

Impacts of Safety Performance and Culture on Work-Related Accidents: A System Dynamics Model

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ABSTRACT

Research shows that when investigating the causal relation between phenomena, adopting a systematic view and assessing the feedbacks of involved variables could lead to much better results. In complex systems where humans act as significant components, the importance of systemic approach and focus on its dynamics become particularly more pronounced. The objective of this study was to use a system dynamics approach to study the safety culture and performance and its impacts on work-related accidents. This objective was pursued through introducing and determining the basic variables, plotting the causal and flow diagrams, and simulating the model by VENSIM software. In the next step, four different scenarios were defined to evaluate the model sensitivity and identify the leverage variables. The results of sensitivity analysis showed that production pressure is the key factor controlling the rate of work-related accidents in the studied organization, so adopting policies aimed at reducing the pressure of production can largely improve the level of accidents in this organization.

Keywords: *Safety, work accidents, System Dynamics*

1. INTRODUCTION

The critical role of human, technical, and organizational factors in catastrophic events have been repeatedly acknowledged in disasters such as Bhopal (1984), Piper Alpha (1988) and Chernobyl (1986) (Salge and Milling, 2006). The lesson learned from these catastrophes was that in highly complex industrial systems composed of numerous sets of components, the relationships between these components give the system a certain level of unpredictability (Reason, 1997; Perrow, 1994; Roberts, 1990). The high complexity of OHS management may lead to difficulty in defining, analyzing and solving safety issues and may even cause

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them to combine and develop into bigger problems (Wagner & Associates, 2010; Rettel and Webber, 1973; Peter). In such complex environments, the OHS measures adopted to deal with problems will have delayed effects, and managers, therefore, may fail to see the direct results of these policies. In such situations, safety managers can use system dynamics models to gain a better understanding of OHS status (Sterman, 2000; Goh et al., 2010a,b).

Over the past 60 years, industry experts tried a variety of methods to lower accident counts and improve their safety records, and the first step toward this objective was to improve the hardware condition (Arghami Sh, Yousefi M.1999). The next steps, which were taken in 60s and 70s, were i) adequate staffing and training, ii) establishing encouragement and reward systems, and iii) improving the managerial systems, and especially safety management. The first official use of the term “culture” (in safety-related literature) dates back to 1986 and the report of International Atomic Energy Agency about Chernobyl (Arghami Sh, Yousefi M.1999).

Schein defines the safety culture as a manner in which safety issues are addressed in a workplace (Schein, 1992: p. 8). The improvement of safety culture through staff assessment has been a popular subject of study (e.g. Zohar, 2000; Yule et al., 2003; Rao, 2007; Lu and Tsai, 2008). In a survey conducted by a questionnaire called safety climate scale, it has been concluded that safety culture is a collective understanding about the way the OHS management is implemented in the workplace. Research on safety climate has determined that safety climate has a correlation of 0.38 with accident ratio and a correlation of 0.42 with US OSHA medical records (Zohar, 2010). Although there is an important relationship between safety climate and OHS performance, the strength of this relationship is debatable. Safety climate researchers have been inclined to study the different aspects of safety climate via hierarchical linear methods (Y.M. Goh et al, 2012) and have paid less attention to the interaction between various components of the system.

Meanwhile, few papers that have assessed the subject of dynamics of safety culture and performance have only expressed and analyzed the causal relationships of this subject. For example, Y.M. Goh et al. (2012) have used system dynamics model to analyze the interaction between internal and external elements that affect an organization’s safety culture and performance. The measurement capability is a critically required feature of performance evaluation systems, but the mentioned study lacks quantitative analyses, simulations, and scenario building required to explore the leverage variables. So in the present paper, we tried to use the variables provided in literature and especially those identified by Y.M. Goh et al. (2012) to develop a quantitative dynamics model of safety culture and OHS performance, and after the simulation, we evaluated the different scenarios and identified the leverage variables contributing to policy-making.

The case study assessed in this paper was a company with 450 employees, of which about 300 were employed in manufacturing department and other 150 were working in administrative sections. Due to failure in acquiring the licenses required to use the name of this company, hereinafter it will be called Organization A. This company is a manufacturer of office equipment.

2. BACKGROUND

In the past, human errors were the primary suspects of all accidents; they were always the start point and often the end point of all investigations, and this, in turn, was blocking the chance of learning anything new about the accidents.

Perrow (1999) found that interactive complexity and tight coupling of system components make organizational accidents a “normal” occurrence of high technology systems. Perrow (1999) measured interactive complexity based on the number of ways system components can interact and tightness of coupling is measured based on the responsiveness of system components to a change in the system. Other researchers also identified that organizational accidents have long “incubation” period (Vaughan 1996; Turner and Pidgeon 1997; Laugé, Sarriegi, and Torres 2009) and the escalation are not always easily observed. Due to the characteristics of organizational accidents, Goh, Brown and Spickett (2010) suggested that traditional accident investigation tools (Sklet 2004) should be complemented by system dynamics tools to reveal the systemic structure associated with the organizational accident.

In recent years, there has been several system dynamics analysis of organizational accidents. However, the methods used are not consistent. Some placed more emphasis on qualitative system dynamics tools (Goh, Brown, and Spickett 2010; Leveson 2010; Marais, Saleh, and Leveson 2006) and others focus on the stock and flow simulation (Cooke 2003; Cooke and Rohleder 2006; Rudolph and Repenning 2002; Salge and Milling 2006). In comparison with traditional organizational accident research, which usually relies on textual analysis to elicit evidence to support theories on accident causation (e.g. Gephart 1993; Hynes and Prasad 1997), system dynamics analysis of organizational accidents is a departure from the usual.

Work-related accidents account for a significant portion of annual mortality in Iran as well as in the world (Mohammadfam I, et al., 2009). According to Iran’s latest statistics, the main cause of work-related accidents in this country has been the negligence and unsafe conduct (Mohammadfam I, et al., 2006).

The increasing rate of accidents in recent years (Tabibi J,et al.,2010) have pushed the traditional safety efforts to become more focused on the aspects of safety engineering. Accidents are the outcomes of unsafe mechanical conditions or unsafe practices, so usually, they are not the product of a single error of one person but instead develop through a series of interactive elements involved at various levels of the system (Tabibi J,et al., 2010).

Over the years, many theories have been propounded to specifically explain the cause of accidents; a brief review on the evolution of most notable theories in this regard is presented below:

A) The era of technical errors: the development of mechanical systems brought about a rapid growth in rates of work accidents. Analyses conducted on these accidents showed that the main causes of these failures were the defects in design, manufacture, and reliability of industrial devices and equipment (Wiegmann DA, & Shappell SA, 2001).

B) The era of human errors: In this period, the investigations on the cause of accidents showed the importance of human-related factors. The accident in a nuclear power plant in Iceland revealed the shortcomings of human factors, most notably the psychological weakness. Therefore, the "human error" replaced the "technical reasons" as the primary cause

of accidents. In this period, the "human" element was identified as the weak link, or the component directly responsible for unsafe practices (Rochlin, G. I., & Von Meier, A, 1994).

C) The era of technical-social errors: In this period, the reaction of humans to "technical" errors was declared as the cause of fatal errors and subsequent accidents.

D) The era of organizational culture: over the recent years, a new approach, which puts great emphasis on organizational culture, has emerged. According to this approach, most accidents are triggered by errors caused by staff and organization's lack of interest to safety culture (Gherardi S, Nicolini D, 2002).

It should be noted that due to the limited ability of human cognition, decision-makers and managers working in complex systems tend to develop a silo mentality (Stermann, 2000; Senge, 2006; Forrester, 2007 Meadows, 2008). Silo approach encourages managers to solve the problems in their area of responsibility by focusing on internal components. These solutions are often ineffective in the long run and may create counter-intuitive behavior in the entire system (Checkland and Scholes, 1999; Senge, 2006).

So to gain a proper understanding of the system and conduct a precise OHS performance evaluation, all components of the organization and their interactions should be assessed in tandem with each other. To achieve this goal, the researcher must first identify the variables and elements affecting the safety culture and performance.

The UK Advisory Committee on nuclear safety has published a report on influence of Human Factors on this issue, and therein it has defined a set of parameters as the key indices of safety culture; these parameters include: management commitment, management style, management visibility, communication, pressure for production, training, housekeeping, job satisfaction and workforce composition (Flin, et al., 2000). In a study conducted by the Irish Aviation Administration (2011), aspects such as safety objectives and policies, safety risk management, commitment to safety, and safety promotion were considered as the main components of organizational safety culture (State Safety Plan 2012-2015). An article titled "dynamics of safety performance and culture" has assessed the factors such as risky behaviors, negative effects of accidents on personnel, safety competency, training and new safety practices, employee morale and external factors such as production pressure, and has then analyzed their interactions (Yang Miang Goh, et al, 2012).

What that reflects the ambiguity of OHS performance evaluation is the still very high count of industrial accidents despite extensive efforts to improve safety conditions. The main purpose of this study was to use system dynamics model and particularly quantitative analysis via simulation and scenario building to examine the effect of safety performance and culture on the rate of accidents.

3. METHOD

We will use the system dynamics methodology for modeling and analysis. This method is one of the appropriate methods to simulate complex systems is based on causal relationships that enabling the system to provide appropriate learning by providing an environment for testing various scenarios. This method can be also used to analyze the problems with the qualitative approach (causal analysis) and quantitative approach (stock and flow). There are some applications of this methodology in social and economic complex problem modeling such as Mobile banking adoption simulation (Abbasi, Bastan, Ahmadvand, 2016), Banking Risk Management (Bastan, Bagheri Mazraei and Ahmadvand,

2016), Banking Paradox (Bastan, Akbarpour and Ahmadvand, 2016), Sustainable Development (Bastan et al., 2016), Organizational demographics (Bastan, Akbarpour and Delshad Sisi, 2016), Brain drain (Kasiralvalad et al., 2016), Dust Emission (Bastan, Abdollahi and Shokoufi, 2013), Waste Management (Ahmadvand et al., 2014), Crisis Management (Khoshneshin and Bastan, 2014), Inflation Rate (Akbarpour et al., 2014), Housing Cost (Bastan, Mosaed and Kashef, 2013), User satisfaction in Healthcare services (Bastan and Soltani Khamsehpour, 2016), Public health (Bastan and Zadfallah, 2016), Clinical Risk Management (Zadfallah, Bastan and Ahmadvand, 2017), Occupational Health and Safety Management System (Azizi Baraftabi, Bastan and Ahmadvand, 2017), Chronic Diseases Growth and Effective Control Costs Management (Tabarzan, Bastan and Ahmadvand, 2017). In order to solve a problem by system dynamics we need to pursue five steps below:

1. Identifying and defining the problem
2. Mapping cause and effect diagrams
3. Developing the mathematical model (stock and flow diagram)
4. Model simulation and validation
5. Scenarios generation and evaluation, then selecting and implementing the most appropriate solution

System dynamics is often employed to analyze complex social and economic systems; as these systems dynamically change due to many unknown causes. Sterman (2000) describes the steps of system dynamics modeling according to figure 1.

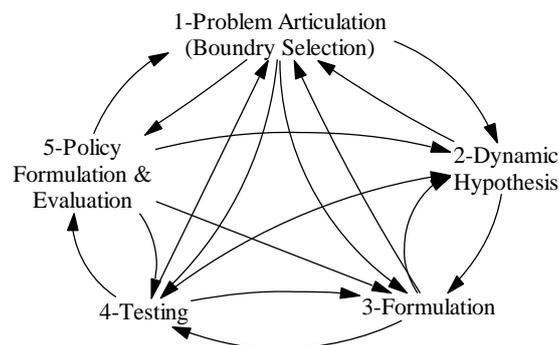


Figure 1-Iterative and feedback process of modeling based on system dynamics methodology (Sterman, 2000)

4. MODEL

To build the dynamic model, we needed to first identify the variables and components involved with OHS culture and performance. So to identify the important parameters in an accurate manner, this study used variables provided by literature and especially those identified by Yang Miang Goh et al. (2012) in tandem with experts' opinions. Experts contributing to this study included: 2 safety managers with 10 and 15 years of experience, safety manager of Organization A, 3 safety expert with more than 15 years of experience, 3 safety experts of organization A, and 1 safety inspector with 7 years of experience. The authors, who were familiar with the system dynamics literature, provided these experts with several articles about safety culture dynamics. After a period of 10 days, during which articles were read by experts, a meeting was held at the office of Organization A. In this

meeting, which was attended by all mentioned experts, variables affecting the safety performance and culture were identified and discussed through a brainstorming process.

4.1. IDENTIFICATION OF KEY VARIABLES

During the meeting, the majority of experts stated that variables identified by Yang Miang Goh, et al. (2012) are largely similar to those affecting the safety performance and culture of Organization A. Therefore, after discussion and addition and removal of a number of variables, the main variables of the study were identified. In addition, to convert a qualitative model to a quantitative one, we needed to formulate the relationships and quantify the qualitative variables. To determine a level for each qualitative variable and turn it into a quantity, we needed to perform a survey at the organizational level. For this survey, the training manager, the production manager, and the members of HSE committee were added to the team of experts. This survey team acquired all documents related to production, hazard detection, risk assessment, statistics, reports, and analyses pertaining to the accident of past 10 years, and training programs of last 5 years, and the list of budgets planned and allocated to OHS applications. Survey plan was announced to all units. Survey process included field studies and analysis of documents. Given the size and scope of activities, the survey process took about 3 days. At this point, a quantification process was needed to determine the current status of constant qualitative variables. So, after the survey, members of the survey team held another meeting. After discussing the results of the survey, this team proposed a scheme for quantifying the qualitative variables. This scheme is shown in Table 1.

Table 1. Quantification of constant qualitative variables based on current status of organization

Variable	Quantification			current status
Accident	Good	0-2	1-25	70
	Average	2-4	26-50	
	Poor	4-6	51-75	
	Critical	Above 6	76-100	
Target	Similar to "Accident"			20
Production pressure	Low	1-3		10
	Medium	4-7		
	High	8-10		
Safety resource available	Limited	0.00-0.25		0.70
	Low	0.25-0.50		
	Medium	0.50-0.75		
	High	0.75-1.00		
Existing technology	Limited	0.00-0.30		0.50
	Medium	0.30-0.70		
	Available	0.70-1.00		
Communication channel	Weak	0.00-0.40		0.70
	Average	0.40-0.80		
	Strong	0.80-1.00		

According to International Labor Organization (ILO), the accident severity rate can be calculated by dividing the number of days lost because of an accident in a certain period multiplied by 1000 by the total effective work hours at the same period of time. Organization A had 450 employees, who worked 900000 hours per year (effective hours of work). In

addition, examining the documents related to the accident recorded in the past year revealed that these accidents had led to the loss of 3,700 hours of work. So, Organization A had an accident severity rate of 4.11, which was rather unsatisfactory. According to the survey team, the score pertaining to the current status of accidents was 70, which represented the poor condition. The classification devised by experts for the parameter “accidents” is shown in Table 1. It should be noted that here the variables “Target”, “Production pressure”, “Safety resource available”, “Existing technology”, and “Communication channels” were all constant, and their current status in the organization needed to be determined. Values of other variables needed to be defined by formulating the relationship between them; this process will be described in later sections. The current values of mentioned variables were determined by the results of survey and comments of the survey team.

Considering the currently poor condition of the organization, the objective was to reduce the rate of accidents and its quantitative index from 70 to the acceptable value of 20. While due to increased volume of orders in the past few months the production rate was extremely high. Thus, members of the survey team, and especially the production manager suggested that quantitative index pertaining to “Production pressure” must be set at its peak value, i.e. 10. Members of the survey team also recommended the value of 0.7 for “Safety resource available”, 0.5 for “Existing technology”, and 0.7 for “Communication channels”. At the time, communication channels between employees and safety managers included accidents and near misses record box, a suggestion system, phone lines and a safety site. Note that values of other variables must be determined through the definition of their relationships; this process will be described in the simulation section.

4.2. CAUSAL LOOP DIAGRAM

The article provided by Yang Miang Goh, et al. (2012) and the opinions of survey team were used to develop the causal loop diagram pertaining to factors of safety performance and culture in Organization A. Figure 2 shows the diagram developed by Vensim software.

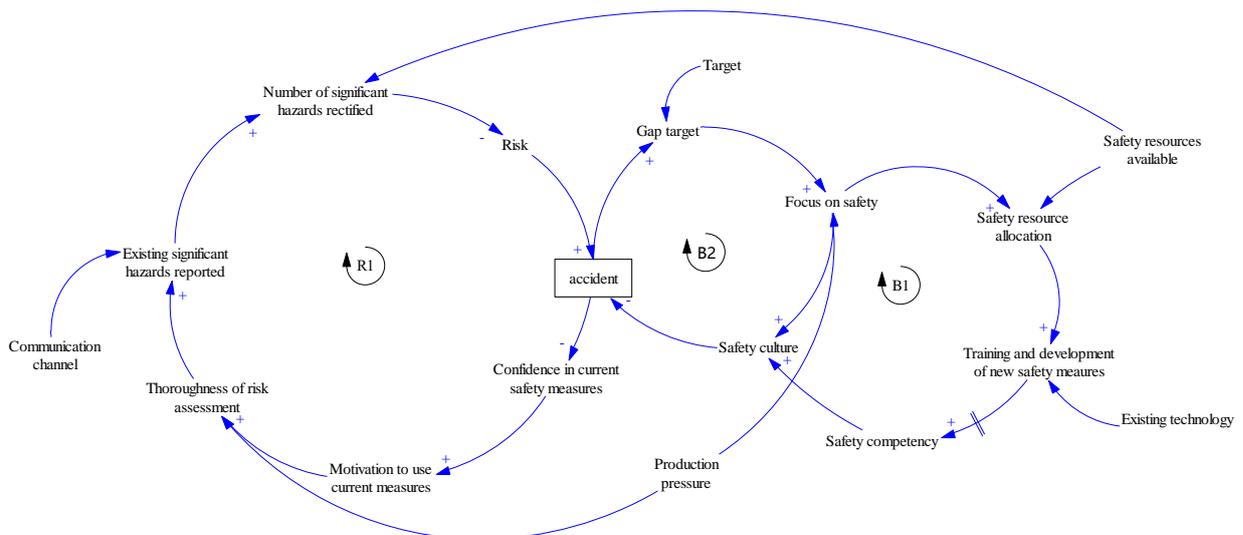


Figure 2. The Causal loop diagram for safety performance and culture

When the gap between current level of accidents and the target condition is wide, like for example when the actual rate of accidents is significantly higher than the target rate, OHS management tend to put more focus and allocate more resources to resolve the issue (Loop B1) (Yang Miang Goh,et al,2012). In addition, focus on safety will also be affected by production pressure. In a very busy production schedule, there will be little time to focus on safety issues. Allocation of more resources requires the availability of resources. More resources provide the groundwork for more training as well as the development of new safety measures. It should be remembered that the development of new safety measures also depends on the availability of technology. Training and development of new safety measures increase the safety competency which in turn increases the safety culture and reduce the rate of accidents. Increasing the safety competency is a time-consuming objective and will have long delayed results (Loop B1). Meanwhile, intensified focus of management on OHS can improve the safety culture (Loop B2) (Yang Miang Goh,et al,2012). Note that intensified focus on B1 and B2 control loops can close the gap between current status and target status. The loop R1 is a potential factor of risk growth. The occurrence of an accident decreases the confidence in the current safety measures. These circumstances lead to decreased motivation to use current safety measures and therefore decreased thoroughness of risk assessment. Decreased thoroughness of risk assessment leads to inadequate reporting of accidents and subsequent failure to address safety issues, and all these consequently lead to higher levels of risk. The important point is that communication channels are the main instruments of reporting, so improving these channels can improve the status of hazard reporting. In addition, eliminating the reported hazards depends on the status of available safety resources. Without a doubt, increased risk of accidents is directly related to increased rate of accidents. (Loop R1).

4.3. STOCK AND FLOW MODEL

Figure 3 shows the flow diagram of safety performance and culture. Here, the status of accidents is a level variable, while risk and safety culture are both rate variables influencing the status of accidents. The risk is directly related to the rate of accidents and an increased risk leads to an increased accident severity rate. On the other hand, safety culture reduces the rate of accidents. Other variables affect both risk and safety culture.

Here, fixed variables are Target, Available resources, Production pressure, Existing technology, and Communication channels, all having a constant fixed effect on safety performance and culture. The next step after developing the flow diagram was to conduct the simulation but to simulate the model we needed to define the relationships between variables.

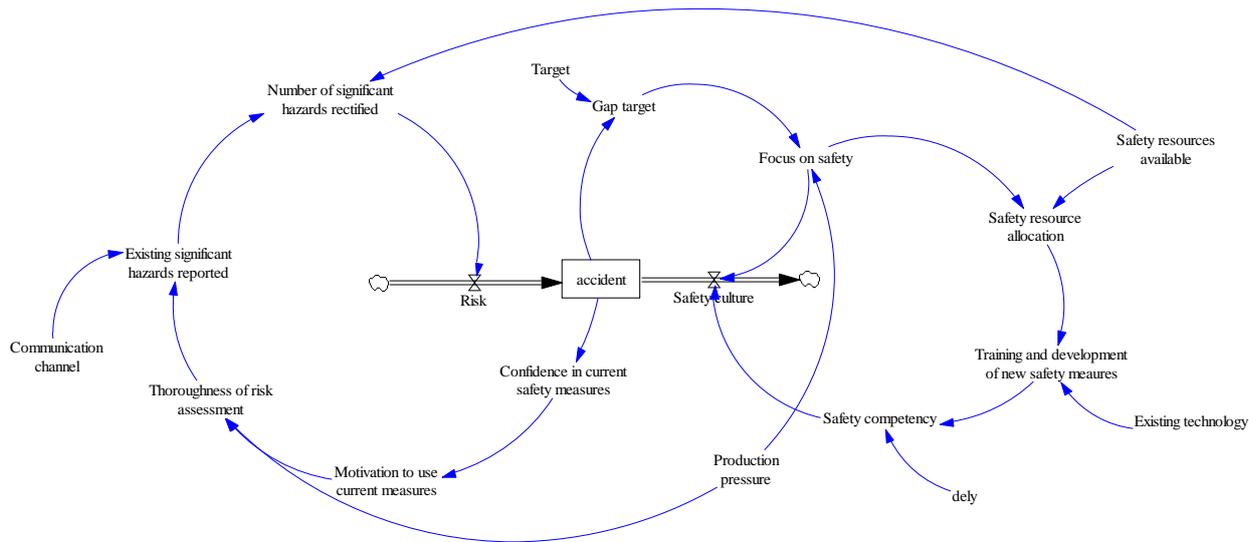


Figure 3. The flow diagram for safety performance and culture

5. SIMULATION RESULTS

After quantifying the qualitative variables of safety culture and performance, the next step was to define the relationships between variables. In fact, the quality of relationships between variables and effects and feedbacks between them were determined earlier in the causal loop diagram. Here, the opinions of experts were again used to define the quantitative relationships between these variables. Table 2 shows the inter-variable relationships devised based on experts' opinions.

Table 2. The quantitative relationships between variables

Variable	Relationship
Accident	Accident=Risk - Safety culture
Risk	Risk=(1/ Number of significant hazards rectified)
Safety culture	Safety culture= Safety competency × Focus on safety
Gap target	Gap target =Accident - Target
Focus on safety	Focus on safety = Gap target ×(1/ Production pressure)
Safety resource allocation	Safety resource allocation = Safety resource available × Focus on safety
Training and development of new safety measures	Training and development of new safety measures = Safety resource allocation × Existing technology
Safety competency	Safety competency = Training and development of new safety measures ×1
Confidence in current safety measures	Confidence in current safety measures =(1/Accident)×100
Motivation to use current measures	Motivation to use current measures = Confidence in current safety measures ×1
Thoroughness of risk assessment	Thoroughness of risk assessment = Motivation to use current measures ×(1/ Production pressure)
Existing significant hazards reported	Existing significant hazards reported = Communication channel × Thoroughness of risk assessment
Number of significant hazards rectified	Number of significant hazards rectified = Existing significant hazards reported × Safety resource available

The relationships shown in Table 2 were coded into Vensim Software and then this software was used to simulate the flow diagram. Experts suggested that a 25-year period will be a

good measure to determine the model behavior. It seems that due to delayed effects of safety performance and culture on OHS performance, 25-year period provides an acceptable scope for gauging this effect. Figure 3 shows the behavior of level variable “accident” and Figures 4 and 5 show the behavior of rate variables “safety culture” and “risk” over the next 25 years.

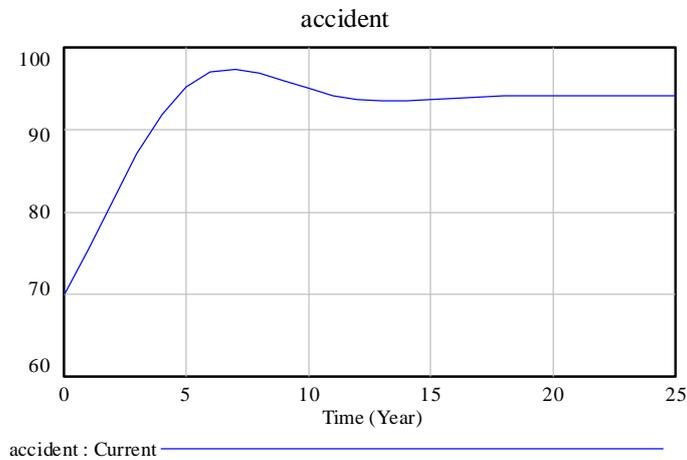


Figure 4. The behavior of level variable “Accident” over the next 25 years

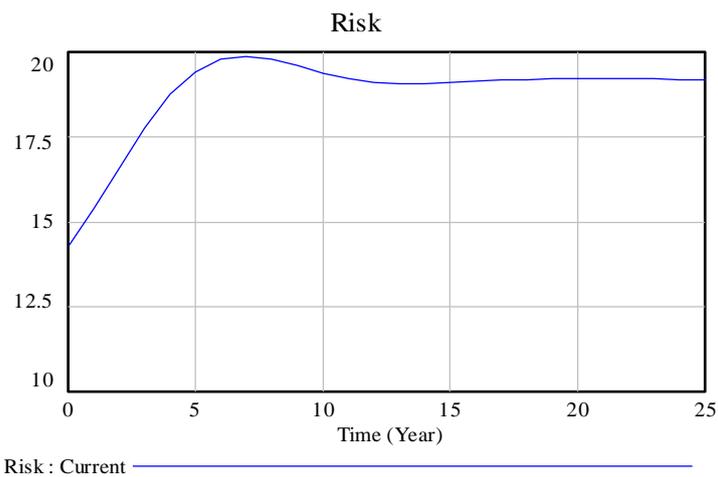


Figure 5. The behavior of rate variable “Risk” over the next 25 years

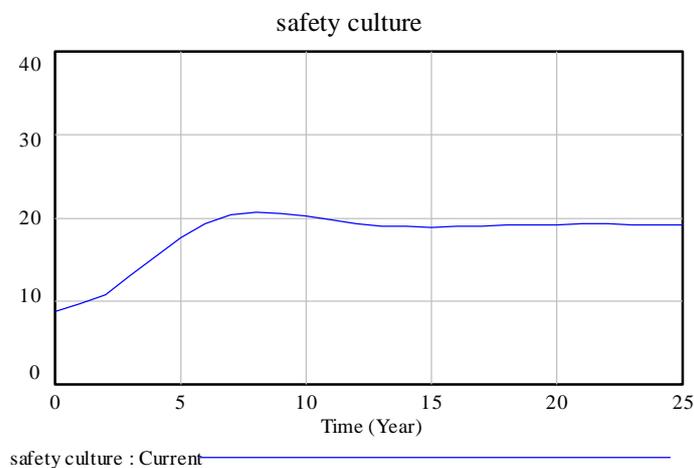


Figure 6. The behavior of rate variable “Safety culture” over the next 25 years

As Figure 3 shows, while today's condition of the organization in terms of accidents is not desirable, it will grow even worse over the next 25 years, reaching to about 95% representing a critical condition. In fact, a continuation of current trends is not acceptable, and some strategy must be adopted to change this situation. An interesting point is that despite a slight increase in safety culture over these years, the risk will still see an increasing trend, and this will, in turn, leads to more accidents. It seems that the reason behind this type of behavior of safety performance and culture should be traced back to variables such as production pressure. In fact, it seems that a variable such as production pressure can essentially foil all efforts made to increase the safety culture. To prove this hypothesis and investigate the effect of other factors on the occurrence of accidents, in the next section, we will present the results of a simulation conducted based on a series of defined scenarios.

5.1. SENSITIVITY ANALYSIS

At this stage, we defined four different scenarios to determine the variables significantly affecting the OHS performance and their impact on the reduction of accidents. In the first scenario the “available resources” was increased from 0.70 to 0.95; in the second scenario the “pressure production” was reduced from 10 to 5; in the third scenario the “Existing technology” was increased from 0.50 to 0.90; and finally in the fourth scenario the “communication channels” was increased from 0.70 to 0.95. The simulation results obtained for the defined scenarios are shown in Figures 6 to 9.

As these graphs show, Scenarios 1, 2 and 3 have reduced the accidents, but the extent of reductions made by scenarios 1 and 3 is minimal, so they will not make a significant contribution to the improvement of the situation over the next 25 year. However, it should be noted that the variable “Existing technology” is largely out of control of the organization. The fourth scenario, i.e. improving the communication channels, has failed to change the trend of accidents and has only managed to slightly hinder the rate of increase.

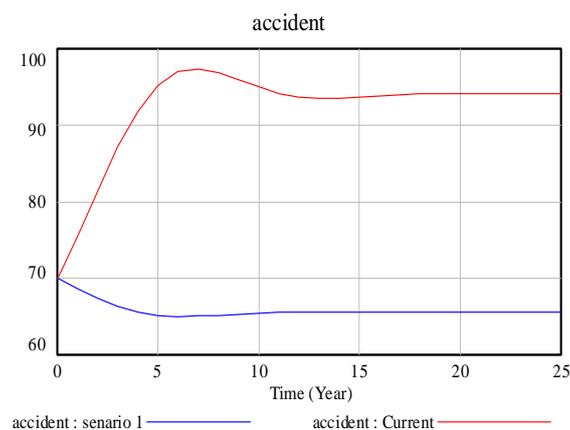


Figure 6. The effect of an increase in “available resources” on “accidents”

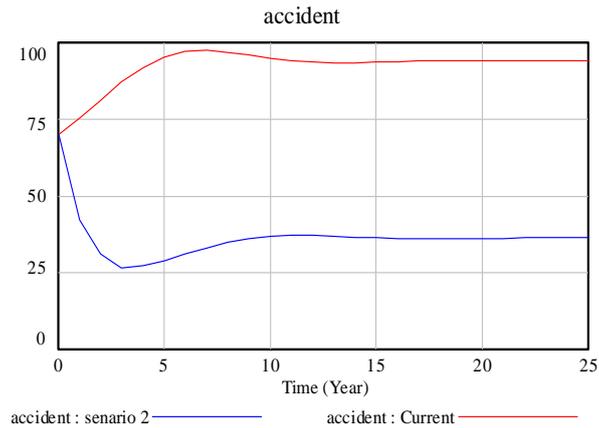


Figure 7. The effect of a decrease in “production pressure” on “accidents”

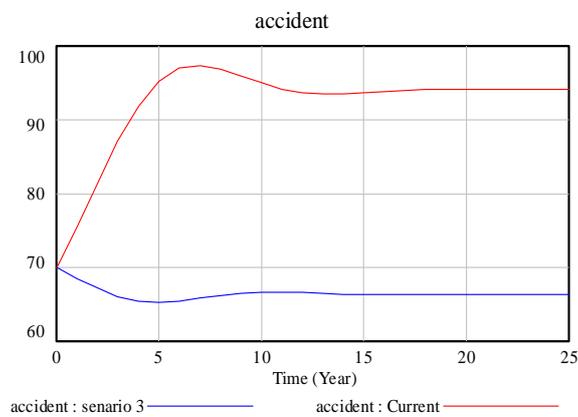


Figure 8. The effect of an increase in “Existing technology” on “accidents”

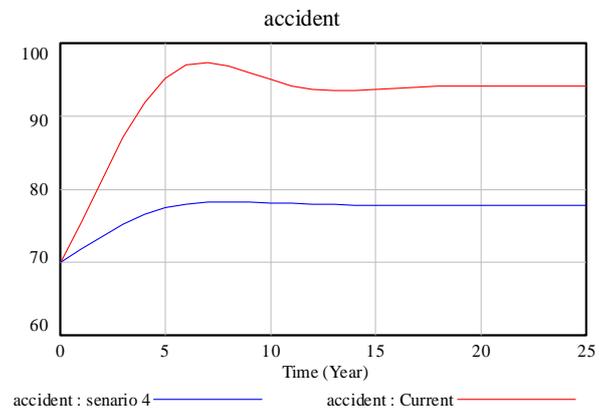


Figure 9. The effect of an increase in “communication channels” on “accidents”

According to scenario 2, i.e. the reduced production pressure, this variable has acted as the most powerful parameter of the model, and its decrease has managed to make a significant contribution to the improvement of accident status, safety culture, and OHS performance. In fact, the implementation of this scenario alone has reduced the level of accidents to an acceptable level. This shows the importance of reducing production pressure through measures such as adequate staffing, setting up extra work shifts and improving the management of orders. It is clear that development and implementation of production

pressure reduction programs require expert studies and focused problem-solving sessions. However, the results of simulation and scenario building indicate that rapid and timely action is essential since the lack of proper attention to this issue will cause irreparable damage to the organization.

6. CONCLUSION

This study used the system dynamics model for investigating the key factors influencing the safety culture and performance, since the complexity of behavioral models and variables feedbacks could easily justify the use of this tool. To assess the variables interaction, first the available literature was used in conjunction with experts' opinions to determine the causal relationships between parameters; next, these parameters and their relations were quantified and their corresponding flow diagram was plotted; in the end the resulting model was simulated. This simulation showed that over the next 25 years the trend of accidents in the studied organization will be far from acceptable. In the next step, a series of scenarios were defined to identify the critical variables. Simulation of these scenarios showed that the variable "production pressure" has a key effect on the reduction of accidents in the studied organization, so adopting policies and objectives aimed at reducing this variable can effectively control the level of accidents. Of course, it is essential to also pay due attention to other variables and does not limit the efforts to production pressure reduction programs. Overall, it seems that in cases where assessed parameters are heavily influenced by both environmental and behavioral factors, the use of system dynamics model can clarify the uncertainties and facilitate the process of problem-solving. The interesting subjects for future research regarding this topic could be the development of model introduced in this paper, determination of effects of safety standards on OHS performance, and dynamic modeling of the effects of organizational performance on other HSE aspects.

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