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Assessment of Safety Regulation by Social Simulation

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Following the worldwide trend of deregulation, safety regulation is under re-consideration, whereas various accidents still endanger our society. Some method that can take both production and safety management into account is therefore required to assess safety regulation. This research proposes a social simulation to assess influence of safety regulation on social utility.

The model used in this study is a multi-agent system where many production companies do business and evolve under the common environment. The model of each company contains elements related to both productivity and reliability. Safety regulation influences companies' activities as the environment. This simulation model is so flexible that it can be extended from simple to more complicated ones.

In conclusion, a useful method for assessment of safety regulation has been developed, and then several insights were obtained from test simulation comparing various regulation styles and methods.

Key Words: social simulation, safety regulation, multi-agent system, genetic algorithm

1. Introduction

Following the worldwide trend of deregulation, which intends to realize a competitive and vital society based on the market mechanism, safety regulation is also under restructuring in many countries [1]. At the same time people demands accountability to administration; scientific, rational, and efficient regulatory administration is highly required so that the maximum effects are obtained with restricted administrative resources. Meanwhile we are recently experiencing many incidents and accidents that endanger our society that people are concerned more and more about safety issues.

Various approaches are being proposed and tried to improve effectiveness of safety regulation such as performance-based or risk-informed regulation. The former, performance-based regulation, is a regulation style where just the functional requirements for achievement of safety are to be specified but choice of its concrete means of realization is left for business opearators. The latter, risk-informed regulation, is a regulation style where risk information is referred to in primary decision-makings in safety regualtion. Reform of safety regulation is now under way in US and European countries. Japanese authorities are also following this worldwide trend, but the progress is not necessarily satisfactory due to many reasons [2), 3)]. It is often because simply importing such ideas does not exactly fit the situation of another country. It is unclear, however, under what conditions a new regulation style functions effectively as expected more than the conventional one.

Safety regulation was ever studied as a socio-economic issue [4)], but rarely studied quantitatively as a technological issue. Many studies have been done in engineering to evaluate safety level of a particular technological system like probabilistic safety assessment [5)] or to assess human and organizational factors relevant to safety [6)]. Almost no methods have been established to assess social system for safety on a theoretical basis.

In this study, an approach of using an artificial society will be proposed to assess impacts of safety regulation on the society. The approach is based on multi-agent social simulation and genetic algorithm (GA). Case simulations will then be done under various conditions to obtain useful insights to design a safety regulation system.

2. Simulation model

Almost every kind of industry is now under some sort of safety regulation, but it is impossible to include all of them and to get universal insights. We will instead consider just an industry of production type. It is characteristic to this type of industry that direct damage will occur if any accident may bring about in its facility.

The target of simulation is a virtual society that consists of many companies producing some commercial goods. This artificial society is represented as a multi-agent system [7)], where each agent represents a company and safety regulation functions as the business environment equally for all companies.

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2.1 Company model

Each company produces some commercial goods and sells them to obtain operation costs and benefits. For simplicity it is assumed all products can sell. The production process of a company is represented as flow of resources, and economic values are represented by the amount of resources. A company is a kind of device, and it accumulates the gain of resources G for the business fund, i.e., output resources remained after deduction of input resources and production costs. If the fund is exhausted, the company goes bankrupt and is eliminated from the society. If any accident happens due to failures of the production facility of a company, the amount of output resources becomes less than the input.

Accumulation of business fund is calculated by the following equation:

$$CP_t = r(CP_{t-1} + G_t), \tag{1}$$

where CP_t is the fund at the end of term t, G_t is the gain obtained in term t, and r is the accumulation rate. In this study $r = 0.98$ was assumed.

Elements that compose a company are described below.

(1) Device

A device is a basic and conceptual element of the system. It performs some sort of transformation on input resources of Z and generates the output resources of Z'. A particular amount of operation cost C is required to operate a device. A situation such as $Z' < Z$ is defined as device failure. The probability that a device is in normal operation is called reliability. A company is referred to as the root device and failure of the root device is called an accident.

(2) Instrument

An instrument is an instantiated device that has three attributes: rate of value added V, reliability R, and operation cost C. For input resources of Z, an instrument outputs $Z' = (1+V)Z$ with a probability of R, and $Z' = 0$ with a probability of $1 - R$. This judgment is done independently for every device in each term. When it is assumed an instrument deteriorates by time, the reliability R decreases as $R = R_0 - TD$, where T and D are terms from the previous maintenance and the deterioration rate.

(3) Unit

A unit is an element of a line, and it contains an instrument. A unit collects resources from its multiple input links, processes the collected resources using the internal instrument, and then distributes output resources into its multiple output links.

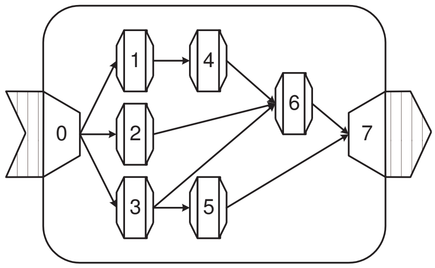

Fig. 1 An example of line.

(4) Link

Parallel links between units work disjunctively. That is, if any unit in the downstream is in failure, the corresponding link does not transfer resources to the failed unit so that no resources are wasted. Units arranged in serial represent conjunctive relation in the production process.

(5) Line

A noncircular directed graph of units is called a line. A line is the representation of a production line or a production facility of a company. An example of a line is illustrated in **Fig. 1**. Each company possesses at least one line. The total number of nodes in a line is called the size of the line and it is also called the size of the company that has the line.

2.2 Natural selection

Natural selection of companies under a competitive business environment is modeled by GA [8].

(1) Gene coding

A gene code of a company consists of two arrays of numbers: a line structure array and an instrument code array.

A line structure array defines the topological structure of a line, and it is composed as described below. Firstly, the units in a line are numbered sequentially descending the hierarchical structure from the input unit. A bit string is then generated for each unit such that a bit $B(i, j)$ is set unity if there is a link from Unit i to Unit j, or zero otherwise. For the case shown in Fig. 1, bit strings to be generated are {1, 1, 1, 0, 0, 0, 0} {0, 0, 1, 0, 0, 0} {0, 0, 0, 1, 0} {0, 1, 1, 0} {0, 1, 0} {0, 1} {1} from the input unit. The line structure array is generated by concatenating these strings.

An instrument code string is an array of class identifiers of instruments that are contained in the units.

(2) Genetic operation

Agents of this model do not have a life span. A company that exhausted its business fund goes bankrupt and is replaced by a newcomer that is generated from selected parent companies. Parents are selected by Russian roulette in proportion to amount of accumulated fund as fitness. This selection scheme is natural, because companies that gained a lot of benefits are apt to expand their business.

A pair of child companies are generated by cross over. In this process, both the line structure array and the instrument code array of the parents are cut at randomly selected positions and conjugated. Let us assume that parents' line structure arrays are B_1 and B_2, their instrument code arrays D_1 and D_2, and that child's line structure array and instrument code array are B and D respectively. Child companies are generated by selecting crossover points k, l, and m randomly, and crossing the parents' genes as follows.

$$B(i,j) = \begin{cases} B_1(i,j) & (i < k; i = k, j \leq l), \\ B_2(i,j) & (i > k; i = k, j \geq l), \end{cases} \tag{2}$$

$$D(i) = \begin{cases} D_1(i) & (i \leq m), \\ D_2(i) & (i > m). \end{cases} \tag{3}$$

If a fatal gene is generated, which does not correspond to any noncircular directed graph, it is recovered by flipping randomly some allele in a row or a column of the line structure array all elements of which are zero.

Mutation is done by rewriting randomly some allele of the line structure array or the instrument code array.

2.3 Safety regulation

Safety regulation is carried out essentially by inspection, and its style is characterized by inspection timing and inspection criteria.

(1) Inspection timing

Three options are assumed for inspection timing: prior, periodical, and posterior regulation. The prior regulation is imposed when a new company is established, periodical regulation at the beginning of term by a specific interval, and posterior regulation when a company caused an accident. If a company cannot satisfy the inspection criteria, it must pay a specified amount of fine.

(2) Inspection criteria

Three options are assumed: penalty-based, specification-based, and performance-based regulation. Penalty-based regulation is applied only to the posterior regulation, and a company that caused an accident is imposed a fine. In specification-based regulation, the class of instruments to be used to construct a line or the method of maintenance of each instrument is restricted. In performance-based regulation, the overall reliability of the production line of a company must achieve a certain criterion.

(3) Amount of fine and inspection rate

A fine is a particular amount of penalty imposed on a company that cannot satisfy the regulation criteria, and the amount of fine is a parameter. The probability that inspection is actually done at the time of inspection period is called inspection rate. If the inspection rate is much less than 100%, whether or not inspection will be actually done is unpredictable, and periodical inspection as such stands for uninformed inspection.

Table 1 Characteristics of instrument group 1.

Parameter	Values
Rate of value added (V)	$V_A = 0.2, V_B = 0.1$
Reliability (R)	$R_A = 0.99, R_B = 0.9$
Deterioration rate (D)	$D = 0.0$
Maintenance interval (M)	$M = \infty$ (no maintenance)
Correction cost (Cd)	$Cd_A = -0.8, Cd_B = -0.2$

3. Simulation with no maintenance

We first performed simulation using instrument classes that have a combination of attributes listed in **Table 1**. Reliability R of an instrument that is operating under a normal condition was constant; maintenance was required only when an instrument failed. A combination of V_A and R_A was not assumed to take trade off between productivity and reliability into consideration. Cost of an instrument was calculated by the following formula:

$$C = (1 + V)(1 - R) + Cd, \tag{4}$$

where correction cost Cd is a term for adjustment. The above cost includes both repayment cost and operation cost of an instrument. Only posterior regulation that the regulatory body imposes penalty to a company that caused an accident was assumed, and company size was fixed five or ten.

In the following, simulation was done with a society of 100 companies, and 100 or 500 runs were repeated for the same condition in case company size is 10 and the fine is equal to or less than 15. The results shown are averages with 95% confidence intervals. The overall performance of society is defined as the average of all companies, and it is evaluated at the end of evolution.

3.1 Relation between penalty and performance

(1) Productivity

Figure 2 shows change of average productivity as a function of penalty. Here, productivity means expected amount of production including risk of an accident.

In case company size is five, productivity monotonically decreases as the penalty-based regulation gets severe. In case company size is ten, however, productivity hits a peak when the regulation is severe to some extent. It

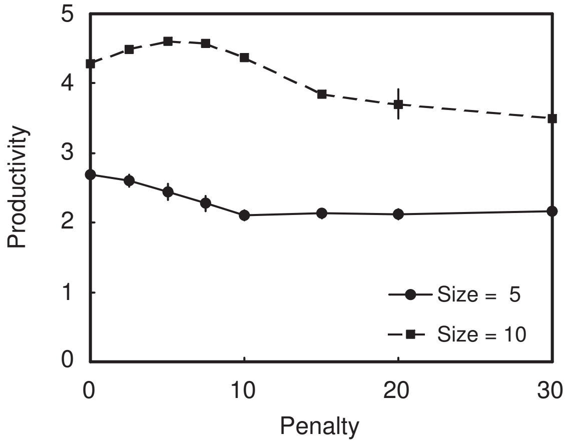

Fig. 2 Relation between penalty and productivity.

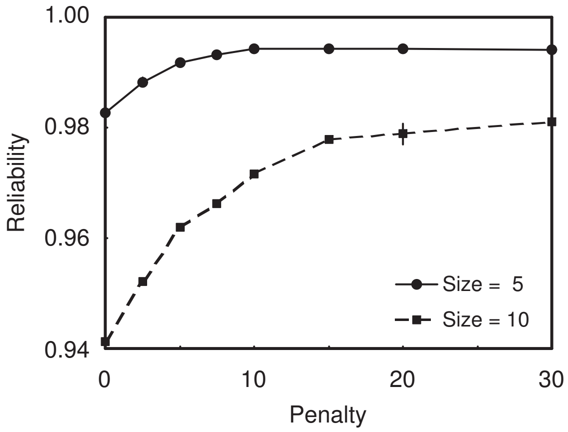

Fig. 3 Relation between penalty and reliability.

will mean that evolution pressure is not enough without regulation for companies of a larger size, because the line structure is too complex for optimization. In such a case, safety regulation works as evolution pressure to improve productivity, and productivity does not trade off with reliability.

(2) Reliability

Figure 3 shows relation between penalty and average reliability of companies. Reliability increases with increasing penalty for the both company sizes. Looking at Fig. 2 and Fig. 3 together, it can be said in general that productivity trades off with reliability. The reason why cases with a company size of five are more reliable than that of ten is because failure of any instrument in the line is more likely to cause shut down of the line for a large line than a small line. The effect of penalty saturates, because it is useless to raise penalty over the limit where a company that caused an accident cannot survive.

3.2 Social utility line and social utility curve

In order to look into closely the trade off relation between productivity P and reliability R, social utility U is defined with the following formula:

$$U = P - L(1 - R), \tag{5}$$

where L is the value of social loss resulted from an accident, which is determined by the scale of an accident and social valuation characteristics.

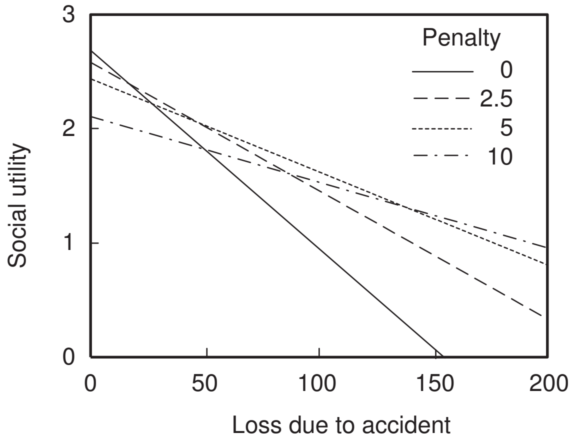

Fig. 4 Social utility achieved by various penalty.

Figure 4 shows the social utility achieved by various penalty levels for a company size of five. We will call the line that shows change of the social utility as a function of loss due to an accident a social utility line. If we choose a proper penalty at each horizontal position and connecting corresponding social utility lines, we can get a concave curve that represents the maximum social utility as a function of loss due to an accident. We will call this concave curve the social utility curve. If expected loss due to an accident is known, the most proper penalty that maximizes the social utility can be evaluated by obtaining the social utility curve.

4. Simulation with maintenance

We next performed simulation using instrument classes that have a combination of attributes listed in **Table 2**. A combination of V_A and D_A was not assumed, either. In these cases maintenance work makes sense, because reliability of each instrument degrades gradually and maintenance makes the status of an instrument new. Cost of an instrument was calculated by the following formula:

$$C = (1 + V)(1 - 5D) + Cd. \tag{6}$$

Maintenance work requires more cost by five times than the above normal operation cost.

Five regulation styles were compared: no regulation, penalty-based regulation, specification-based regulation

Table 2 Characteristics of instrument group 2.

Parameter	Values
Rate of value added (V)	$V_A = 0.2, V_B = 0.1$
Initial reliability (R_0)	$R_0 = 1.0$
Deterioration rate (D)	$D_A = 0.002, D_B = 0.02$
Maintenance interval (M)	$M_A = \infty, M_B = 5$
Correction cost (Cd)	$Cd = -0.8$

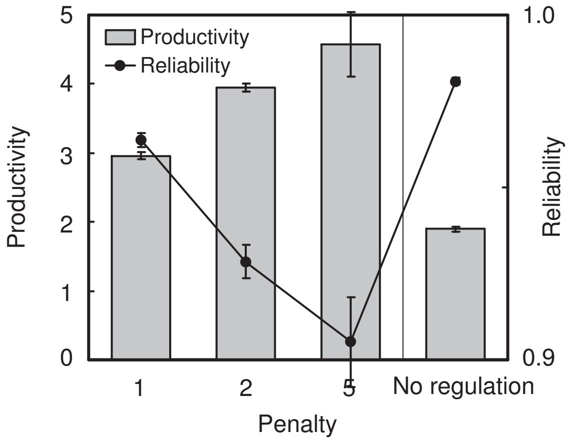

Fig. 5 Performance achieved by specification-based regulation 1.

(Specification 1) to enforce use of instruments with a deterioration rate of D_A, specification-based regulation (Specification 2) to enforce carrying out maintenance every five terms, performance-based regulation to request keeping reliability of the line above 0.98. The amount of fine for Specification 2 was two, and otherwise five.

4.1 Comparison of regulation styles

The specification-based regulation that enforces use of instruments with a low deterioration rate fails as safety regulation. **Figure 5** shows the performance of companies obtained in case of Specification 1 with changing fine from zero to five. Reliability decreased while productivity increased as a result of regulation. This result indicates that companies evolved such that they can get enough profits to repeat violating the regulation and paying the fine. Actually the society must criticize and impose sanction to companies that continue such behavior; this situation will motivate companies to cover-up violations. Anyways, an inappropriate regulation style may enforce companies to evolve in the opposite direction of expectation.

Figure 6 shows comparison of reliability between the five cases of dufferent regulation styles. In addition to reliability achieved at the end of simulation ($T = 250$), that averaged over the simulation period from the beginning to the end ($T = 0 \sim 250$) is also shown.

In case of Specification 2, companies are almost obey-

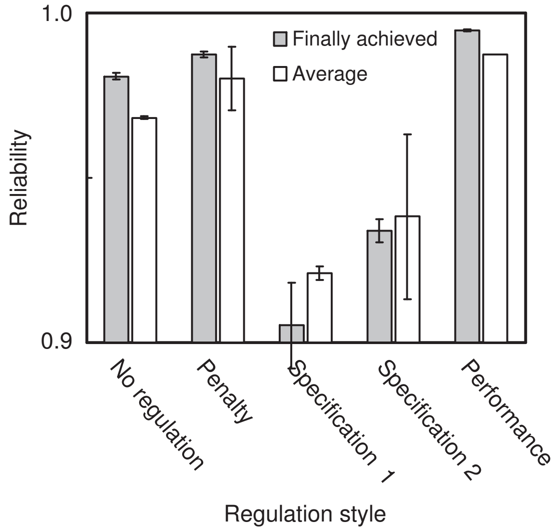

Fig. 6 Reliability achieved by various regulation styles.

ing the regulation, but reliability is still worse than the no regulation case. Since reliability of a line is determined not only from specification of instruments but also from its composition, simplistic specification-based regulation does not result in favorable effects.

Both penalty-based and performance-based regulation showed favorable effects to improve reliability. These regulation styles seem effective, because they are directly based on safety relevant measures.

4.2 Difference in assessment criteria

The result given in the previous sub-section shows that there exist significant differences between the final and the average performance. The final performance stands for the performance achievable in the long run, while the average performance up to a certain time point reflects a transient process of societal maturation. The result depends on choice of assessment criterion from these measures.

Figure 7 and **Fig. 8** show the final ($T = 250$) and the varage ($T = 0 \sim 250$) values of social utility, respectively. Though significant differences are found in productivity and reliability, the order of performance is maintained between different regulation styles. The order in the vertical direction of the social utility lines are the same but the positions of crossing points are different reflecting the differences between the two measures. This implies that the optimal regulation style differs between a short-intermediate period and a long period depending on estimated loss due to an accident.

4.3 Comparison of inspection methods

Four inspection methods listed in **Table 3** will be com-

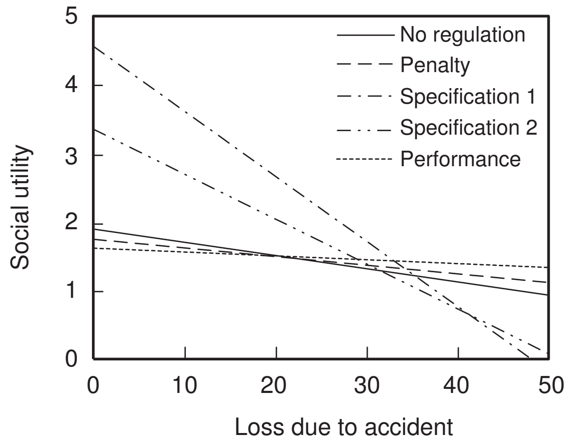

Fig. 7 Social utility achieved at $T = 250$.

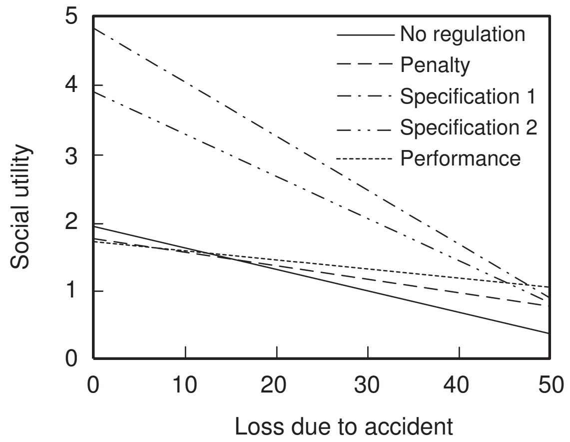

Fig. 8 Average social utility for $T = 0 \sim 250$.

Table 3 Test cases for comparison of inspection methods.

Case	P1/T1	P5/T5	P5/U	P5/T1
Inspection interval	1	5	1	1
Penalty	1	5	5	5
Probability of inspection	1.0	1.0	0.2	1.0
Average penalty per term	1	1	1	1

pared here with the performance-based regulation that reliability of a line must be kept over 0.98. The result is shown in **Fig. 9**.

Inspection frequency is equal on the average for Case P5/T5 and P5/U, and average penalty per term of the both cases is equal also to Case P1/T1. There are no significant differences in performance between Case P5/T5 and P1/T1, both of which are periodical inspection. Reliability of Case P5/U, which corresponds to uninformed inspection, is better and closer to Case of P5/T1 than Case P1/T1.

In practice, compliance to regulatory criteria is usually checked periodically. If average frequency of inspection is the same, the result obtained here indicates that uninformed inspection is more effective than informed one.

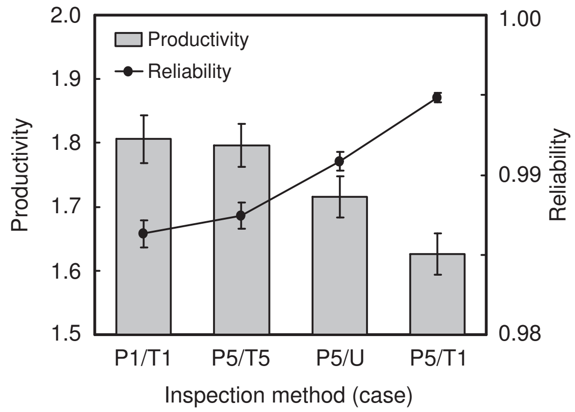

Fig. 9 Performance achieved by various inspection methods.

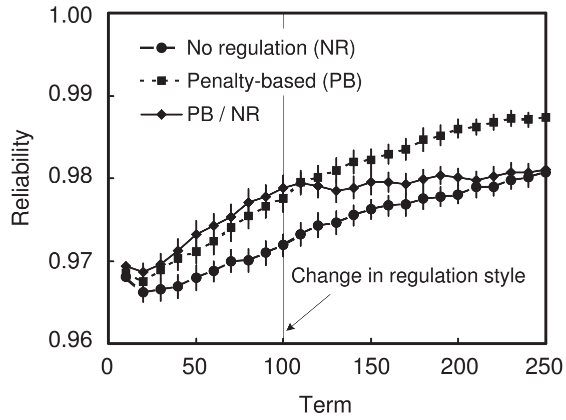

Fig. 10 Effect of change in regulation style.

5. Change in regulation style

Finally a case that the regulation style is changed is simulated with the same instrument classes of Table 1. In **Figure 10**, reliability is compared between three cases: no regulation (NR), penalty-based regulation (PB), and that penalty-based regulation is abandoned at $T = 100$ (PB / NR).

In Case PB / NR, after the regulation style has been changed, reliability stops increasing and approaches the same trend of no regulation. It shows performance of companies depends on the present environment, and the present regulation style dominates in the long run. Any good practice does not last without corresponding environmental pressure.

6. Conclusion

Using an evolutionary multi-agent system, it is demonstrated that the style of safety regulation determines average performance of productivity and reliability in the society as the environment. Companies will evolve to fit to safety regulation under given conditions. It is possible to assess whether or not a particular regulation style is effective for achieving the designated regulation goal by watching behavior of simulated agents.

The result of simulation revealed the following concrete insights related to design of safety regulation. Posterior regulation on an accident does not necessarily trade off with productivity, but occasionally enhance productivity. Specification-based regulation results sometimes in an outcome opposite to the original expectation. Since reliability as a whole depends on the current safety regulation, reliability will degrade to approach to the same level as no regulation is applied from the beginning. Finally, inspection is more effective if it is carried out as uninformed rather than informed inspection.

This study thereby proposed a useful model to assess safety regulation, and some findings have been obtained on qualitative nature of safety regulation.

Elements of the simulation model used in this study are rather simplified, and it is expected in future studies that the simulation model is improved further to include elements not considered so far. For example, an accident in this model is just break down of production, but scale of damage due to an accident should be taken into consideration. Modeling organizations within a company is another idea to introduce organizational factors into the simulation model. A multi-agent system such as used in this study is flexible enough to add detailed features of actual safety issues.

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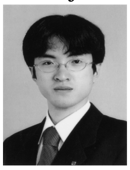

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