# FLEXIBLE METHOD TO EVALUATE SEISMIC FRAGILITY

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## SUMMARY

In this paper, we discuss significance of the customer-oriented approaches in which problems such as seismic fragility evaluations can be solved even if the analytical data are not provided sufficiently. A flexible method to evaluate the seismic fragility of structures based on the concepts of co-Problem-Solving (co-PS) and measurable-objects is proposed as an example of the customer-oriented approach. The co-PS concepts are the dual of problem-solving concepts and the measurable objects are introduced in order to realize the co-PS concepts. Definition and characteristics of the measurable objects available to the co-PS activities to evaluate the seismic fragility of structures are discussed in detail. Since logical consistency is of particular importance even in the customer-oriented approach, the rules which controls methods to measure the fragility in the measurable objects are derived based on the fragility algorithm developed in the frequency domain. An agent capable of supporting the measurable objects is presented as well. Finally, the implemented agent system is introduced briefly.

## INTRODUCTION

In this paper we discuss on a flexible method to evaluate seismic fragility of structures. Usually, it is difficult to evaluate seismic fragility of structures since the complexity of seismic input motions and the nonlinear behaviors of structures intervene in the evaluation procedures. Recently a lot of researches on seismic fragility have been done. These researches are developed for important structures provided that sufficient technical data such as seismic records and physical parameters characterizing the grounds and structures are available. As far as insignificant structures are concerned, this is not the case. However, in all kinds of seismic risk management domains, seismic fragility evaluations are necessary for these insignificant structures as well. We should recognize the significance of the customer-oriented approaches in which problems such as seismic fragility evaluations can be solved even if the analytical data are not provided sufficiently.

We have proposed a flexible way of thinking of seismic fragility analysis in the frequency domain based on the energy concepts of seismic ground motions. The premise of the analysis method is to consider an abstract level. At a concrete level, detailed fragility analyses using comprehensive data are required. On the contrary, at an abstract level, flexible fragility analyses using incomplete data that need to be interpolated are necessitated. In the flexible method, it may be plausible to derive seismic fragility from the input described by sentences such as "typical 9 - story RC building on soft ground." In such cases, a knowledge based analysis method may play an important role to relate the input sentences and the fragility information to be obtained. Constructing such a fragility analysis method capable of deriving fragility information from symbolically described inputs is the objective of this paper.

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The fragility analysis method is developed in the frequency domain using energy indices of seismic input motions. This method should be flexible as mentioned before. In order to be flexible, we have introduced the agent architecture in which an agent has three engines: a fragility analysis engine, an input-translation engine, and an output-interpret engine. The input-translation engine translates symbolically described inputs to ones of the fragility analysis engine, and the output-interpret engine which supplies fragility information based on the outputs of the fragility analysis engine. The discussion of the method in this paper will be on the framework of these engines. In other words, the fragility analysis method in the frequency domain is analyzed for the purpose of developing the agent architecture capable of producing fragility information given incomplete symbolic inputs.

Firstly, in this paper, we discuss the significance of customer-oriented approaches in which problems can be solved even if the analytical data are not provided sufficiently. The approach based on concepts of co-problem-solving (co-PS) and measurable-objects is explained as an example of the customer-oriented approach. Next, a flexible method to evaluate seismic fragility is synthesized as the architecture of an agent system. Finally, the implemented agent system is introduced briefly.

In our standpoint, fragility information is indispensable for any kinds of structures even if there is no comprehensive data available. In seismic risk management problems, the flexible methods capable of evaluating fragility of structures without comprehensive data are needed. The contents discussed in this paper will contribute to develop such flexible methods.

## DEFINITION OF FLEXIBLE METHOD

### Customer-Oriented Approach

It is frequently pointed out that there is a definite gap between the knowledge provided by experts and the one required by customers. Experts cannot help presenting the methods that are familiar to them. Therefore, experts will emphasize the importance to consider the method-oriented characteristics, such as precision of methods, existence of sufficient data available, necessity of sufficient calculation time, etc. On the other hand, for customer, usually such methods are not essential.

In Fig.1, the image of the gap is illustrated. In the figure, the knowledge of experts is show by the notation $K$, and the one of customer $\partial K$, which is assumed as the boundary of $K$. In reality, experts' knowledge is divided into two parts; one is related to problem solving and the other to decision-making. In this paper, each assembly of knowledge is assumed to be a set. This means that we restrict the range of knowledge into the one that can be represented by sets. In this case, the boundary $\partial K$ can be defined in a topological fashion. For a set $K$, we can determine its interior $K^i$ and exterior $X \quad K^a$, where X denotes the support set of $K$ and $K^a$ the closure of $K$. The boundary $\partial K$ is equal to $K^a \cap K^{ic}$, where $K^{ic} = X \quad K^i$.

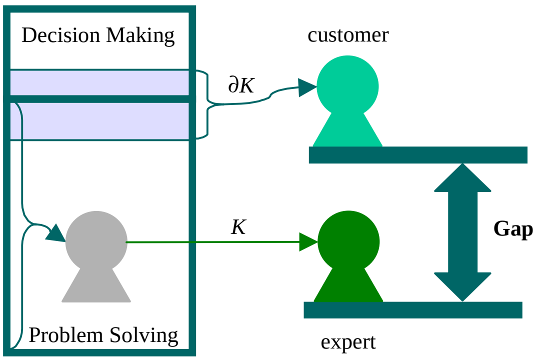

**Fig. 1 Image of Knowledge Gap**

The discussion on the distinction between $K$ and $\partial K$ is similar to the one in object-oriented approaches. In object-oriented approaches, methods should be encapsulated internally. In boundary $\partial K$, the interior of $K$ is eliminated. In this paper, we develop a customer-oriented approach assuming that this similarity holds. Namely, we assume that, although experts may respect the interior of $K$, customers place an emphasis on the boundary of $K$. Under this assumption, we can say that to grasp the boundary of knowledge is very important for customer-oriented approaches. Any methods included in the interior part of experts' knowledge should be encapsulated in customer-oriented approaches.

If analytical data is short, then experts cannot utilize their methods. Authors believe that any knowledge given by the experts in such a situation corresponds with its boundary $\partial K$.

## Co-Problem-Solving

In general, problem solving activities by experts are time consuming and expensive in cost. This is due to the fact that experts are fully constraint by customers during the activities. In this paper, it is assumed that the problem solving activities of experts are performed for the purpose of customers' satisfaction. Results obtained by the problem solving activities may contain descriptions that are specific to the corresponding customers. Frequently, such results may possess general properties available to every customer. For example, a result by seismic risk analyses applying to a region for a customer is also available to other customers related to the region. This means that results of problem solving should be utilized effectively.

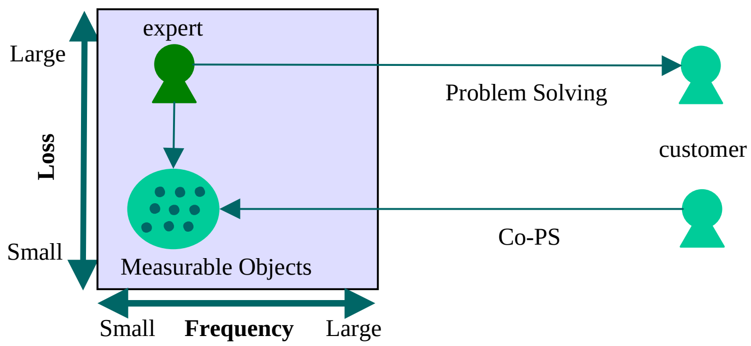


**Fig. 2 Image of Problem Solving and co-PS**

The authors have proposed a concept that is dual to problem solving. The concept is referred to as co-problem-solving (for short, we denote co-PS). The co-PS is dual to problem solving in that customers access to the results of problem solving by experts. Namely, the directions of operations are reverse of each other. For problem solving the direction of operations is from experts to customers and for co-PS from customers to experts. In Fig.2, the image of co-PS is illustrated. In co-PS, customers will try to find out the results akin to their problems to solve. If such results are found out, then we can say that customers' problems have been solved.

## Measurable Object

In order for customers to utilize co-PS approaches, results of problem solving by experts have to be provided. We refer to the results as measurable objects if and only if each of the results is defined autonomously and contains measured values such as risk and return. Since a measurable object is defined autonomously, customers will be able to access the object. And since a measurable object contains measured values, customers can

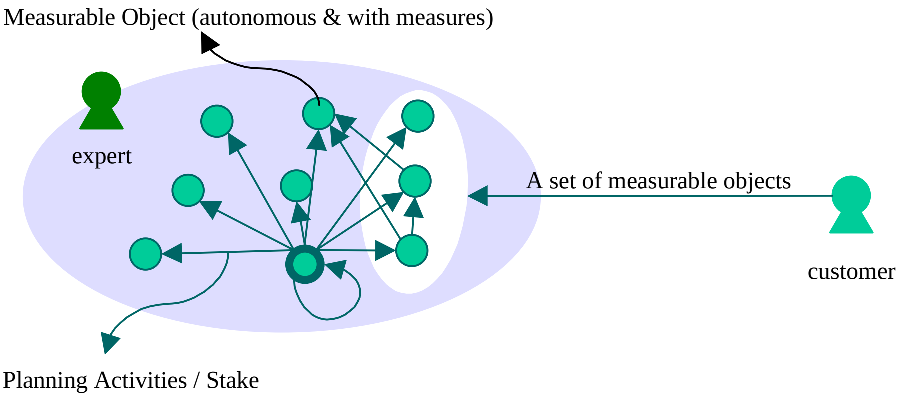


**Fig. 3 Image of Measurable objects**

examine the meanings of the object through the values.

In Fig.3, the image of measurable objects is illustrated. In the figure, using objects and arrows, measurable objects are described in a categorical way. The object in category corresponds with a measurable object, and the arrow with the relation between two measurable objects. We allot planning activities and stake relations to the arrow. Therefore, by examining an arrow, customers can recognize the differences between the corresponding measurable objects.

Usually customers will analyze their problem to reach a standard measurable object that is related to the definition of problem. Then, by assembling relating objects, a set of measurable objects can be synthesized by the customers. In this process, information on planning activities may be referenced. We refer to the obtained set as a portfolio since it contains objects with measures such as risk and return. Finally, in an evaluation process, a target object is selected from the portfolio considering stake relations. These processes correspond to the problem solving ones for customers. Thus customers can obtain a solution from the measurable objects which are derived by experts.

### Flexible Method

Flexible method can be characterized by three concepts: customer-oriented, co-PS, and measurable objects. Flexible method is customer-oriented in that we think the method should be constructed mainly for the purpose of customers' convenience by encapsulating sophisticated methods specific to experts. It supports co-PS in that its emphases are placed not on dynamic problem-solving activities by experts but on static results obtained through problem-solving activities by experts. Its main construct is measurable objects in that customer can obtain information on their problem solving through accessing to the measurable objects.

In this paper, we apply the flexible method to evaluate seismic fragility of structures. The main task is to derive measurable objects for the evaluation of the seismic fragility of structures. In the next section, we will explain the concrete contents of the task.

## SEISMIC FRAGILITY

### Definition of Seismic Fragility

Usually, the seismic risk of structures can be obtained through the two successive procedures, seismic hazard and seismic fragility evaluations. In seismic hazard evaluation, the probability characteristics of input ground motions are determined mainly from the fault source information. In the fragility evaluation, the conditional damage probability of structures given input ground motions is examined. Combining the hazard and fragility evaluations probabilistically, seismic risk is determined. In this paper, however, we refer to the seismic risk as seismic fragility. By the term 'seismic fragility' of structures, we imply the seismic risk of structures.

Risk is interpreted as the possibility of damage or loss. So, authors have tried to make a framework in which hazard plays a role of possibility and fragility a role of damage or loss. It is difficult, however, to make such a framework since the boundary between hazard and fragility evaluations is not crisp. In this paper, considering conversely, we esteem fragility as risk.

### Fundamental Algorithm

[Fukuwa, N. et al. (1999)] have proposed an effective approach in earthquake disaster prevention using Geographical Information System. The approach is essentially customer-oriented since all of its results on seismic risk are prepared for regional usage. However, it does not support measurable objects. In this paper, referring to the approach, we construct the measurable objects with information on the seismic fragility of structures.

One of the characteristics of this paper is to adopt the simplified method called flexible method to evaluate seismic fragility of structures. As [Fukuwa, N. et al. (1999)] illustrated, a data flow in earthquake response analyses consists of source, path, soil, soil-structure interaction (SSI), and structure. In most simplified methods, technically complicated procedures such as SSI evaluation are often neglected. In case of the SSI evaluation, its difficulty in frequency domain analysis prevents the simplified methods from considering SSI effects. Furthermore, in simplified methods, nonlinear behaviors of structures are also neglected.

In this paper, we introduce a data flow of seismic fragility evaluations that consists of source, path, soil, SSI, structure, facility, and fire environment. In the flow, facility and fire environment are prepared for evaluating the nonlinear behaviors of structure. Damage to structures causes damage to facilities, damage to facilities causes damage to fire environment, damage to fire environment trigger fires, and the fires causes damage to structures. This is an example of the nonlinear behaviors of structures considered in this paper. As far as loss is concerned, it is very important to consider damage to facilities. For customer-oriented approaches, both facility and fire

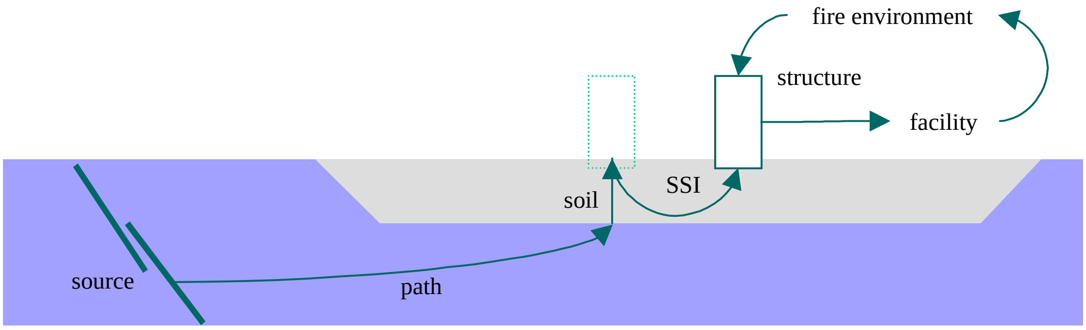


**Fig. 4 Data Flow of Seismic Fragility Evaluation**

environment are not neglectful in the data flow of seismic fragility evaluations.

In Fig.4, the data flow of seismic fragility evaluations in this paper is illustrated schematically. Note that the elements appearing in the figure are utilized to characterize attributes of the arrows defined among measurable objects in this paper. We refer to the elements as states.

Utilizing the states, an algorithm of seismic fragility can be represented as shown in Fig. 5. We refer to algorithm represented by states as core algorithm. In Fig.5, the core algorithm to evaluate seismic fragility is shown, where $a_B$, $a_S$, and $a_F$ are indexes of ground motion strength, and amplification factors are denoted *amp*

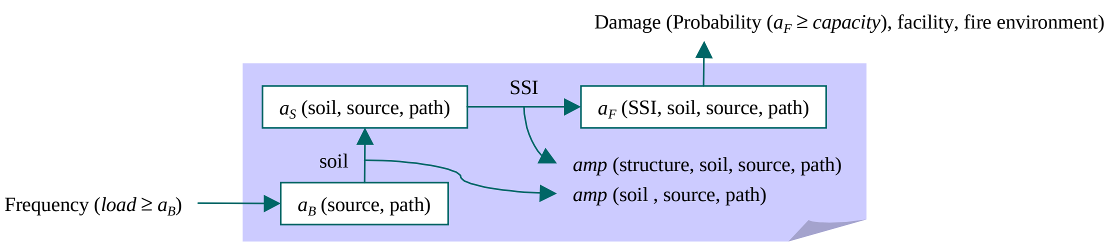


**Fig. 5 Core Algorithm to Evaluate Seismic Fragility**

for short. We think the algorithm is core since the similar architecture can be seen for general risk problems as well.

The dynamic behavior of structures must be evaluated in the frequency domain since the properties in SSI phenomena are frequency dependent. In the evaluation, energy indexes of seismic input motions play an important role. By the term energy indexes of a seismic input motion, we mean basic characteristics relating to its energy spectrum in the frequency domain. Accordingly, in order to determine the SSI effects, the relations among structure, soil, source, and path must be arranged in the frequency domain using energy indexes. The relations represented symbolically play a central role in flexible method since incomplete data can be coped with only by the aid of knowledge such as expertise. We refer to the represented relations as frequency-domain knowledge.

It becomes our target to represent the core algorithm for seismic fragility evaluations in terms of the frequency-domain knowledge in a customer-oriented fashion. The following standard states contribute to this end.

**Standard States**

In co-PS approaches, it is assumed that experts cannot utilize the sufficient data specific to customers. It is also assumed that what is available to experts is basically standard data. This means that we evaluate seismic fragility only for structures with standard sources, standard paths, standard soils, etc. The standard states should be defined to cover the whole problems that may be introduced by customers.

The standard states can be described by classifying each of states. For each state, based on expertise, we can derive a set composed of its typical instances. We refer to the set as a class. Note that classes must be specified and designed to be available to the frequency-domain knowledge representing the frequency dependent SSI effects. Let $C_s$ be the class corresponding to the state *s*. Then the values appearing in the core algorithm can be represented by the mappings whose domains are the Cartesian products of the classes. For example, the amplification factor *amp*(*soil*, *source*, *path*) can be determined by a mapping $f : C_{soil} \times C_{source} \times C_{path} \rightarrow \boldsymbol{R}$, where $\boldsymbol{R}$ is the set of real numbers. By these mappings derived for standard states, the values appearing in the core algorithm can be determined. We refer to the values as standard core values.

In determining the classes of states and the standard core values, we think the expertise plays an important role. Therefore, we ask several experts to determine the classes and standard core values. In this paper, we don't discuss the contents of the classes and standard core values, because we think not implementing the contents but creating the framework is essential in flexible method.

**Deviation from Standard States**

It is not plausible that customers' states are just corresponding to the standard ones. In these cases, if customers require, deviations from the standard states must be considered.

In this paper, deviation from standard is described by deviation factors. The deviation factors are specification factor (defects of configuration and/or continuity), maintenance factor (lack of diagnosis and repairs), exposing factor (appearing defects and/or inconvenience), design factor (insufficient design), technical factor (lack of technical consideration), time factor (rating based on adopting codes and guidelines), and arrangement factor (insufficient arrangement). In this definition we assume that there are specification and design activities introduced for classifying the standard of each state. These activities are related to the measurement of risk and return in deriving measurable objects. In other words, we acknowledge the existence of risk and return in each of states. The risk and return are implicitly generated when the standard of states is specified and designed as a class. The acknowledgment of risk and return is inevitable in flexible method. It is also assumed that maintenance and exposing factors are neighborhoods of the specification factor, and technical and time factors are neighborhoods of the design factor. Furthermore, by the arrangement factor, we try to consider the deviation introduced by the arrangement activities between specification and design.

We allocate an index for each of deviation factors. The index is determined so that no deviation from standard or no information leads to null effects. We refer to the index as deviation index. Constructing a scoring algorithm based on deviation indexes, for each of states, we can calculate a score that indicates the deviation level from the standard. The scores of states are used to modify the standard core values to obtain the core values of deviated states.

In customer-oriented approach, the scoring algorithm must be designed so that the obtained core values can cover the whole of the plausible cases for customers. In order to realize this coverage condition, we firstly determine the deviation indexes, and then allocate their contents. In the task to allocate contents, we think expertise plays an important role, and we ask the task to several experts.

**Architecture of Measurable Objects**

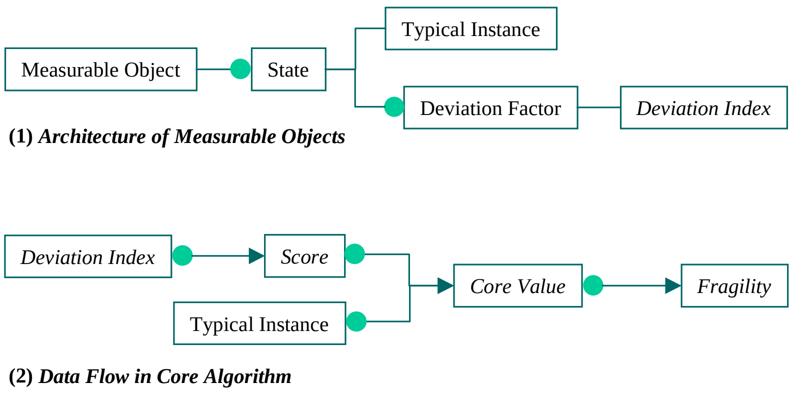


**Fig. 6 Architecture of Measurable Objects and Data Flow in Core Algorithm**

Based on the fundamental algorithm, standard sates, and deviation factors, we can derive measurable objects with the measures on seismic fragility. The architecture of the measurable objects can be illustrated as in Fig.6, where dots mean plural. In Fig.6, data flow of the core algorithm is also shown. Measurable objects shown in Fig.6 are autonomous and measurable in that these possess all data necessary to determine fragility.

As is recognizable from Fig.6, the architecture is independent of evaluating seismic fragility excluding the contents. Accordingly, the architecture on measurable objects can be applicable to other risk problems. This fact indicates that, only by exchanging contents or knowledge, we can construct other risk evaluation systems under the same framework.

**Implemented System**

An agent-based system that supports flexible method for seismic fragility evaluations of structures has been developed. The system is designed as the web server on inter-net, to which customers can access through the

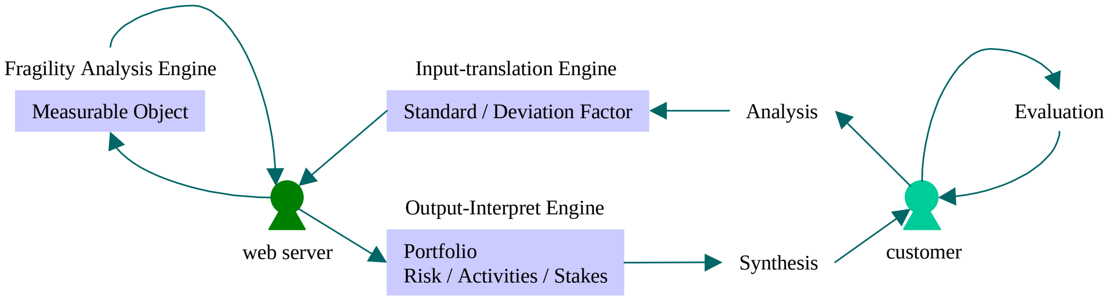


**Fig. 7 System architecture of web server to support the problem solving of customers**

web browsers. The cooperative architecture of the web server is introduced by means of considering an agent framework. The architecture of the system is summarized in Fig.7. In Fig.7, the process, which starts from the analysis task, is also shown.

The system is designed to support problem-solving tasks of a customer. In the system, the web server always possesses a solution and is composed of three engines with a rule-based inference function. The solution possessed by the web server is assumed to be a set of the data representing one of the measurable objects. The engines are input-translation engine, fragility analysis engine, and output-interpret engine. The input-translation engine translates the standard and/or deviation data given by the customer into the data available for the fragility analysis engine. This engine helps the customer to perform analysis tasks. By the data, the web server turns to possess a solution for the customer. The fragility analysis engine is utilized in order to change the solution previously derived to the one for the customer. The output-interpret engine supports to construct a set of the plausible solutions that are related to the customer's interest. We refer to the set as portfolio. The constructed portfolio plays a role of the plausible solutions for the customer's synthesis task. By the information derived from the portfolio, the customer can proceed problem-solving tasks to the evaluation tasks, which are responsible to the customer.

Now the implemented system is designed to support basically the synthesis tasks of customers. For customers, the main consequence of using the system is to obtain a portfolio, i.e. a set of plausible solutions. It is our next target to apply the same framework to crisis management problems after a large earthquake takes place. In the crisis management, the portfolio-based information with alternative action plans plays an important role since decision making is strongly required under the condition that no data is available.

## CONCLUDING REMARKS

In this paper, we discuss significance of the customer-oriented approaches in which problems such as seismic fragility evaluations can be solved even if the analytical data are not provided sufficiently.

Firstly we defined a flexible method to evaluate seismic fragility of structures in a customer-oriented fashion. The flexible method is characterized by three concepts: customer-oriented approaches, co-PS, and measurable objects. The characteristics of the concepts are explained in detail. Next the flexible method is applied to the seismic fragility problems as one of the realizations of the concepts. In the application, a particular emphasis is placed on the soil-structure interaction (SSI) effects that are frequency dependent and complicated to solve. Although SSI effects are too complicated to take into account in most simplified methods, we believe that considering the effects is indispensable for customer-oriented approaches. Measurable objects based on frequency-domain knowledge using energy indexes are developed for this purpose. In the development, the classification of the standard states, the architecture and meanings of deviation factors, and the derived risk and return are discussed. Finally, the system implemented as a web server with inference functions is briefly explained.

## ACKNOWLEDGEMENT

The mathematical framework in this paper can be considered as the application of the mathematical plan developed by Dr. M. Izumi (Izumi Research Institute, Shimizu Corporation). Likewise, the agent framework used in this paper is conceptualized through the researches done previously [Nakai, S. et al., Fujii, H. et al., and Huang, H. et al.].

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