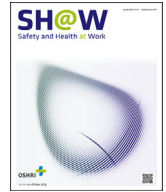




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Original Article

Control of Industrial Safety Based on Dynamic Characteristics of a Safety Budget-Industrial Accident Rate Model in Republic of Korea

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ABSTRACT

Background: Despite the recent efforts to prevent industrial accidents in the Republic of Korea, the industrial accident rate has not improved much. Industrial safety policies and safety management are also known to be inefficient. This study focused on dynamic characteristics of industrial safety systems and their effects on safety performance in the Republic of Korea. Such dynamic characteristics are particularly important for restructuring of the industrial safety system.

Methods: The effects of damping and elastic characteristics of the industrial safety system model on safety performance were examined and feedback control performance was explained in view of cost and benefit. The implications on safety policies of restructuring the industrial safety system were also explored.

Results: A strong correlation between the safety budget and the industrial accident rate enabled modeling of an industrial safety system with these variables as the input and the output, respectively. A more effective and efficient industrial safety system could be realized by having weaker elastic characteristics and stronger damping characteristics in it. A substantial decrease in total social cost is expected as the industrial safety system is restructured accordingly.

Conclusion: A simple feedback control with proportional–integral action is effective in prevention of industrial accidents. Securing a lower level of elastic industrial accident-driving energy appears to have dominant effects on the control performance compared with the damping effort to dissipate such energy. More attention needs to be directed towards physical and social feedbacks that have prolonged cumulative effects. Suggestions for further improvement of the safety system including physical and social feedbacks are also made.

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1. Introduction

Design of a safety-guaranteed industrial environment is important because it determines the ultimate outcomes of industrial activities involving safety of workers. Looking back over the past 20 years, the industrial accident rate in the Republic of Korea has drastically reduced to less than half of that 20 years ago. Industrial accident rate (IAR) is typically defined as the number of injuries and deaths per 100 workers. Despite the increasing efforts to prevent industrial accidents in recent years, IAR in the Republic of Korea has not improved much beyond a value of 0.7 since 1998 (Table 1). IAR in Japan, however, varied from 0.5 in 1989 to 0.2 in 2009, the average being 0.31 over the past 21 years [3]. Table 2

shows that the fatality rate in the Republic of Korea, as defined by the number of deaths in industrial accidents per 10,000 workers, is from five to 30 times greater than in most developed countries. Note that the UK uses different measures for calculating the accident rate and, therefore, these values in Table 1 are not directly compatible with data in other countries.

In addition to the statistical data in Tables 1 and 2, the current industrial safety system including both the policies and the management systems in the Republic of Korea is known to need improvement in two aspects. First, the current industrial safety system in the Republic of Korea, which resulted in 2,114 deaths and 93,292 injuries in 2011, is not effective in terms of preventing industrial accidents [1,4]. Second, safety policies and safety

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Table 1

IAR, the number of deaths in industrial accident and the normalized industrial accident prevention fund (IAPF) over the past 23 years in the Republic of Korea [1,2]

| Year | IAR* | Normalized IAR | No. of deaths | IAPF (10 ⁸ KRW) | Normalized IAPF [†] | CPI | CPI-adjusted normalized IAPF |
|------|------|----------------|---------------|----------------------------|------------------------------|------|------------------------------|
| 1989 | 2.01 | 0 | 1,724 | 112 | 1.00 | 1.00 | 1.00 |
| 1990 | 1.76 | 2.78 | 2,236 | 134 | 1.20 | 1.09 | 1.11 |
| 1991 | 1.62 | 4.33 | 2,299 | 365 | 3.03 | 1.19 | 2.55 |
| 1992 | 1.52 | 5.44 | 2,429 | 684 | 6.11 | 1.26 | 4.85 |
| 1993 | 1.30 | 7.89 | 2,210 | 1,014 | 9.05 | 1.32 | 6.85 |
| 1994 | 1.18 | 9.22 | 2,678 | 1,181 | 10.54 | 1.40 | 7.51 |
| 1995 | 0.99 | 11.33 | 2,662 | 2,129 | 19.01 | 1.47 | 12.96 |
| 1996 | 0.88 | 12.56 | 2,679 | 2,313 | 20.65 | 1.54 | 13.42 |
| 1997 | 0.80 | 13.44 | 2,742 | 2,396 | 21.39 | 1.61 | 13.31 |
| 1998 | 0.68 | 14.78 | 2,212 | 2,856 | 25.5 | 1.73 | 14.75 |
| 1999 | 0.74 | 14.11 | 2,291 | 3,015 | 29.92 | 1.74 | 17.17 |
| 2000 | 0.73 | 14.22 | 2,528 | 2,878 | 25.7 | 1.78 | 14.42 |
| 2001 | 0.77 | 13.78 | 2,748 | 2,864 | 25.57 | 1.85 | 13.79 |
| 2002 | 0.77 | 13.78 | 2,605 | 2,966 | 26.48 | 1.91 | 13.90 |
| 2003 | 0.90 | 12.33 | 2,923 | 2,942 | 26.27 | 1.97 | 13.32 |
| 2004 | 0.85 | 12.89 | 2,825 | 2,832 | 25.29 | 2.04 | 12.38 |
| 2005 | 0.77 | 13.78 | 2,493 | 3,275 | 29.24 | 2.10 | 13.93 |
| 2006 | 0.77 | 13.78 | 2,453 | 3,571 | 31.88 | 2.15 | 14.86 |
| 2007 | 0.72 | 14.33 | 2,406 | 3,687 | 32.92 | 2.20 | 14.96 |
| 2008 | 0.71 | 14.44 | 2,422 | 3,717 | 33.19 | 2.27 | 14.62 |
| 2009 | 0.70 | 14.56 | 2,181 | 3,470 | 30.98 | 2.33 | 13.30 |
| 2010 | 0.69 | 14.67 | 2,200 | 3,438 | 30.70 | 2.40 | 12.79 |
| 2011 | 0.65 | 15.11 | 2,114 | 3,712 | 33.14 | 2.47 | 13.42 |

* IAR is defined as the number of injuries and deaths per 100 workers. IAR is also described as the actual (current) IAR in feedback control representation. Workers include both employees and self-employed.

[†] IAPF was normalized using the value in 1989.

CPI, consumer price index; IAPF, Industrial Accident Prevention Fund; IAR, industrial accident rate.

Table 2

Fatality rates in major countries*

| Country | Fatality Rate | per 100,000 | Year | Data source |
|-----------------------|---------------|----------------------|------|--|
| Republic of Korea | 14.7 | Workers [†] | 2011 | KOSHA |
| Japan | 2.2 | Workers | 2009 | JISHA |
| Singapore | 2.1 | Workers | 2012 | Workplace Safety & Health Institute |
| Germany | 0.9 | Employees | 2009 | Eurostat |
| UK | 0.5 | Employees | 2012 | HSE |
| | 0.6 | Workers | 2012 | |
| France | 2.1 | Employees | 2009 | Eurostat |
| Australia | 2.3 | Employees | 2008 | National Occupational Health & Safety Commission |
| USA | 3.2 | Workers | 2012 | US Bureau of Labor Statistics |
| High income countries | 4.6 | Workers | 2008 | ILO |

* Fatality rate is defined as the number of deaths per 100,000 workers or employees.

[†] Workers include both employees and self-employed.

HSE, Health and Safety Executive; ILO, International Labor Organization; JISHA, Japan Industrial Safety and Health Association; KOSHA, Korea Occupational Safety and Health Agency.

management in industrial work places in the Republic of Korea are inefficient. A major cause of such inefficiency is the non-symmetry in which small-sized companies with < 10 employees and IAR > 1.0 (Table 3) are in general unaware of industrial safety, and often lack

Table 3

IAR by number of employees in the Republic of Korea, KOSHA (2011)

| No. of employees | IAR | No. of companies |
|------------------|------|------------------|
| < 5 | 1.55 | 1,234,158 |
| 5–9 | 1.00 | 248,910 |
| 10–29 | 0.75 | 182,788 |
| 30–49 | 0.54 | 34,524 |
| 50–99 | 0.40 | 21,698 |
| 100–299 | 0.26 | 12,638 |
| 300–499 | 0.18 | 1,812 |
| 500–999 | 0.13 | 1,110 |
| > 1,000 | 0.19 | 558 |
| Average/total | 0.65 | 1,738,196 |

IAR, industrial accident rate; KOSHA, Korea Occupational Safety and Health Agency.

safety staff and other resources needed for safety activities. Large companies with > 300 employees and IAR < 0.2 (Table 3) are, however, relatively free from these shortcomings [4,5].

It is noted that the current safety management system is neither able to cope with the increasing demand for safer work places nor effective in terms of reducing the accidents and saving the lives and properties of workers and industries. Thus, a new method to enhance the overall performance of safety management systems must be devised and implemented.

Safety activities by government, industries, and non-government organizations (NGOs) require a safety budget whose source may vary depending on the types of those activities. Industrial safety, in general, can be viewed as an economic commodity. It can be enhanced only by the consumption of scarce resources, which if not allocated to safety, could serve other beneficial purposes [6]. In most instances, the resources necessary for industrial safety have an obvious economic character. For example, machine guards, protective headgear, and safety directors all represent resources that could be devoted to other beneficial purposes if not used to increase safety. Less obvious, but not necessarily less significant, is the personal behavior resource of acting with care and caution.

Among many safety policies that affect the safety of workers in general, the safety budget is known to have the fastest and most significant influence on preventing and reducing industrial accidents [2]. Another advantage of safety budgets over other safety policies is that it is easily controlled and, therefore, easy to evaluate its performance. Safety budgets by the government or the government agency such as Korea Occupational Safety and Health Agency (KOSHA) are used to supply resources with obvious and less obvious economic characteristics to industrial workplaces. In particular, attention needs to be paid to the Industrial Accident Prevention Fund (IAPF), which is distributed and controlled by KOSHA. Five percent or more of budgetary expenditure of Industrial Accident Compensation Insurance is allocated to the IAPF pursuant to the Act on Subsidizing Industrial Accident Compensation Insurance with Special Accounts Budget. IAPF comprises > 90% of the KOSHA budget. Its control performance for prevention of industrial accidents needs to be evaluated in relation to the IAR.

Previous studies showed the control performance of IAPF for prevention of industrial accidents [1,2,7]. The present study focused on the dynamic characteristics of industrial safety systems and their effects on safety performance in the Republic of Korea. Specifically, the effects of damping and elastic characteristics of the second-order industrial safety system model on safety performance were examined, and the implications of establishing safety policies were explored. Control performance in the feedback mechanism was then explained in view of cost and benefit. Suggestions for

further improvement of a safety system including physical and social feedbacks were also made.

2. Materials and methods

2.1. Safety budget–IAR relationship

Assessment of the effect of the KOSHA safety budget (IAPF) on IAR using logarithmic regression analysis has been reported [8]. Specifically, the model in logarithmic regression analysis has a generic form in Eq. (1) with IAR (x_1), fatality rate (x_2 , deaths per 10,000 workers), number of lost work days (x_3), and insurance premium rate (x_4) as the input variables, and investment per insured worker (y) as the output variable. a is a constant. Investment per insured worker is calculated simply by dividing IAPF by the number of insured workers.

$$\ln y = a + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 \quad (1)$$

The model was identified using the KOSHA budget over the past 16 years since the foundation of KOSHA in 1987 to 2002. The model is convincing with 90.5% at the level of $p < 0.001$, and only IAR shows similarity at the level of $p < 0.001$. The p values for fatality rate, number of lost workdays, and insurance premium rate were 0.052, 0.161, and 0.167, respectively. If fatality rate, number of lost workdays, and insurance premium rate are assumed to be fixed, one can find a relationship between investment per insured worker (y) and IAR (x_1) to be in exponential form as [8].

$$y = e^{(c-1.372x_1)} \quad (2)$$

Investment per insured worker is inversely related to IAR in the Republic of Korea. Eq. (2) states that investment per insured worker necessary to reduce IAR by a given value, say 0.1, increases as IAR decreases. Both effectiveness and efficiency of industrial safety system are put into question as saturation of IAR is seen in the figure. The result in Fig. 1, for example, indicates that a large amount of IAPF would be needed to reduce the IAR of 0.65 in 2011 to 0.31 (the average IAR over the past 21 years in Japan) over the years to come.

2.2. Dynamic characteristics of industrial safety system in the Republic of Korea in relationship between IAPF and IAR

Restructuring and therefore securing the effectiveness and the efficiency of industrial safety systems in the Republic of Korea require understanding of the dynamic characteristics of such a system. The analysis results in Eq. (2) and Fig. 1, however, do not



Fig. 1. IAR as a function of investment per insured worker as calculated by Eq. (2). Investment per insured worker y in Eq. (2) is a reference value and constant c and was arbitrarily set to best fit the simulation results to actual data in 2011. IAR, industrial accident rate.

explain such dynamic characteristics of the industrial safety system in the Republic of Korea. In order to explain the dynamic characteristics of the industrial safety system in the Republic of Korea, the statistical relationship between IAPF and IAR was modeled using the second order linear system as follows.

Fig. 2 shows the past trends of IAPF and IAR in Table 1 from 1989 to 2011. In the figure, IAPF was consumer-price-index-adjusted and normalized using the value in the beginning year 1989. IAR was also normalized to fit to the form:

$$\alpha_1 + \beta(1 - \alpha_2) \quad (3)$$

$\alpha_1 (= 0.31)$ is the average IAR over the past 21 years in Japan, α_2 is the current (actual) IAR in Table 1, and β is the proportionality constant [1]. Ignoring various factors that might affect IAR other than IAPF, the figure indicates a striking similarity and, therefore, a remarkable correlation between them. This implies that one can model a system that has the normalized IAPF as input and IAR as output.

A second order continuous time industrial safety system model in the Republic of Korea that has the normalized IAPF as the input and the normalized IAR as the output was identified to be [1]:

$$G(s)_{\text{Current}} = \frac{0.135(s + 2.037)}{(s^2 + 0.288s + 6.331)} \quad (4)$$

The model in Eq. (4) is assumed to represent the current industrial safety system. Eq. (4) can be rewritten in a more generic form as:

$$G(s) = \frac{0.135(s + 2.037)}{s^N(s^2 + bs + k_m)} \quad (5)$$

Damping factor b and elastic factor k_m signify the damping characteristic and the elastic characteristic of the industrial safety system, respectively. The type number N is zero in the current industrial safety system in the Republic of Korea. In Eq. (5), the elastic characteristic in industrial safety system works to store the industrial accident driving energy, and the damping characteristic, on the contrary, acts to dissipate such energy.

2.3. Framework for feedback control of IAR

A feedback mechanism to control IAR was suggested in Fig. 3 where the current industrial safety system model [$G(s)_{\text{Current}}$] consists of processes in workplaces and behaviors of workers [1]. Industrial accidents take place as a result of interaction between such processes and behaviors. Any difference (error) between the

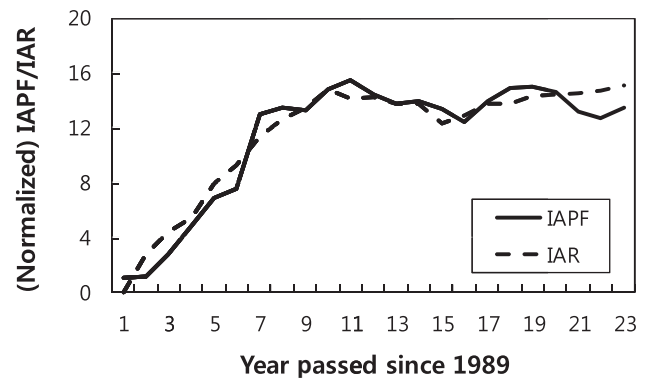


Fig. 2. Comparison of the normalized IAPF with the normalized IAR over the past 23 years in the Republic of Korea. IAR was normalized using Eq. (3). IAPF, Industrial Accident Prevention Fund; IAR, industrial accident rate.

target IAR (input to the feedback system which was set to the average IAR over the past 21 years in Japan, 0.31) and the actual (current) IAR (output of the feedback system) works to drive physical and social efforts to improve the industrial safety environment. The actual IAR reflects all the safety activities based on the physical feedbacks such as machines, devices, equipment and facilities, and social feedbacks such as laws/regulations, education, and training.

3. Results

3.1. Simulations with the current industrial safety system model

Current industrial safety system being “type 0”, simulation study revealed that, coupled with the simple proportional action (P control) only, the control objective of achieving the target IAR in the Republic of Korea may not be accomplished [1]. In this case, the proportional–integral action (PI control) of the form in Eq. (6) needs to be introduced in the feedback controller [9]:

$$G_C(s) = k_p + k_i \frac{1}{s} \tag{6}$$

The proportional control gain k_p and the integral control gain k_i signify the intensity of remedy actions to nullify the error between the target IAR and the actual IAR.

Even if the control objective is met with PI control, the extra IAPF to be put on every year in addition to IAPF in 2011 reaches to 2 trillion Korean Won (KRW, approximately 2 billion US Dollar (USD)) in a single year 2031 [10]. This is more than five times IAPF in 2011 and certainly exceeds the level of social consensus. Then, a method or a policy to alter the current industrial safety system to a more effective and efficient one needs to be devised and implemented.

3.2. Modification of the current industrial safety system model for improvement

3.2.1. Effects of the damping characteristic and elastic characteristic

Simulation tests were performed with different combinations of damping and elastic factors to evaluate their effects on the safety control performance. Fixed values of $k_p = 1$ and $k_i = 1$ were used for simplicity of simulations. Figs. 4 and 5 show the effect of damping factor and elastic factor, respectively, on the control of IAR for different combinations of these values in Eq. (5). No noticeable effect of damping factor on the behavior of the industrial safety system is seen in Fig. 3, whereas the effect of the elastic factor is more pronounced in Fig. 5. This implies that securing a lower level of “elastic” industrial accident-driving energy is more important than the effort to dissipate such energy. Efforts in industrial safety activities in the Republic of Korea, therefore, need to be directed toward modifying the internal structure of the industrial safety system from an elastic characteristic dominant one to a more damping characteristic, securing one with less elastic energy.

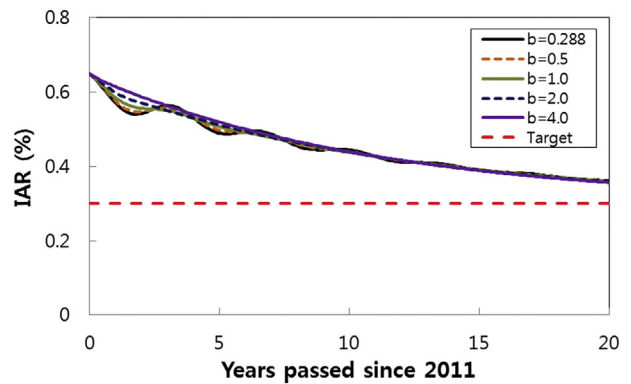


Fig. 4. The actual IAR estimated over the next 20 years with proportional–integral action in the feedback controller for different values of damping factor in Eq. (5). The elastic factor k_m was set to 3.0. Both k_p and k_i were set to 1. IAR, industrial accident rate.

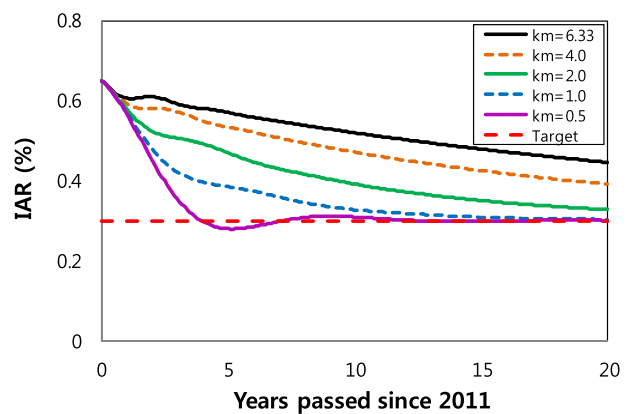


Fig. 5. The actual IAR estimated over the next 20 years with proportional–integral action in the feedback controller for different values of elastic factor in Eq. (5). The damping factor b was set to 1.0. Both k_p and k_i were set to 1. IAR, industrial accident rate.

The current industrial safety system in Eq. (4) exhibits stronger elastic characteristic than damping characteristic. The improved industrial safety system, therefore, needs to exhibit a weaker elastic characteristic but stronger damping characteristic [7,10]. One example to minimize or restrict the industrial accident driving elastic energy involved in industrial machines and devices used in workplaces is safety certification at the stage of manufacture where danger is generated. Unsafe industrial machines and devices manufactured without proper safety or protective functions are said to be elastic in that they can store the energy to cause the industrial accidents. Such energy is then dissipated by damping efforts, such as safety inspection on users at the stage of usage where danger is encountered. As the effect of the elastic characteristic is more pronounced in industrial safety management,

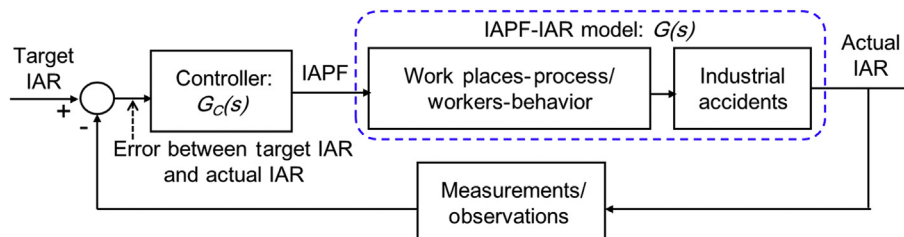


Fig. 3. Block diagram representation of feedback control of IAR. IAPF, Industrial Accident Prevention Fund; IA, industrial accident rate.

efforts to minimize such elastic energy at the stage of danger generation appear to be more effective.

From the system point of view, in the limit where the elastic factor is sufficiently small compared to the damping factor, the safety system becomes a Type 1 system. Type 1 systems have a pole on the origin of the s plane so that the industrial safety system inherently has the integral action in it. The industrial safety system in this case has a remedy function to track the target IAR without the help of auxiliary integral action in the feedback controller. In cases where the system is not a Type 1 system, one can add the integral action in the feedback controller.

3.2.2. Effectiveness of the improved industrial safety system model

In Fig. 6, values of damping factor and elastic factor that give the optimum result without the actual IAR going beyond the target IAR were found to be 2.1 and 1.0, respectively. The transfer function of the improved industrial safety system is then given by:

$$G(s)_{\text{Improved}} = \frac{0.135(s + 2.037)}{(s^2 + 2.1s + 1.0)} \quad (7)$$

The actual IAR estimated over the next 10 years with the improved model $G(s)_{\text{Improved}}$ in Eq. (7) is shown in Fig. 7. The integral control gain k_i was again set to 1 for simplicity of simulation. The effectiveness of the improved industrial safety system model is

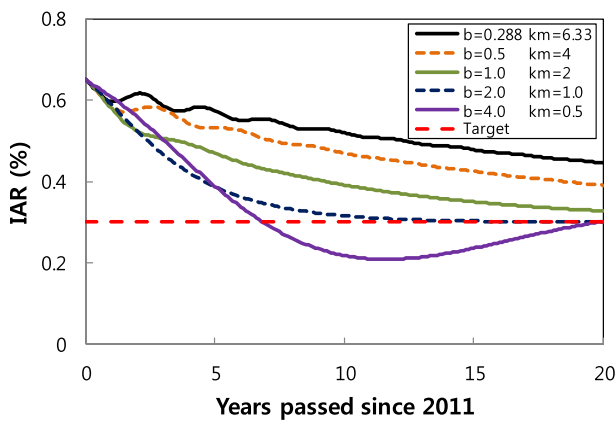


Fig. 6. The actual IAR estimated over the next 20 years with proportional–integral action in the feedback controller for different combinations of damping factor and elastic factor in Eq.(5). Both k_p and k_i were set to 1. IAR, industrial accident rate.

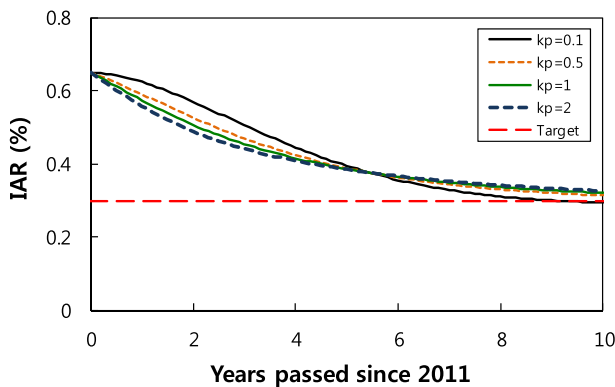


Fig. 7. The actual IAR estimated over the next 10 years with the improved industrial safety system model in Eq. (7) and proportional–integral action in the feedback controller. The integral control gain K_i was again set to 1 for simplicity of simulation. IAR, industrial accident rate.

assured as the target IAR can be achieved within ~ 10 years. The proportional gain k_p does not produce notable difference among the outputs. The integral gain k_i is then set to the lowest possible value for the efficiency as will be described in the subsequent section.

Fig. 8 depicts the extra IAPF needed in addition to IAPF in 2011 to accomplish IAR in Fig. 7. Comparing these results with those in previous studies indicates saving of the extra IAPF by $> 80\%$ [1]. The efficiency of the improved model, however, needs to be further justified in relation to the cost–benefit involved.

4. Discussion

4.1. Efficiency of the improved industrial safety system model

Root-locus of the current industrial safety system $G(s)_{\text{Current}}$ in Eq. (4) is shown in Fig. 9. The closed-loop pole on the real axis will prevent any oscillatory behavior of IAR with time [11]. Oscillatory behavior does not imply lack of effectiveness but lack of efficiency in feedback control of IAR. Rougher and oscillatory transition from the current IAR to the target IAR is expected with the closed-loop poles located elsewhere [1]. The system gain that gives the stable closed-loop pole on the real axis should have a value > 91.1 for the values of $k_p = 1$ and $k_i = 1$. Such a system gain is > 0.135 in Eq. (4), which implies a substantial amount of IAPF needed to hit the target IAR. A system gain that gives the stable closed-loop pole on the real axis for transfer function $G(s)_{\text{Improved}}$ in Eq. (7) is, however, 41.7 in Fig. 10 for the value of $k_p = 1$ and $k_i = 1$. With the improved safety system model in Eq. (7), a lower amount of extra IAPF would be needed to hit the target IAR.

4.2. Comparison of the improved industrial safety system with the current one in view of cost–benefit

Safety can only be produced by the use of scarce resources, therefore, the absence of safety, as manifested in accidents, can itself be considered as equivalent to an economic resource [6]. As with other economic resources, a willingness to risk accidents may yield certain benefits such as the ability to undertake activities that produce wages for workers, profits for firms, and products for consumers. However, these benefits can be generated only with associated costs. The costs of accidents include costs to the worker such as anxiety over potential accidents, pain and suffering, lost wages, medical care, and rehabilitation. Other accident costs include delay and disruption of work processes, training of replacements, and damage to capital and raw materials. Because the

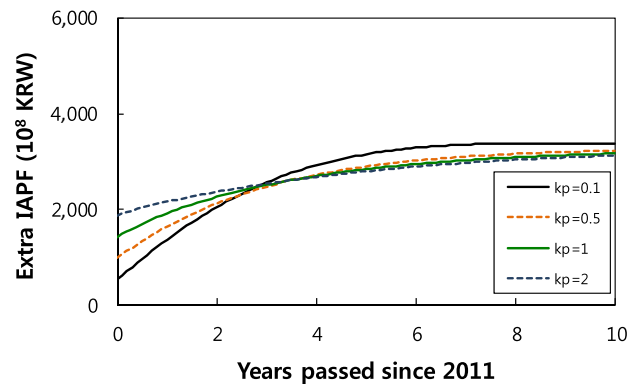


Fig. 8. Estimated extra IAPF needed in addition to IAPF in 2011 to accomplish the actual IAR in Fig. 7. The integral control gain K_i was again set to 1. IAPF, Industrial Accident Prevention Fund; IAR, industrial accident rate; KRW, Korean Won.

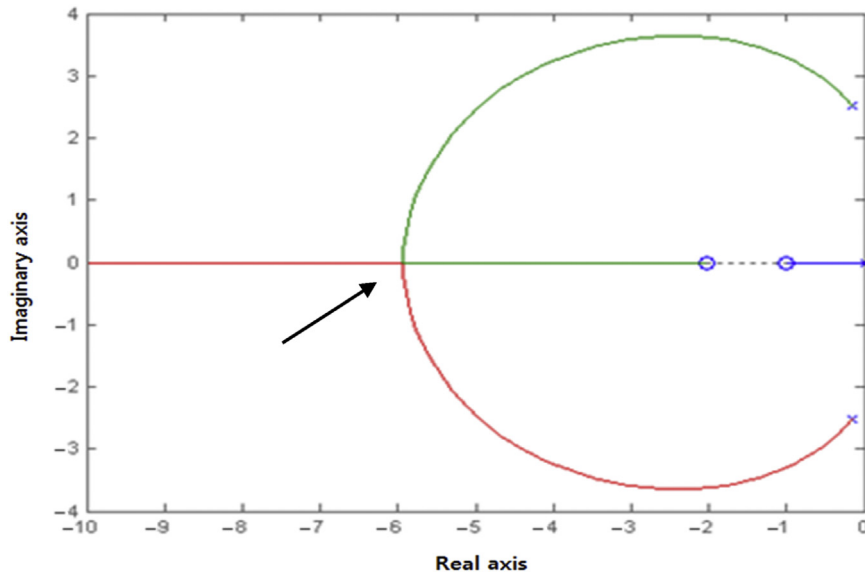


Fig. 9. Root-locus of the current industrial safety system $G(s)_{current}$ in Eq. (4).

activity of work yields exposure to accidents, which in turn yields both costs and benefits, it becomes desirable to weigh these costs and benefits to estimate the efficiency of industrial safety system.

Validity of the improved industrial safety system model can be verified by cost–benefit analysis. More safety-securing efforts within the improved industrial safety system incur a cost. Such efforts, however, are a more efficient way of securing industrial safety in terms of cost–benefit. Cost and benefit in industrial safety are estimated according to the following procedures. (1) Safety budget such as the extra IAPF spent by government (input to the industrial safety system) is viewed as a cost. (2) Reduction in social cost due to deaths and injuries arising from reduction in IAR are viewed as a benefit in the Averting Behavioral Method, which is popular in cost–benefit analysis of safety-related issues. Then, the control objective in industrial safety is defined to minimize the total cost over the years of control action, which is the total social cost due to loss and IAPF needed to control IAR. One can find the optimum combination of the system model that minimizes the object function:

$$Total\ Cost = \min \left[\int_0^t (Total\ Social\ Cost + IAPF) dt \right] \quad (8)$$

(3) IAR (output of the industrial safety system model) in the coming years is estimated using either Eq. (4) or Eq. (7) with proper feedback control gain, $k_p = 1$ and $k_i = 1$ for example. (4) Number of deaths can be estimated using the statistical relationship between IAR and number of deaths in industrial accidents. (5) Social cost due to deaths in industrial accidents are estimated using the basic value in 2011 and the average increase rate in consumer price index. (6) Social cost due to injuries in industrial accidents are estimated using the ratio of social cost due to deaths to social cost due to injuries calculated in 2011. (7) Safety budget such as the extra IAPF spent by government (input to the industrial safety system) to guarantee IAR in the coming years is easily calculated in the feedback control mechanism in Fig. 3.

In order to calculate the social cost due to deaths and injuries in industrial accidents, one needs to first estimate total number of deaths in the coming years. A statistical relationship between IAR and the total number deaths due to industrial accidents in the

Republic of Korea was established using the statistical data from the year 1996 to 2011 (Table 1). Such a relationship can be described by a simple linear function in Fig. 11 as [10]:

$$\text{Number of deaths} = 1,511 \cdot \text{IAR} + 1,349 \quad (9)$$

One can extrapolate the linear function in Eq. (9) to estimate the number of deaths in the coming years once the estimated values of IAR are available as in Fig. 7. Injuries in industrial accidents include both the event-caused injuries and the occupational diseases. Distinct relationship between IAR and the number of injuries is, however, not easily established.

The estimated total social cost announced by the Ministry of Employment and Labor in 2011 was KRW 17.62 trillion (USD 17.27 billion). It includes both the direct cost, which is announced every year by Korea Workers' Compensation and Welfare Service, and the indirect cost, which is assumed to be approximately four times the direct cost based on classical Heinrich's theory. One can break total social cost into two parts: social cost due to deaths and that due to injuries. Social cost due to deaths is estimated as follows: social cost per death in industrial accidents, which includes both cost and indirect costs estimated to be KRW 0.87 billion (approximately USD 852,940) in 2011 [12]. Then:

$$\begin{aligned} \text{Social cost due to deaths} &= 2,114 \text{ deaths} \times \text{KRW } 0.87 \text{ billion/death} \\ &= \text{KRW } 1.84 \text{ trillion (USD } 1.80 \text{ billion)} \end{aligned} \quad (10)$$

Social cost due to injuries is the rest and estimated to be:

$$\begin{aligned} \text{Social cost due to injuries} &= \text{Total social cost} - \text{Total social cost due to deaths} \\ &= \text{KRW } 17.62 \text{ trillion} - \text{KRW } 1.84 \text{ trillion} \\ &= \text{KRW } 15.78 \text{ trillion (USD } 15.47 \text{ billion)} \end{aligned} \quad (11)$$

Reduction in social cost due to injuries in the improved industrial safety system model appears to be more important than reduction in social cost due to deaths. Number of injuries was 93,292 in 2011 and social cost per injury is estimated to be:

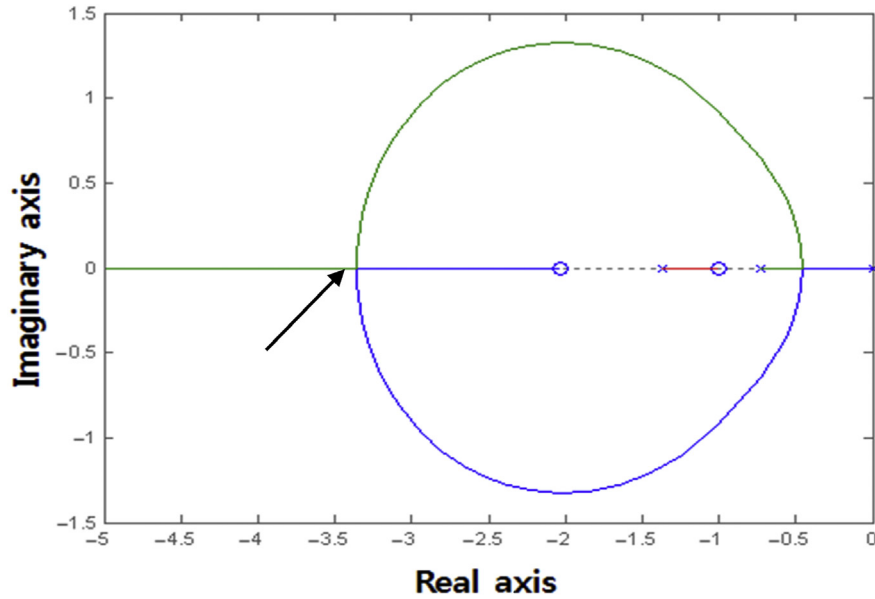


Fig. 10. Root-locus of the improved industrial safety system $G(s)_{improved}$ in Eq. (7).

$$\begin{aligned}
 \text{Social cost per injury} &= \text{KRW } 15.78 \text{ trillion (USD } 15.47 \text{ billion)} / \\
 &93,292 \text{ injuries} \\
 &= \text{KRW } 0.17 \text{ billion (approximately USD} \\
 &164,260) \quad (12)
 \end{aligned}$$

A ratio of social cost due to deaths to social cost due to injuries is 1:8.57. Other assumptions and simulation conditions for cost-benefit analysis are as follows. (1) Only benefit considered was reduction in IAR (output of the industrial safety system model), hence reduction in social cost due to deaths and injuries in industrial accidents according to averting behavioral method. (2) There could be a number of other social costs needed to alter the current industrial safety system to the improved one. Safety budget in private sectors is one example. They are, however, beyond the scope of this study, in that the dynamics of industrial safety systems are characterized by single input (IAPF)–single output (IAR) relationship. (3) Only cost considered was safety budget (the extra IAPF spent by government), which is the input to the industrial safety system. Other social costs are not considered in this study. (4) A ratio of social cost due to deaths to social cost due to injuries (1:8.57) is assumed to apply in the coming years so that social cost

due to injuries is calculated from social cost due to deaths based on this ratio. (5) Average increase rate in consumer price index over the 3 years from 2011 to 2014 was used.

Fig. 12 depicts the estimated net benefit (benefit–cost) over the next 20 years when the current industrial safety system model in Eq. (4) is used. The current industrial system exhibits oscillatory behavior in the course of following the target IAR. Accordingly, benefit arising from reduction in IAR (or reduction in deaths and injuries) also exhibits oscillatory behavior in Fig. 12. Inefficiency is also seen as the cost increases monotonically for the first few years. As both benefit and cost saturate, net benefit is limited below a certain level even after 20 years. Substantial net benefit, however, is seen in Fig. 13 with the improved model. As efficiency improves in Eq. (7), net benefit is almost tripled just 10 years after restructuring of the industrial safety system in the Republic of Korea. It is, however, noted that such restructuring to the optimal industrial safety system model would take place over the years and society would benefit from such an improvement. Restructuring of the industrial safety system appears to be a key foundation for the effectiveness and efficiency, hence reducing the total social cost.

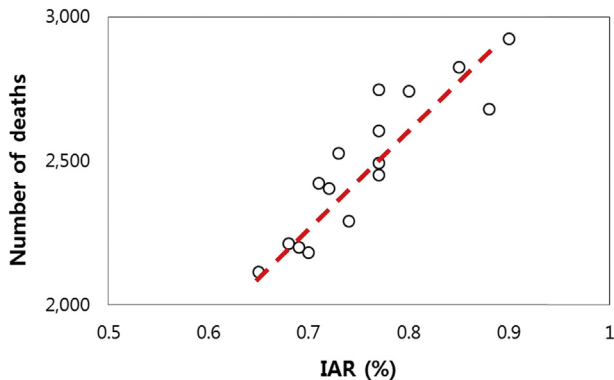


Fig. 11. Linear approximation of the relationship between IAR and the number of deaths in industrial accidents over the past 16 years. IAR, industrial accident rate.

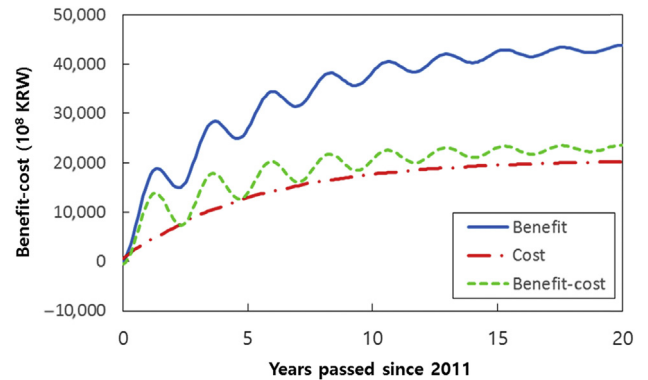


Fig. 12. Estimated net benefit (benefit–cost) due to reduction in deaths and injuries in industrial accidents over the next 20 years when the current model in Eq. (4) is assumed. KRW, Korean Won.

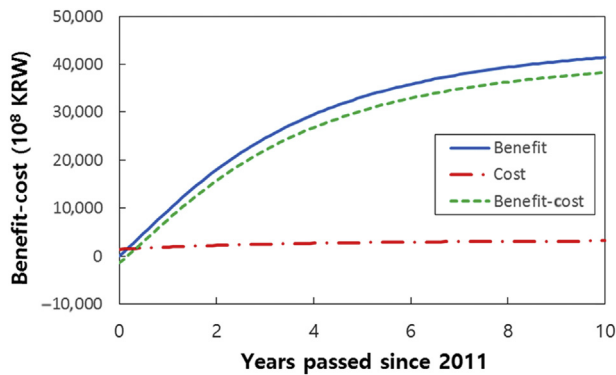


Fig. 13. Estimated benefit–cost (net benefit) due to reduction in deaths and injuries in industrial accidents over the next 10 years when the improved model in Eq. (7) is assumed. KRW, Korean Won.

4.3. Further implications for improvement of the performance of integral control

4.3.1. Implications of dynamic characteristics of industrial safety system

As simulation examples suggest, the damping factor has a minimal effect on the behavior of the safety system model, whereas the elastic factor has a significant effect. More effective and efficient safety system models with stronger internal damping nature but with weaker elastic nature then need to be devised and implemented in the future. In view of restructuring the industrial safety system in the Republic of Korea, any safety activity or culture has to be altered to nullify or minimize the inherent elastic nature, which will in turn lead to laws, regulations, and policies suitable for the workplaces and management policy of the company that is prior to other policies. This will make the safety activities more effective and efficient. Dissipation of the accident-driving energy by the stronger damping nature will be made possible by reward that is connected to safety tasks or contingent to safety performance and education or training of workers and managers. The safety performance may be measured actively and regularly by the government. The workers and companies need to have the ability to undertake such education or training.

4.3.2. Physical and social feedbacks for improvement of the performance of integral control

When the industrial safety system is not perfectly effective and efficient, without the cumulative characteristics as noted for a Type 1 system, the feedback controller in Fig. 3 needs to have its own integral action. The appropriate gains for proportional and integral actions in the feedback controller can be found to drive the actual IAR to the target value in a desirable fashion. Key factors in integral action are, in particular, the cumulative effects of physical and social feedbacks, and their use for remedy action in Fig. 3. For example, Table 4 summarizes the projected lives of physical and social feedbacks in workplaces. More attention needs to be paid to physical and social feedbacks that have prolonged cumulative effects. Prolonged cumulative effects will guarantee the performance of integral action without having higher values of integral control gain k_i , which causes higher social costs. Such feedback includes, in order, higher cumulative effect, implementation of safety laws/regulations, training and education of workers, active regular measurements of safety performance by the government, safety certification and inspection of dangerous machines, guards and protecting devices, and timely replacement of personal protective equipment for safety of workers. Integral control gain and the

Table 4

Projected lives of physical and social feedbacks in work places

| Physical or social feedback | Life in work places (y) |
|---|-------------------------|
| Personal protective equipment (helmet, shoes) | < 1 |
| Guards, protecting devices | ~5 |
| Dangerous machines (press, roller, etc.) | ~10 |
| Education or training (of workers) | ~3 to 20 |
| Laws/regulations | Infinity |

corresponding safety policies are then selected to effectively balance the maximum benefit of such effects and their costs.

4.3.3. Balanced direct regulations on both manufacturers and user

Costs and benefits of an industrial safety activity frequently accrue to different decision makers; for example, products go to customers while injuries go to workers. It is necessary, therefore, for society to devise mechanisms by which the balancing of these costs and benefits can be achieved. The goal of such mechanisms should be to encourage interaction so that decision makers gaining rewards from an industrial safety activity can compensate potential bearers of the costs, thereby inducing them to participate. In terms of industrial safety this goal is manifested in the desire to ensure that workers are exposed to accident risks only to the extent that the benefits of these risks are at least as great as the costs. The optimal amount of industrial accident risk exposure is achieved when the difference between the total of benefits and costs occurring from industrial accidents to all parties is at a maximum.

Current direct regulations on industrial machines used in workplaces in the Republic of Korea are, however, mainly focused on users including workers, causing more cost to them. Skewed safety device regulation on users, which is unique in the Republic of Korea, is a good example. Limited responsibility of manufacturers may lead to a situation where effective elimination of sources of danger at the stage of manufacture is not realizable and more cost accrues to users of industrial machines. There also arises a question as to whether such a direct regulation is efficient enough to lower IAR associated with industrial machines to the level in most developed countries in the near future, with limited resources put in [13]. Industrial safety activities must then be directed towards eliminating the sources of danger at the stage of danger creation, thereby securing safe industrial machines. Safety inspection complements safety certification in securing the safety of workers at the stage of danger use. The overall balance between such direct safety regulations and proper distribution of cost is achieved by proper distribution of industrial machines subject to such regulations and the intensity of each regulation. Cost–benefit analysis on conveyor clearly justifies such transition to balanced direct regulations [13]. This will also work to guarantee the overall effectiveness of the industrial safety system.

5. Conclusions

A strong correlation between safety budget such as the industrial accident prevention fund and the industrial accident rate enables modeling of an industrial safety system in the Republic of Korea with these variables as the input and the output, respectively. Feedback control of the current industrial safety system, however, indicated that the amount of extra industrial accident prevention fund needed to achieve an IAR rate as low as in most developed countries would be far beyond the social consensus. Restructuring of the industrial safety system is essential to guarantee both effectiveness and efficiency.

The elastic characteristic of the industrial safety system works to store the industrial accidents driving energy. The damping

characteristic, on the contrary, acts to dissipate such energy. As simulation results suggest, securing a lower level of elastic energy appears to have dominant effects on the control performance compared with the damping effort to dissipate such energy. More effective and efficient industrial safety systems can then be realized by having weaker elastic characteristics but stronger internal damping characteristics in them. Estimated total social cost with such an improved industrial safety system decreases drastically, which is a manifestation of both the effectiveness and the efficiency. Cost them. Estimated total social cost with such an improved industrial safety system the number of deaths in industrial accidents with the efficient safety system model would sufficiently make up for the cost required. Restructuring of the industrial safety system in such a direction is, therefore, a key factor in both saving lives of the workers on site and reducing the total social cost.

More attention needs to be directed towards physical and social feedbacks that have prolonged cumulative effects. Such feedback includes, in order of preference, implementation of safety laws/regulations, training and education of workers, active regular measurements of safety performance by the government, safety certification and inspection of dangerous machines, guards and protecting devices, and timely replacement of personal protective equipment for safety of workers. Balanced direct safety regulations and proper distribution of cost on both manufacturers and users of industrial machines is a good example of balancing of costs and benefits to guarantee the overall effectiveness of industrial safety system.

Conflicts of Interest

All authors declare no conflict of interest relevant to this article.

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