System Dynamics Modeling of Construction Safety Management Based on Site Corrective Actions

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Abstract

Safety is one of the effective factors on the operation of construction projects and plays a major role in the success of a project. According to the statistics presented from various institutions, the majority of the accidents among different industries are related to construction industry. Therefore, safety improvement in construction projects is one of the most significant issues to consider. Construction projects are naturally complex, dynamic, and include many feedback processes. Thus, construction projects can be regarded as complex dynamic systems which their management requires possession of tools to overcome their dynamic complexities. In this study, the structure governing safety management in construction workshops is regarded as one system. Also, concerning the dynamic nature of the variables over the passage of time, system dynamic modeling is applied. In current study, it is illustrated that by applying learnings from safety scrutiny, accident investigation and corrective actions based on them, the severity and number of accidents as well as losses can be reduced significantly and improve the safety operation of construction projects. This study suggests the corrective actions as a helpful policy to prevent accidents.

Keywords

System dynamics, construction industry, safety, corrective actions

Introduction

Construction industry is one of the largest and most challenging industries in the world. Using a great portion of national resources of the countries, construction industry plays a main role in GDP[2]. Construction industry has fundamental difference with other industries in the world. This difference includes its unique varieties and complexities which is due to uniqueness of each construction project. The goal of stockholders of construction projects is optimizing the benefits and reaching appropriate quality level in proper time by spending optimal cost. There are many factors which affect the accomplishment of this goal the most prominent of which is safety during project progress. According to statistics presented by several institutions, the most amount of loss occurs in construction industry. For instance, based on the report of National Safety Council of America, although construction industries employ only 5% of the labor of the industries, more than 20% of fatalities and damages are related to this industry. According to the study conducted by Atrkar Roshan and Alizadeh(2015), average cost of each accident in construction industry of Iran in 2013 was $3600 and 4984 accidents happened in the construction industry of Iran in that year. Consequently, with regard to high statistics of accidents as well as high costs of accidents in construction industry, one of the major issues in this regard is the improvement of the safety of projects. One of the necessary measures to increase the safety of projects is recognition of affecting factors on safety in construction workshops. By recognition and control of such factors, safety can be improved in this industry. However, these factors are scarcely independent of each other and have complex interactions to one another, the way that whether one factor is usually the cause of another and heightens its effect, or it is created by another factor. In this article the structure governing construction safety management is regarded as a system and by creating a system dynamic model it is shown that by utilizing system dynamic modeling, a better understanding of dynamics of safety management would be obtained in construction projects. In this study, the policy of corrective actions is investigated based on the learning from safety scrutiny and accident investigation. The aim of the study is to show the extent to which corrective actions are effective on continuous improvement of safety operation of construction projects. Current research tries to improve this area of knowledge based on previous valid developed modeling structures and addition of new structures in the area of safety modeling of construction projects.

Literature review

Suraji et al (2001) argues that the analysis of 500 accidents registered by the UK Health and Safety Executive shows that principle factors which cause an accident in construction projects include inappropriate construction planning (28.8%), inappropriate construction control (16.6%), inappropriate construction operation (88.0%), inappropriate site condition (6.0%), and inappropriate operative action (29.9%).

After the investigation of accidents, Evelyn Ai Lin Teo et al (2005) figured out that the probability of accidents is higher when 1. Policies of the company are inappropriate. 2. There are unsafe actions in the site. 3. Personnel show inappropriate behavior in terms of safety. 4. Managers' commitment is low. 5. Training is not enough.

[2] Gross Domestic Product

In his study, Seokho Chi (2013), concluded that in normal working condition, the possibility of an accident reduces when physical, mechanical, and human conditions are appropriate. However, if any of these three factors be inappropriate, the possibility of an accident raises. Also the incorrect workers' judgement on dangerous conditions is identified as the most serious human error which causes accident.

In the study by H.L.Guo (2013), accident factors involve:

1. Inappropriate site layout
2. Multi-interface
3. Incorrect administration of large workshops
4. Wrong setting of protection items
5. Infeasible construction sequences
6. Insufficient or lack of safety training
7. Unsafe human behavior
8. Insufficient or lack of safety cautions

Feng (2014) shows that 10 effective factors on the safety of construction environments include:

1. Management commitment
2. Communications and feedback
3. Supervisory environment
4. Supportive environment
5. Work pressure
6. Individual appreciation of risk
7. Training and amount of eligibility
8. Safety rules
9. Association of workers
10. Job risk evaluation

In most of the studies regarding safety, causal interactions are not concerned between variables. In fact, researchers have been looking for mostly effective factors on safety and have not concerned complex interaction of factors. However, some researchers have investigated causal interactions between variables applying system dynamic. System dynamic tool presented by Farster (1961) makes it possible to accurately evaluate available dynamics in project with regard to its effective factors. To date, some researchers have used system dynamic tool and its concepts to investigate dynamics of safety management that a number of highly significant ones are discussed below.

Suraji et al (2001) presented a causal model of construction accident causation. They classified the effective factors of accident to proximal and distal in their model. The distal factors include project conception constraints, project design constraints, project management constraints, construction management constraints, subcontractor constraints, and operative constraints. Proximal factors include inappropriate construction planning, inappropriate construction control, inappropriate construction operation, inappropriate site condition, and inappropriate operative action.

Cooke (2003) illustrated the interaction of three subsystems of human resources, mine capacity, production and safety by investigating Westray Mine Disaster and employing system dynamic. Also Cooke (2003), using system dynamic, has shown that investigating and learning from occurred accidents can have a major role in reducing accident rate.
Zhongming Jiang et al (2014) identified three crucial factors of management conditions, individual conditions, and environmental conditions which were effective on the number of incidents and then investigated the interaction between these factors by system dynamic.

Dynamic model

Model boundary

Model boundary in current study is building construction and it does not include other construction industries such as construction of roads and dams. Also the effects of organizational structures, employment and dismissal of labor, and training of the personnel are disregarded in this study. The considered period for this study is 25 months.

Recognition of effective factors on safety

To identify the effective factors on safety in construction projects, in the first step, general effective factors on safety of building projects were determined by library studies including books, articles, and previous researches. To continue, multiple data collection techniques were used such as organized interviews, questionnaires, and archive records. 40 contractors were chosen randomly from the list of contractors and they were asked to help us in this study. 27 contractors confirmed and the data was collected from them. Based on the principle of observer triangulation (Neuman, 2005) which states that the data from a phenomenon should be gathered from at least three observers, we asked three employees of the site (project manager, construction manager/site engineers, safety manager/ safety inspectors and supervisors) to fill the questionnaires to raise the validity of data for each project. Finally, based on the expert opinion and conducted field studies, the most significant effective factors on safety level of construction projects were determined. To define effective factors and their classification based on the amount of effect and significance as well as elimination of negligible factors, Likert Scale (very much, much, medium, little, very little) was applied. The software SPSS was used to analyze the data. Finally, the most significant effective factors on the safety of construction projects were identified and classified in 32 categories.

Table 1: *Effective Factors on the Safety of Construction Projects*

Effective management factors on safety	1. Management commitment to safety	2. Amount of safety priority over work	3. Selection and formulation of policies and executable safety standards and their improvement
	4. Safety supervision	5. Performance of corrective actions	6. Safety training
	7. Promoting safety	8. Inclination to investigate accidents	9. Learning form accidents

	10. Correct identification of risks	11. Effective safety association of management with supervisors and workers	12. Recognition of individuals with better safety performance
Effective individual factors on safety	13. Individual commitment to safety	14. Knowledge of safety	15. Experience
	16. Applying safety tools	17. Correct risk identification	18. Acceptable workers' behavior in terms of safety
	19. Effective association of management and supervisors	20. Psychological state	21. Physical state
	22. Morale to observe safety	23. Being temporary or permanent worker	24. Individual inclination to ease
Effective environmental factors on safety	25. Safety atmosphere	26. The effect of coworkers and their support of more desirable safety performance	27. Appropriate workshop layout and merging safety planning into site layout planning
	28. Variety of actions	29. The number of subcontractors	30. The number of workers relative to the size of workshop
Factors associated with project stakeholders	31. Stakeholder participation in safety decision-making	32. Stakeholder's unrealistic expectations	

As illustrated in table 1, safety effective factors are classified into four subcategories of management factors, individual factors, environmental factors, and factors associated with stakeholders of the project.

Model structure

As it was determined in the previous section, several factors highly affect the safety level of the project which have interaction with one another. Therefore, in this study a structure is presented based on a system thinking approach in order to show the interactions clearly. Subsystems of Model are depicted in figure 1. In order for a better description of system dynamic structure of the present model, it is classified into four sections of safety function, commitment, investigation of occurred accidents, and safety scrutiny. Different sections have interactions due to common variables. Commitment is both effective on all other sections and is affected by them. It is also true for safety function. It affects and is affected by all other sections.

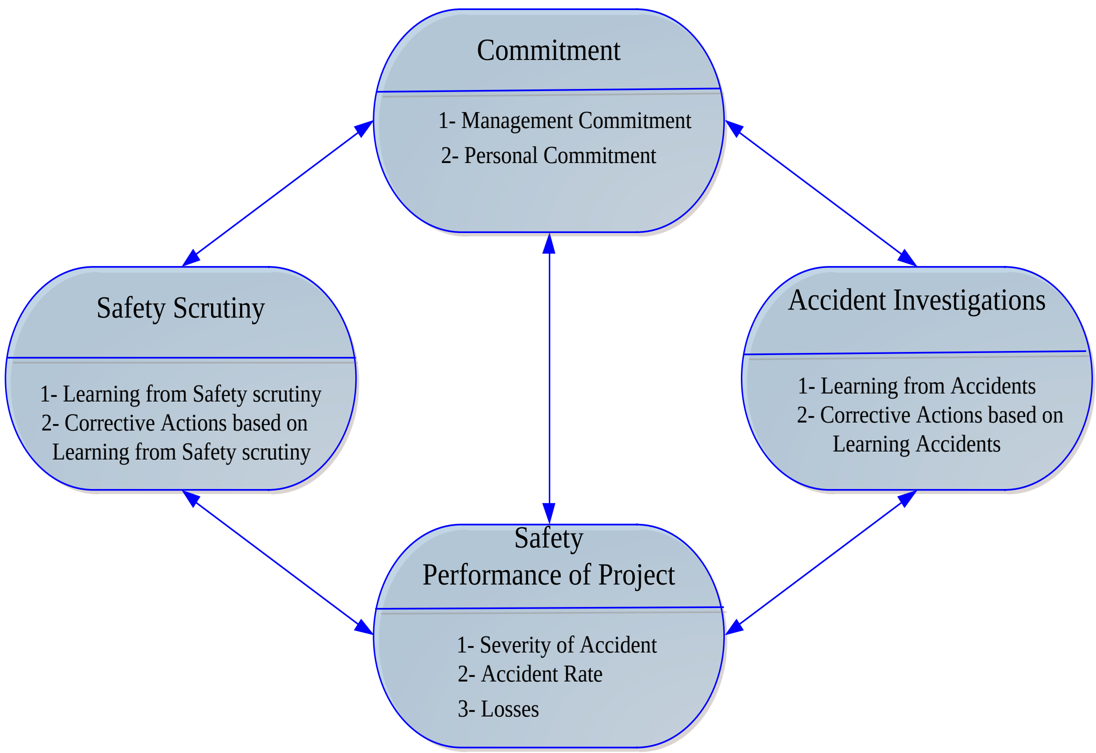

Figure 1: Subsystems of Model

In figure 2, causal diagram is shown. There are positive and negative causal loops in causal diagrams. Positive loops reinforce the changes. Conversely, negative loops modify themselves, oppose disorder, and have balancing effects. There is a brief review of the most important causal loops in the following. As the illustration of the presented model in figure 2 shows, with increase of management commitment to safety, it will be regarded as a prominent issue and by emphasizing safety and developing safety policies, management will increase individual commitment to safety. Consequently, fewer unsafe behavior will occur. Following a reduction in unsafe behavior, accident rate falls. However, with the reduction of accident rate, pressure on management to reduce and control the accident rate decreases and as a result, management commitment to safety reduces. In fact, B1 balancing loop will be created.

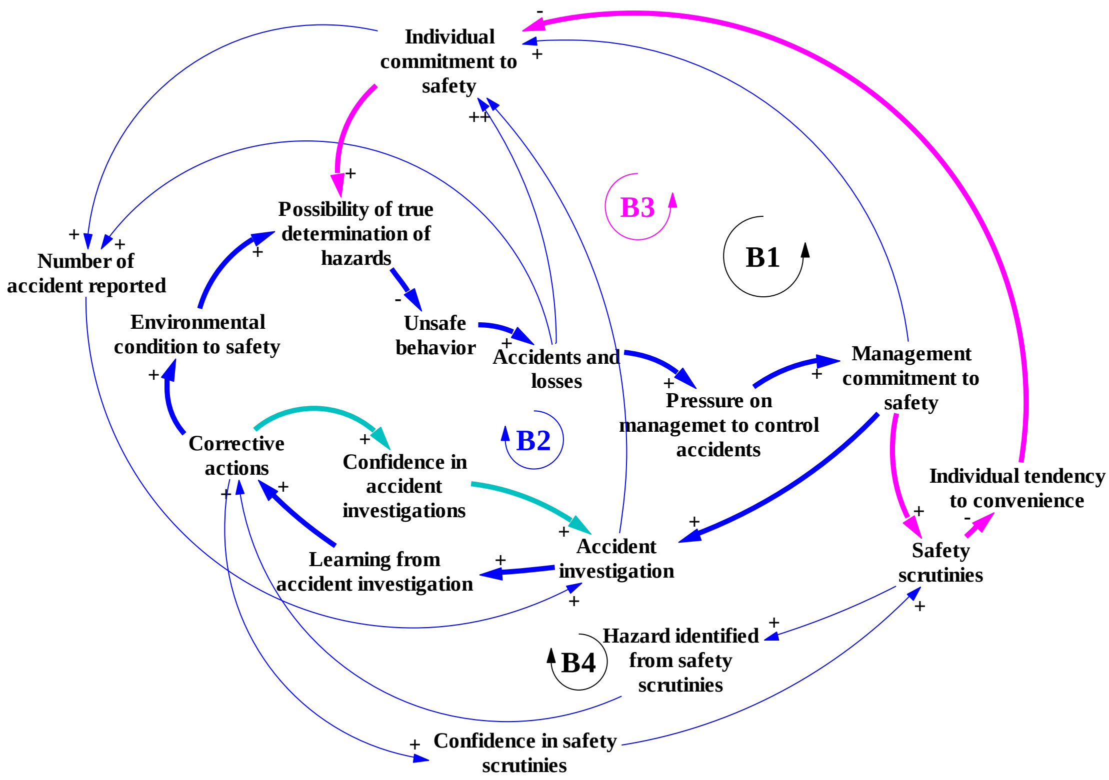

Figure 2: Causal Loop Diagram

Increase of accidents and losses lead to higher pressure on management to control the accidents. Therefore, management commitment to safety goes up which causes more and effective accident investigation. Consequently, learning from accident grows and more corrective actions take place to eliminate risks and improve safety which leads to fewer individual risk exposure and accident rate reduce (balancing loop B2).

As the accidents and losses increase, management commitment to safety increases. Therefore, safety scrutinies get better and more serious. This makes individuals who find it difficult to use safety tools and equipment and, for their own comfort, would like to violate safety rules make commitment to safety. Thus, individual commitment to safety increases which results in safer behavior and lower accident rate (balancing loop B3). On the other hand, by an increase in safety scrutinies, more risks are identified and more corrective actions are performed to eliminate risks that finally leads to a reduction in accident rate (balancing loop B4).

Stock and flow structure for management commitment and individual commitment is shown in figure 3. In the structure of this figure the interactions of the following variables are obvious: the interaction of management commitment with individual commitment, the interaction of management commitment and individual commitment with accident rate, the effects of affective variables on individual commitment and management commitment. It is assumed in the model that the managers and individuals begin their job in the project with a normal amount of safety commitment. It is changed during time under the influence of affective variables. Management commitment changes due to the pressure of the variable of work priority over safety, the variable of accident rate, and the variable of losses.

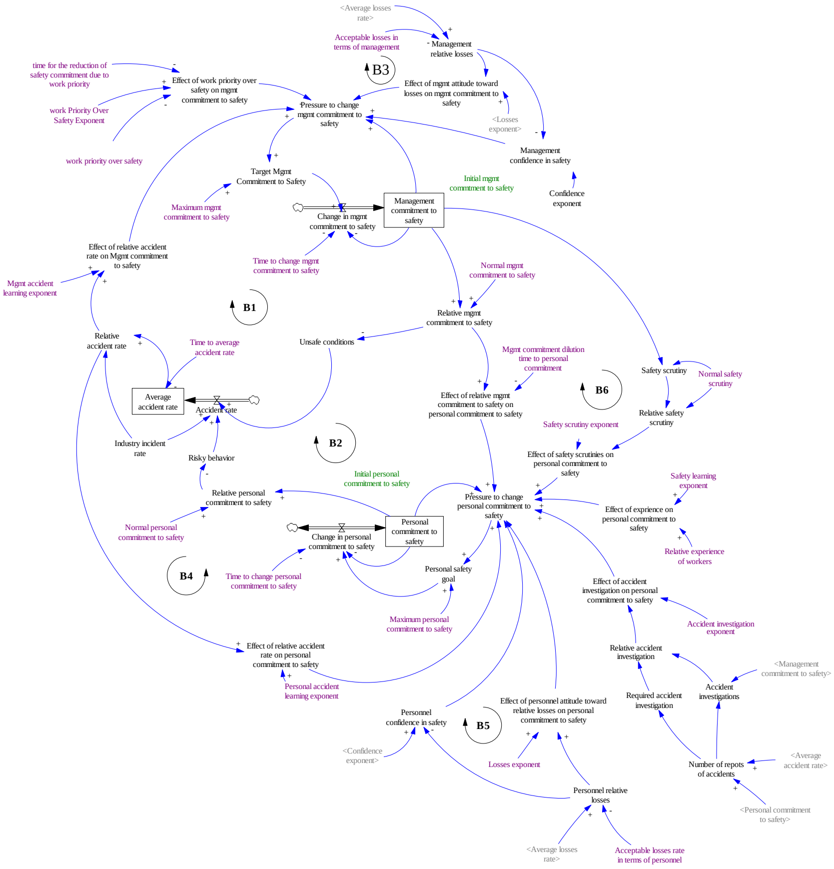

Figure 3: Stock-Flow Structure of Commitment and Average Accident Rate

Individual commitment of the members of the project change during time due to the pressure of the following variables: management commitment to safety, experience, accident rate, safety scrutiny, accident investigation, and the amount of losses. According to Cook (2002), risky behavior and individual commitment to safety are inversely related. Also, unsafe conditions and management commitment to safety are inversely related. In this study, along with the effect of management commitment to safety on unsafe conditions, the effect of corrective actions on unsafe conditions is observed as well. Because the more corrective actions are performed in the site, the unsafe conditions are reduced.

Reduction of management commitment to safety causes the increase of accident rate directly and indirectly. If management commitment reduces, unsafe conditions raise in the project. On the other hand, along the reduction of management commitment to safety the individual commitment to safety falls, too, which results in more unsafe behavior. Both lead to the increase of accident rate. However, the increase of accident rate and consequently, increase of losses result in more pressure on management to control the accidents which leads to the increase of management commitment to safety. In fact, three balancing loops of B1, B2, and B3 are created. If individual commitment to safety falls, accident rate will go up, and if accident rate gets more than normal, workers will feel threatened and therefore, increase their commitment to safety and balancing loop B4 works out. Accordingly, in case individual commitment to safety reduces, losses will increase. If the amount of losses exceed the acceptable amount by the individuals, they will increase their commitment to safety and create balancing loop B5. If management commitment goes up, safety scrutiny occurs in more numbers. Consequently, individual commitment to safety increases and the employees show fewer unsafe behaviors. As a result, accident rate falls. Reduction of accident rate leads to reduction of pressure on management which finally ends up in reduction of management commitment to safety. In fact, balancing loop B6 is formed.

The stock and flow structure of accident investigation and its learning is presented in figure 4 and safety scrutiny flow is shown in figure 5.

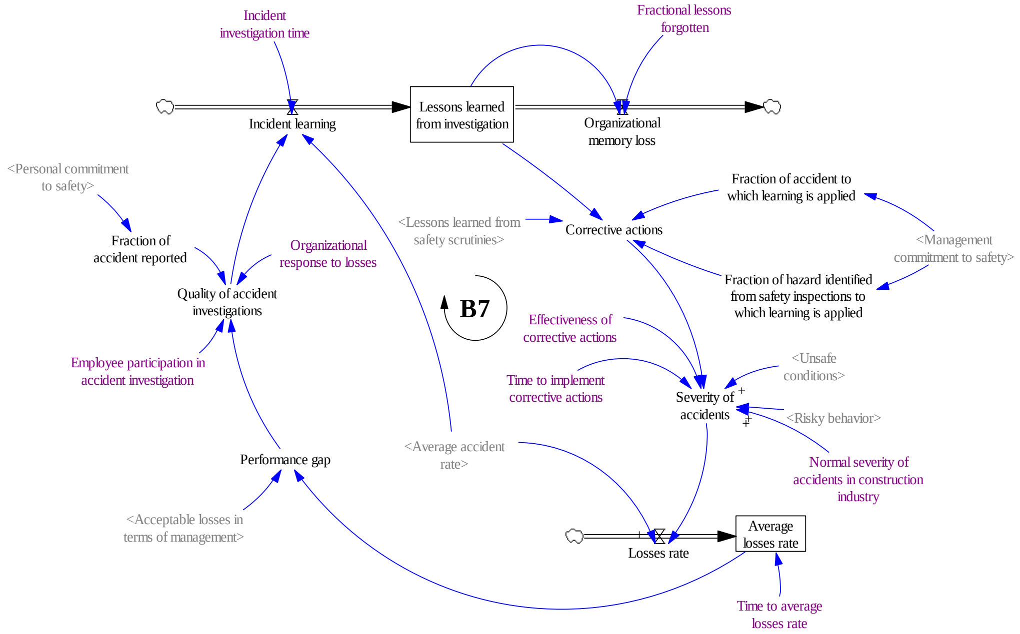

Figure 4: Stock-Flow Structure of Accident Investigation and its Learning

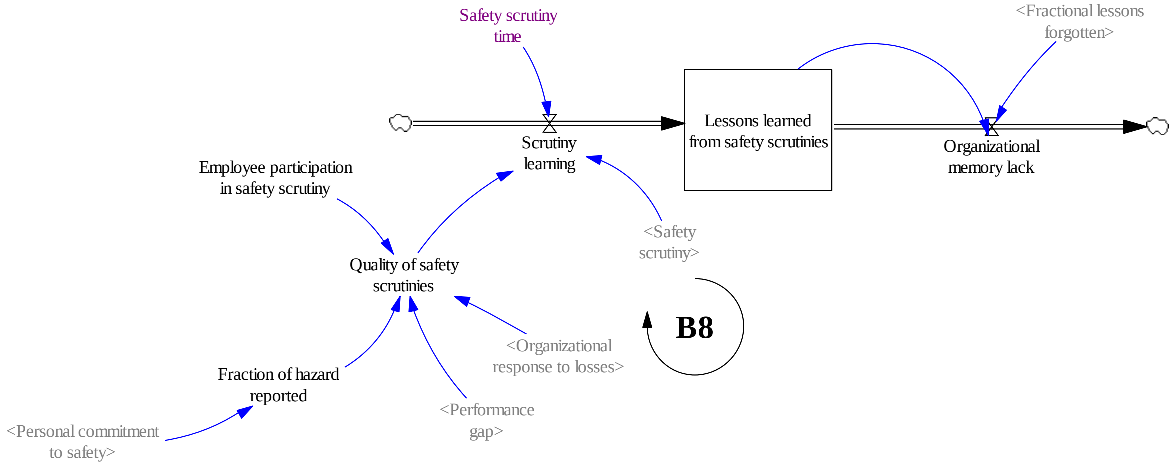

Figure 5: Stock-Flow Structure of Safety Scrutiny

Basis of stock and flow structure of accident investigation and its learning is derived from the study of Cook (2003) in Wesrtay Mine. The difference is that in this study Cook's presented model is developed and adapted to the conditions of construction industry. The developed model in this study is exactly explained in details.

Lessons learned from accidents rise with the rate of learning from accidents and reduce due to the forgetting of the organization. Corrective actions which are performed in the project depend on four variables. The greater the number and quality of safety scrutiny and accident investigation, the more will be learned from them and therefore, it is expected that more corrective actions be performed. However, performance of corrective actions in project relies on management commitment to safety. To put it differently, if the management commitment to safety be low, corrective actions will not be performed without a doubt. Corrective actions affect the severity of accidents. Indeed, more corrective actions can lessen the severity of accidents. Also the severity of accidents follow unsafe conditions of project and risky behavior of employees. According to Atrkar Roshan and Alizadeh (2015), normal severity of construction accidents in Iran is $3600 for each accident. The more unsafe conditions and risky behavior in the project, the greater is the possibility of more severe accidents. More severe accidents will have more losses. The quality of accident investigation relies on the amount of accident losses and acceptable losses in terms of management. If the amount of losses be more than acceptable losses in terms of management, management makes more effort to investigate the accidents in order to recognize the cause of large losses. In fact, as the losses increase, the quality of accident investigation increases too. As figure 5 shows, the quality of safety scrutiny depends on the amount of losses. If the losses get more than acceptable in terms of management, management will increase the number as well as the quality of the scrutiny. As the number of accidents and losses increase, the quality of scrutinies and investigations increase and therefore, lessons learned from scrutinies and investigations increase. Following the increase of learnings and with regard to the fact that escalation of losses leads to a rise in management commitment, more corrective actions perform in project which finally result in the reduction of accident rate and severity. In fact, balancing loops B7 and B8 are formed.

Model Validation

Since model validation is continuous, present model was validated from the beginning of development until completion from various aspects. Basic source for describing and performing validation tests is Sterman (2000). Validation of the presented model in this study was investigated by tests of boundary adequacy, structure assessment, dimensional consistency, parameter assessment, and extreme condition testing. It was also investigated by safety information of the past two years of one of the projects in Tehran Boston Engineers. In addition, presented model and its results were shown to 12 experts of construction safety who altogether confirmed the model and its results.

Results

Model operation without performance of corrective actions

In this study, the model is run for a 25 month duration. In the test of model, accident rate in construction industry is one accident a month which means it is assumed that in a construction project, there is average one accident in a month with normal severity of 10781314 Toman (equal to 3600 USD). Values of all constant variables in this study are in accordance with data obtained from construction industry in Iran.

In the first run, it is assumed that there are not any policies to perform corrective actions in the project. The results are shown in figure 6.

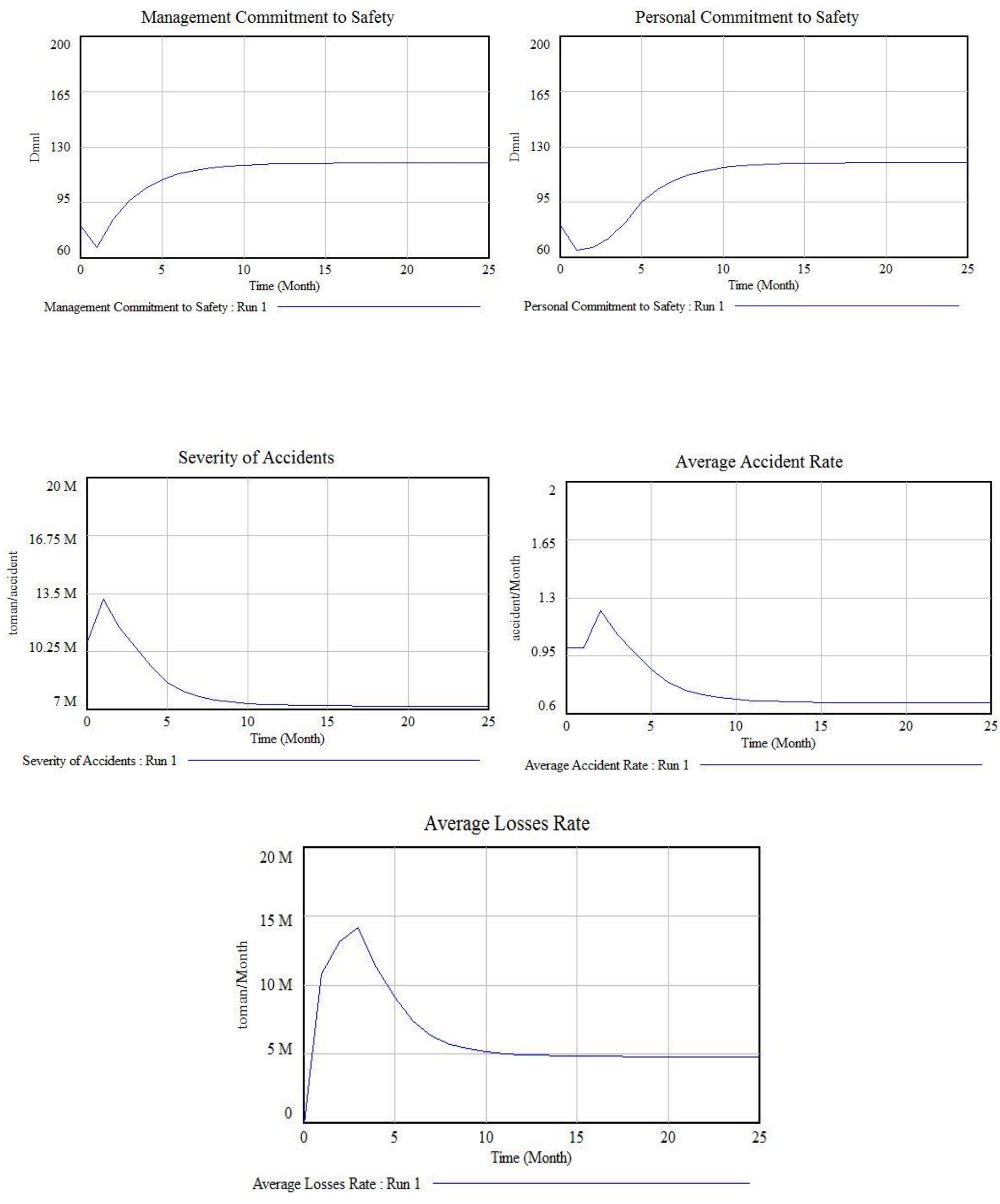

Figure 6: Model operation without performance of corrective actions

At the start of the project due to low accident losses, complacency of safety rises in managers and management commitment to safety reduces. According to this reduction, unsafe conditions escalate. Also with the reduction of management commitment to safety, individual commitment to safety reduces as well and risky behaviors increase in the project. Consequently, number of accidents and their severity increase in the project and accident losses increase dramatically. Following the increase of accidents and their relative losses, pressure on management rises to control the accidents. With more pressure to control the accidents, managers are committed themselves to safety. Since the personnel copy the project managers, an increase in management commitment leads to an increase in individual commitment which results in the reduction of risky behaviors. Therefore, the number of accidents, accident severity and losses reduce.

Model operation with performance of corrective actions

In the second run, all model parameters are similar to the previous run. Except that the policy of performing corrective actions is included. Actually, this time it is assumed that learning from safety scrutiny and accident investigations are applied and according to which corrective actions are performed. The results obtained from the second run are depicted in figure 7.

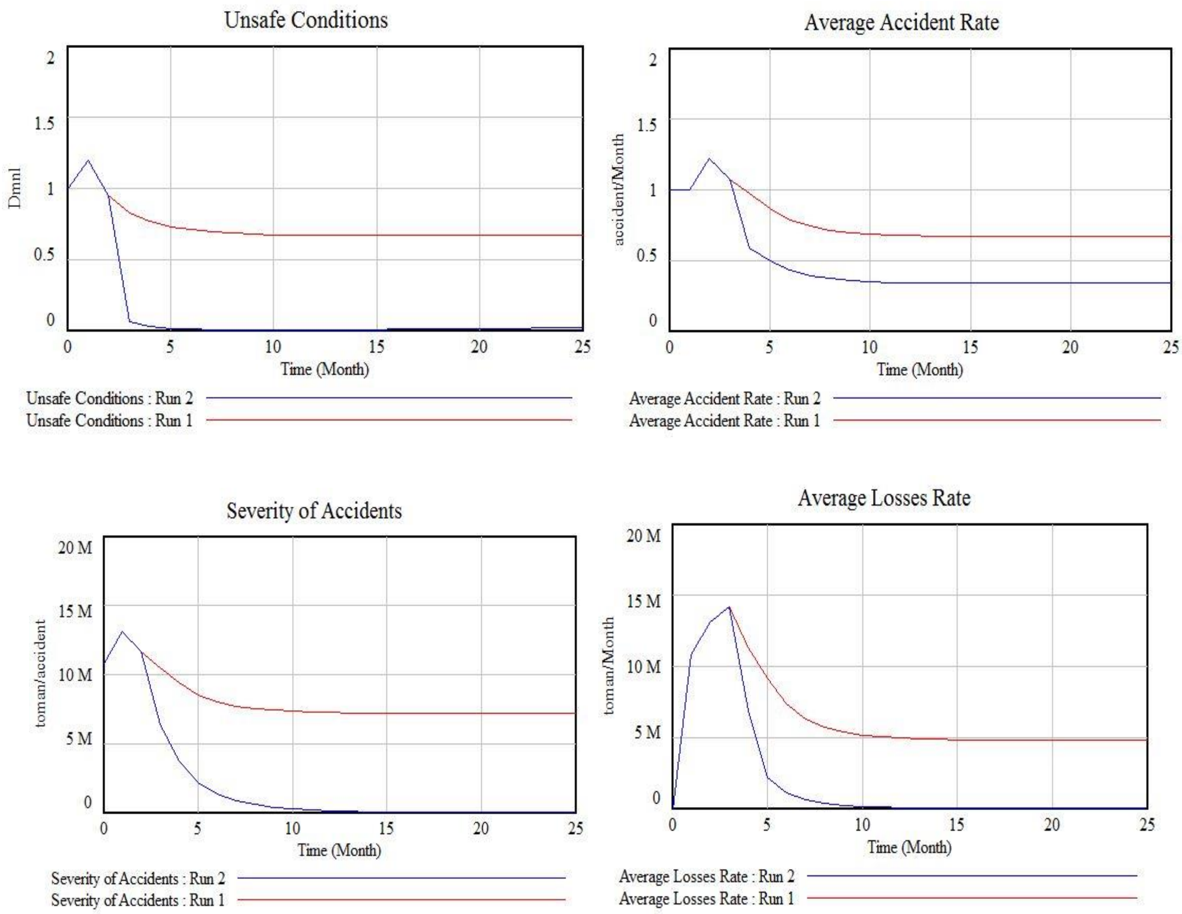

Figure 7: Model operation with performance of corrective actions

As it is shown, unsafe conditions are sharply reduced by performing corrective actions in site. According to the reduction of unsafe conditions, number and severity of accidents are considerably reduced. Therefore, accident losses are significantly reduced. Thus, it can be concluded that the policy of performing corrective actions in site is a highly successful policy to improve safety conditions and reduce accident losses.

Conclusion

In this study, by the simulation based on system dynamic, the subsystem of safety management of construction projects is modeled. However, as the old saying goes, all models are wrong but only some models are useful. We believe that the presented model in this study is a fruitful model to understand the behavior of a complex safety system in construction projects. In this study using capabilities of system dynamic modeling in considering nonlinear interactions and applying causal interactions, behavior recognition of safety system of construction projects becomes possible. In addition, results of this study is well able to show the capability of system dynamic in modeling complex construction systems.

Applying the presented model in this study, it is concluded that management commitment to safety, compared to other factors, is highly effective on the safety operation of construction projects. As it is obvious in the presented model, management commitment affects many effective variables in the safety of construction projects. Indeed, if project managers be committed to safety, it is expected that the project be in great safety condition, and vice versa.

Also it was presented in this study that the performance of corrective actions in site is highly effective on the reduction of the number and severity of accidents and their relative losses. If project managers apply the learnings of safety scrutiny and accident investigations to perform corrective actions, they can significantly improve the safety of construction projects. Performance of corrective actions not only prevents accidents with high losses, but also prevents accidents which are assumed to be part of the job.

Since no model is comprehensive, it is recommended that in the future studies causal interactions be developed and other effective factors on safety in construction projects be considered.

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