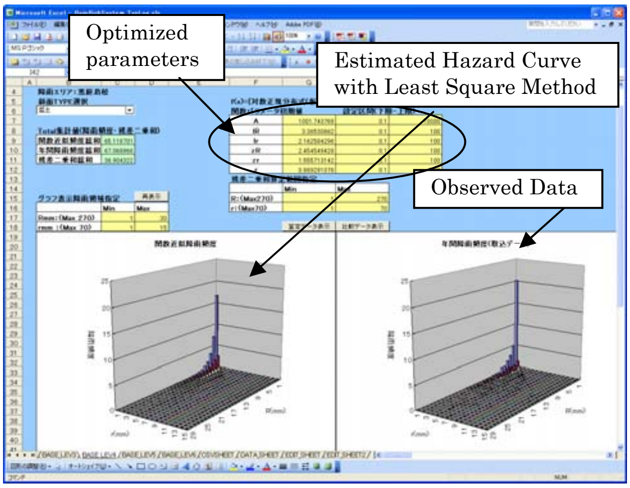


Fig.15 View of hazard definition mode

This screen is for defining hazard curves with Least Square Method from observed data.

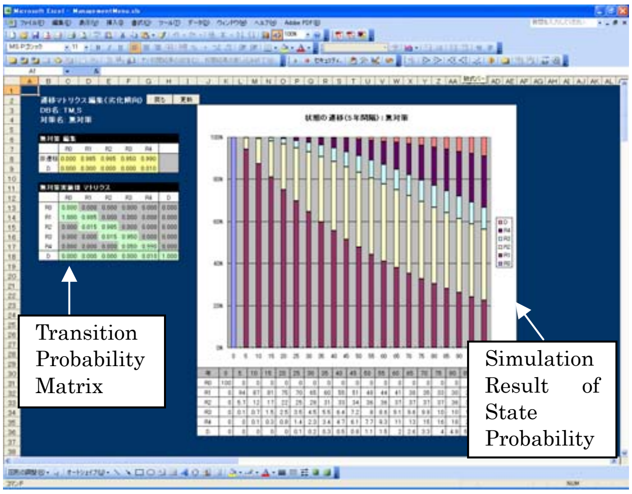


Fig.16 View of state probability simulation result

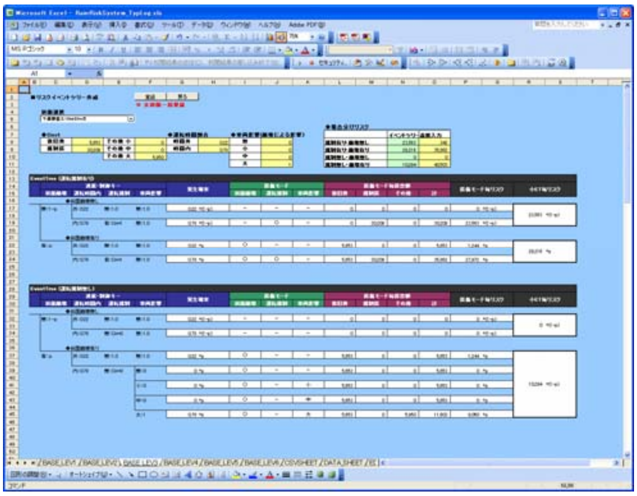
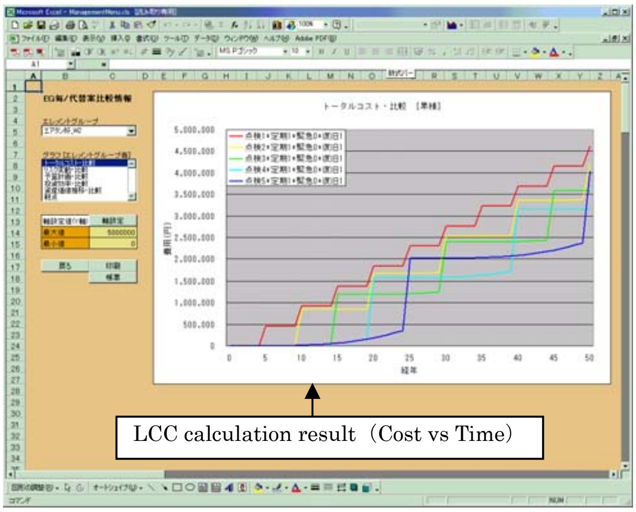


Fig.17 View of event tree definition mode

This menu is for event tree definition. Probability and cost for each event is denined here.



LCC calculation result（Cost vs Time）

Fig.18 View of LCC caluculation results output

This view shows camparison of LCC’s for deteriorating structures, calculated with various inspection intervals. Each line shows LCC increase on the condition of given inspection interval. Risk cost, which is supposed to be caused by potential accidents is included in LCC. Inspection cost causes discrete change of LCC curve at the time of inspection, while risk cost increases continuously with time.

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