Original Research

SAFETY STRATEGY ALLOCATION SIMULATOR FOR ACCIDENT REDUCTION AND COST SAVINGS IN SAFETY MANAGEMENT SYSTEM

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ABSTRACT

Accidents happen and they upset the normal functioning of any organization causing real damage to persons, equipment, and loss of revenue. To mitigate these problems, safety performance metrics, and system dynamics have been implemented widely to solve the challenges of delays, feedback, and nonlinearity. A mathematical description of the relationships among the identified variables coupled with computer modeling was used to develop the Computer Programme Simulator (CPS) using MATLAB to code the dynamic relationship of the manufacturing safety system to determine accident prevention strategies.

The safety dynamic equations were subsequently computed and this was followed by the processes of model application and experimentation. The results of the study showed that parameters such as "the constants", "initial state variables", "graphs to plot", "export graph" and "export table" allows the user plug the desired variables into the CPS and provide data on the number of accidents to be reduced after the selection of the appropriate strategy. The first successful simulation of the CPS also produced a P = 60% and T = 10% reduction in the number of factory accidents. This study concluded that the CPS interactive interface which was developed serves as a useful tool for predicting, preventing, and even reducing factory accidents and makes safety management systems easy. The outputs of all the simulations also revealed that the reduction of accidents and the cost of accidents in all the values of the proportion of available budget and desired accident reduction target computed are practicable.

Keywords: Computer programme; Cost; Safety Management; Safety Strategies; Simulator

INTRODUCTION

Accidents usually are unplanned occurrences that disrupt the normal activities of any particular organization and this can end up resulting in property damage or even personal injury [1]. Studies have equally confirmed that accidents often follow the same pattern of events and occurrence, which may have happened before because of negligence and or unsafe working conditions. Consequently, Jacobson et al., [2] submitted that accidents at work cause workers to apply for sick leave which also leads to a lot of organizational downtimes. This ultimately exposes the organization to risks such as reduced productivity, payment of compensation to workers, and loss of competitive advantage. Therefore, the assessment of safety performance provides a valuable opportunity for managers to work towards the implementation of best practices that will effectively lead to the highest probable safety outcome.

Furthermore, the implementation of safety performance metrics is essential for directors, senior and line managers, supervisors, and safety professionals, who need a tool for monitoring goal achievements, progress, and expected results [3]. A large number of studies show that emphasizing the commitment of a firm's management to safety protocols is an essential element of the firm's climate and is an extremely important factor in achieving a good safety performance [4]. This commitment is reflected in the ability of the managers to correctly appreciate and understand the complexities and dimensions of existing problems, their conviction that the firm can achieve high levels of safety, their ability to demonstrate a lasting positive attitude towards safety, and their ability to promote safety actively at all levels in the organization.

To this end, SD has been established as a methodology for studying and managing complex feedback systems, such as may be encountered in business and other social systems [5]. Furthermore, it is a tool that has been successfully deployed to address complex issues involving delays, feedback, and nonlinearity. According to Tidwell et al., [6], SD is an approach necessary for the right understanding of the behavior of complex systems over time, while also helping to deal with internal feedback loops and time delays that affect the behavior of the entire system. Therefore, the incorporation of SD into a well-programmed computer-visual-user interface will eventually minimize the stress of analysis of these complex models, while also saving valuable time that managers expend during the calculation and analysis of these complex models.

METHODOLOGY

- *The Computer Programme Development*

Owing to the complex dynamic cases and the volume of iteration that results per time, MATLAB was used to code the dynamic relationship of the manufacturing safety system. The process of defining, developing, and documenting key variables and relationships of the computer programme consists of the knowledge of the stakeholders in the manufacturing industry (manufacturing engineers, safety engineers, factory workers, and the management). The computer programme seeks to integrate and capture the dynamic nature of the identified accidents causing and prevention variables and parameters to estimate the number of accidents, predicted preventions, and monetary benefits derivable over time, respectively in the use of a strategy during a safety programme. The classes of accidents and prevention strategies were identified accordingly. The computer programme was built to show future trends and their dynamic interrelationships of the accidents caused, predicted preventions, and safety programme benefits with time.

In developing the Computer Programme Simulator (CPS), a mathematical description of the relationships among the identified variables coupled with computer modelling was employed. The descriptions are based on the principles of dimensional consistency. Two sets of differential equations representing the accident causing and prevention were developed. Solving the differential equations, the dynamic function of several factory accidents (X_t) was developed in terms of an accident causing factor (h), potential accidents (GL), factory man-hours of the workforce, and proneness factor (f). Also, a dynamic function of the number of prevented accidents(Y_t), was developed in terms of budgeting factor (β), the proportion of planned budget (P), the effectiveness of each prevention activity (μ_k), factory workforce (q), accident proneness factor (f), pre-safety accidents level (X_p), safety strategy time lag, and potential accidents (GL). These two models were dynamically linked together to develop other required safety programme performance measurements, i.e. Factory Accidents (X_t), Prevented Accidents (Y_t), Cost Saving (SN), Probability of accidents caused (ρ_1), Probability of prevented accident (ρ_2), Accident prevention rate (γ_t), Factory Hazardous Condition (FC), Implemented Budget, Rate of Accident causation (α_t), and Potential Accidents (GL).

The models were developed in form of a calculation chain involving repeated stages and MATLAB programme was used to code the models.

- *Manufacturing Safety Programme Application*

In developing and validating the developed safety programme, the three stages: data collection, parameters estimation, and computer programme application as given by Adebiyi [7] were applied.

i. Data collection

Data collected by Adebiyi and Ajayeoba [9] were adopted.

ii. Parameter estimation:

The required input parameters were then estimated as follows:

Step 1: Determination of the prevention time lag {T} by running the programme for some periods and observed the time at which the accidents started reducing. For example, the programme was run for the first week, observe the accidents; run for second, third, fourth, till the twelfth month. The time at which it was first observed that there was a decrease in accident occurrence was to be taken as the time lag.

Step 2: Determination of the safety accident reduction target (T) that the organization is willing to achieve at the end of the simulation period.

Step 3: Determination of the proportion of safety budget (P) that the organization is willing to commit to the programme

Step 4: Determination of the system input parameters from the data of pre-safety programme periods

iii. Computer programme validation

The estimated parameters from the pre–safety programme and safety programme data collected by Adebiyi and Ajayeoba [9] were adapted for this research.

However, the following steps were followed:

Step 1: Click and input the data required in the following: cost of safety strategy for each strategy (₦), effectiveness index for each strategy (dimensionless), estimated cost of each class of accident (₦), and proportion of prevented accident (dimensionless).

Step 2: Input the following parameter: Budgeting factor, time lag, simulation time, accident causation factor, factory workforce, accident reduction target, pre-safety programme accidents, and the proportion of planned budget actually implemented.

Step 3: Input the initially stated parameters i.e. the pre-safety factory accidents and the prevented accident

Step 4: Run the programme to generate the following: Factory accidents, prevented accidents, cost saving, probability of accidents caused, probability of prevented accident, accident prevention rate, factory hazardous condition, implemented budget, accident causation rate , and a potential accident.

Step 5: By clicking Run, Tables of parameters in step 4were generated which can be exported into another folder. Also, any graph from the generated parameter can be generated by selecting the required parameters and then click the plot button.

- *Safety Dynamic Equations*

The required models for factory accidents (X_t), prevented accident (Y_t), and the cost savings (SN) (as shown in Equations 1 – 3 respectively) according to Adebiyi et.al. (2018) were used in the simulator.

$$X_t = Y_t - X_p \left(1 - \ell^{-ht\left(1-\ell^{-\lambda(qf-y_t)}\right)}\right) - X_o \ell^{-_1 ht\left(1-\ell^{-\lambda(qf-y_t)}\right)} \quad (1)$$

$$Y_t = X_p \beta P \mu_k \left[1 - \ell^{-\ell^{-[(qf-Y_t)\cdot\lambda]t}}\right] + Y_o \ell^{-\ell^{-[(qf-Y_t)\cdot\lambda]t}} \quad (2)$$

$$SN = X_p \beta P \left\{\left[\left[\mu_k\left(1 - \ell^{-\ell^{-[(qf-Y_t)\cdot\lambda]t}}\right) + Y_o \ell^{-\ell^{-[(qf-Y_t)\cdot\lambda]t}}\right] \sum_{n=1}^{4} (N_n \times C_{nt})\right] - 1\right\} \quad (3)$$

The accident prevention rate (γ_t) which is a function of target decision, prevented accident and probability of prevented accident is given as

$$\gamma_t = \frac{dY_t}{dt} \quad (4)$$

But $\gamma_t = f(TD, Y_t, \rho_2)$

Therefore, γ_t can be written as:

$$\gamma_t = (TD - Y_t)\rho_2 \quad (5)$$

Also, the accident causation rate can be expressed as:

$$\alpha_t = \frac{dX_t}{dt} \quad (6)$$

But $\alpha_t = f(X_t, GL, \rho_1, h)$

$$\therefore \quad \alpha_t = (X_t - GL)\rho_1 h \quad (7)$$

The potential accident (GL) defines the difference between the pre-safety accident level and prevented accident at any instant (t) of the safety programme.

i.e. $GL = f(X_p, Y_t)$

$\therefore$ using the principle of dimensional consistency

$$GL = X_p - Y_t \quad (8)$$

The number of accidents occurrence depend on the number of employee in an establishment. In this case, the hazardous condition is a function of man-hours of workforce, the accident proneness factor, and prevented accident [9, 10]. Therefore,

$FC = f(q, f, Y_t)$

From the principle of dimensional consistency

$$FC = qf - Y_t \quad (9)$$

The probability of accident caused (ρ_1) depends on the hazardous condition, F, (Variant), and λ (parameter). Employing the exponential distribution employed by Duzgun and Einsten [10] and Adebiyi [11], the probabilities of accidents caused and prevented accident are given as:

$$\rho_1 = 1 - \ell^{-\lambda(qf - Y_t)} \quad (10)$$

Thus, $\rho_1 + \rho_2 = 1$

$$\therefore \quad \rho_2 = \ell^{-(qf - Y_t)\lambda} \quad (11)$$

- *Model Application*

Experimentation was carried out using data collected by Adebiyi et. al. [11] m a manufacturing company with a well-organized safety system. The proportion of available budget (P) and desired accident reduction target (T) control the mechanism of the simulator. The proportion of budget seeks to achieve the desired reduction target by ensuring that the cost of the safety strategy that can fulfill the reduction target is met. However, when the industry or establishment is not ready to invest in safety (P = 0%), the accident record reverts to the pre – safety level and the trend of accident occurrence follows. The proportion of budget (P) is implemented in a step of 0.1 while Reduction target (T) is implemented in a step of 5% starting from 10% of the pre-safety accident.

RESULTS AND DISCUSSION

- *The Computer Programme Simulator (CPS)*

The developed Computer Programme Simulator (Figure 1) is a user-interactive interface programme simulator that accepts system input parameters from the user through input tabs and dialog boxes on the interface, performs the necessary calculations, and then produces the output. The CPS shows an easy to understand interactive platform enabling first time users to understand and run simulations as early as their first trials. The CPS is of five sections:

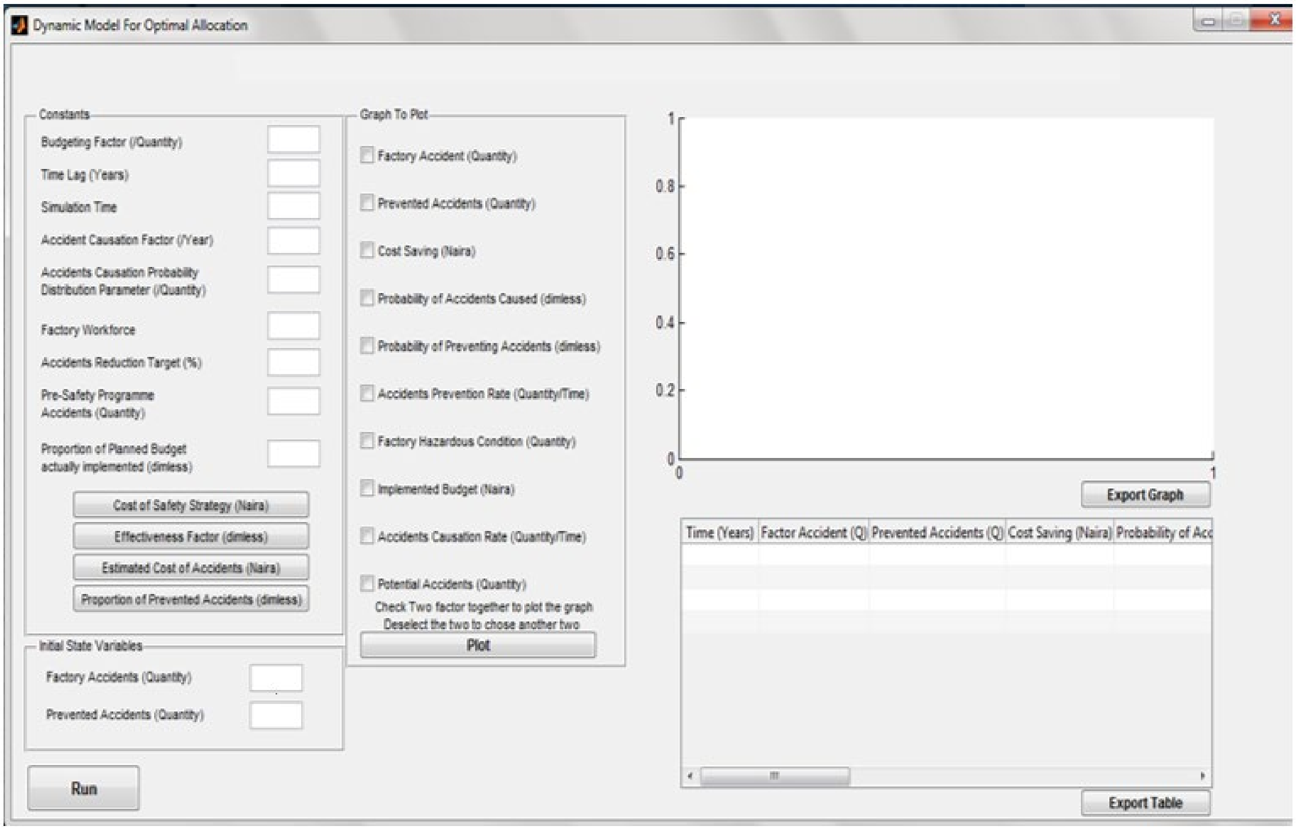

FIGURE 1
THE SAFETY PROGRAMME INTERFACE

- **The Constants**: This is where all the calculated variables and the required target and proportion of budget are computed into the simulator, including all other estimated parameters which will drop up as another interfaces as shown in Figures 2 – 5, respectively
- **Initial State Variables**: These are the initial conditions of the factory and the prevented accidents before each simulation
- **Graphs to plot:** This is where the parameters to be plotted on the graph are selected. Not more than two parameters can be selected at any given time.
- **Export graph:** This is the portion where the plotted graph of the selected parameters are displayed, and this could be exported
- **Export Table:** This is where all the resulted parameter of the simulation are displayed in a table format for necessary analysis.

The CPS is budget cost and target based. Plugging the desired percentage reduction target and the proportion of budget into the CPS, the CPS then enforces this target by choosing a strategy that can fulfill the number of accidents to be reduced. The strategy to fulfill this target would only be chosen if the proportion of budget indicated can cater for the cost of the strategy and in the event when more than one strategy can fulfill the target based on the proportion of the budget, the model chooses the strategy that offers the highest cost-saving. The CPS displays in the export table all model outputs based on the parameters indicated for simulation. A message is displayed for a successful run of the CP with the strategy as well as its cost and the combination of interventions that makes it up. It is of note that the CPS chooses the strategy automatically with accident reduction target (T), the proportion of the budget, and minimum cost implication as preconditions.

If the desired reduction target and proportion cannot be fulfilled, a message is displayed to advice on how the target can be fulfilled. The CP generates values at every quarter of a year, at each of this quarter, the values of respective system quantities are logged into the table. These values are then used to plot the resultant behavioral curves of any quantity against time or quantities against time. The graphs of these plots can be saved in different picture formats with the table as well as exportable into Microsoft excel sheet.

The CPS carries out a predictive evaluation in determining the effectiveness of resources being employed, cost implication, and effects of safety programme parameters on the programme's performance based on desired targets. The reduction target is expressed as a percentage of the pre-safety accident (X_p) and since accident occurrence is discrete in nature, target values are rounded up to the nearest whole number by the CPS.

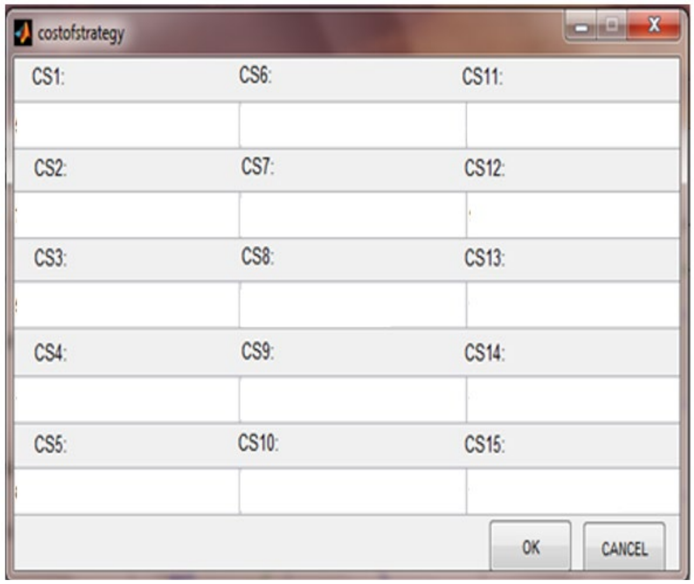

FIGURE 2
COST OF SAFETY STRATEGY INPUT FIGURE INTERFACE

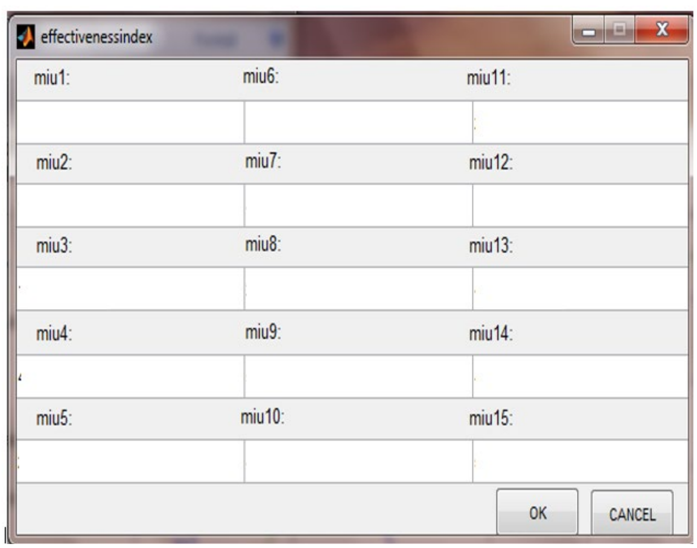

FIGURE 3
INPUT DIALOG BOX FOR EFFECTIVENESS INDEX OF THE SAFETY STRATEGY

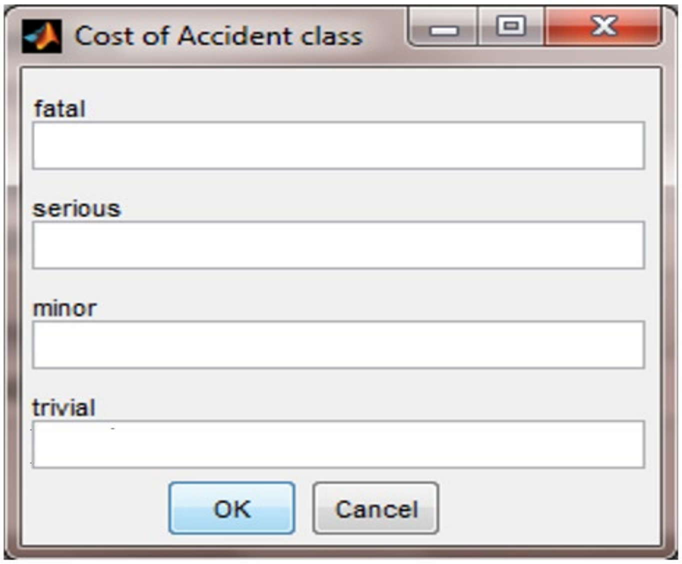

FIGURE 4
INPUT DIALOG BOX FOR COST OF ACCIDENT CLASSES

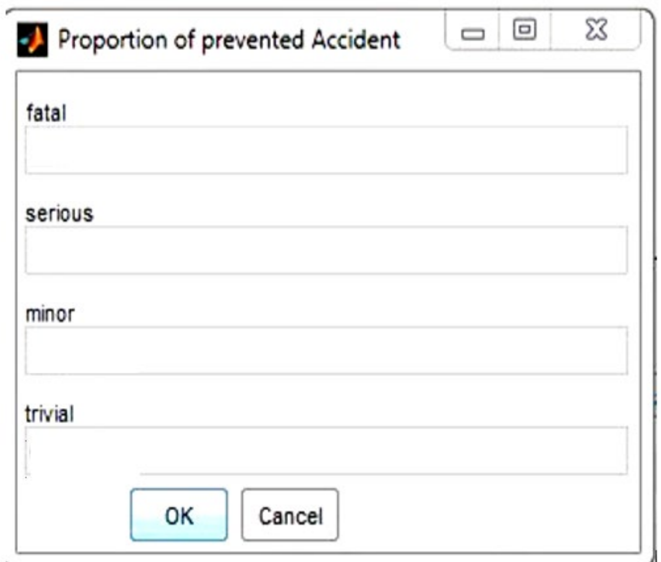

FIGURE 5
INPUT DIALOG BOX FOR PROPORTION OF ACCIDENT CLASSES

- *Safety programme outputs*

The values (as given by Adebiyi et. al. [11] for all the parameters in the constant and initial state variables sections of the CPS were supplied accordingly as shown in Figures 6 – 10. The first successful simulation run was at P = 60% of the budget (i.e. 0.6) and T = 10% reduction in the number of factory accidents. On pressing 'Run' the simulation will start and the results will be displayed in the 'Export Table' and the selected strategy (with its cost) will also be displayed as shown in Figure 11. The graph could then be plotted by clicking the parameters.

The first successful simulation run showed that any money spent below 60% of the budget would not be enough to reduce the number of accidents nor save any cost. For this run, the safety programme selected strategy 3, which is a combination of PPE, Training, and Accident Investigation (Figure 11), as the most cost-effective strategy to fulfill the 10% reduction target, thus, saving ₦14.5 million. It is however shown (in Figure 12) that there is a gradual reduction in an accident per year from the beginning of the first year to the end of the 3rd quarter of the 6th year, reducing the accident from 89 to 81 and no accident was reduced again till the middle of the 8th year when reduction started till the last quarter of the same year when the 10% target reduction was achieved. Likewise, as the accident is prevented, the number of factory accidents was also reduced (Figure 12). Meanwhile, the graph of prevented accidents against the simulation year showed an exponential growth while that of the factory accidents against the simulation year displays an exponential decay. This is expected because an effective safety programme reduces hazardous conditions and improves safety.

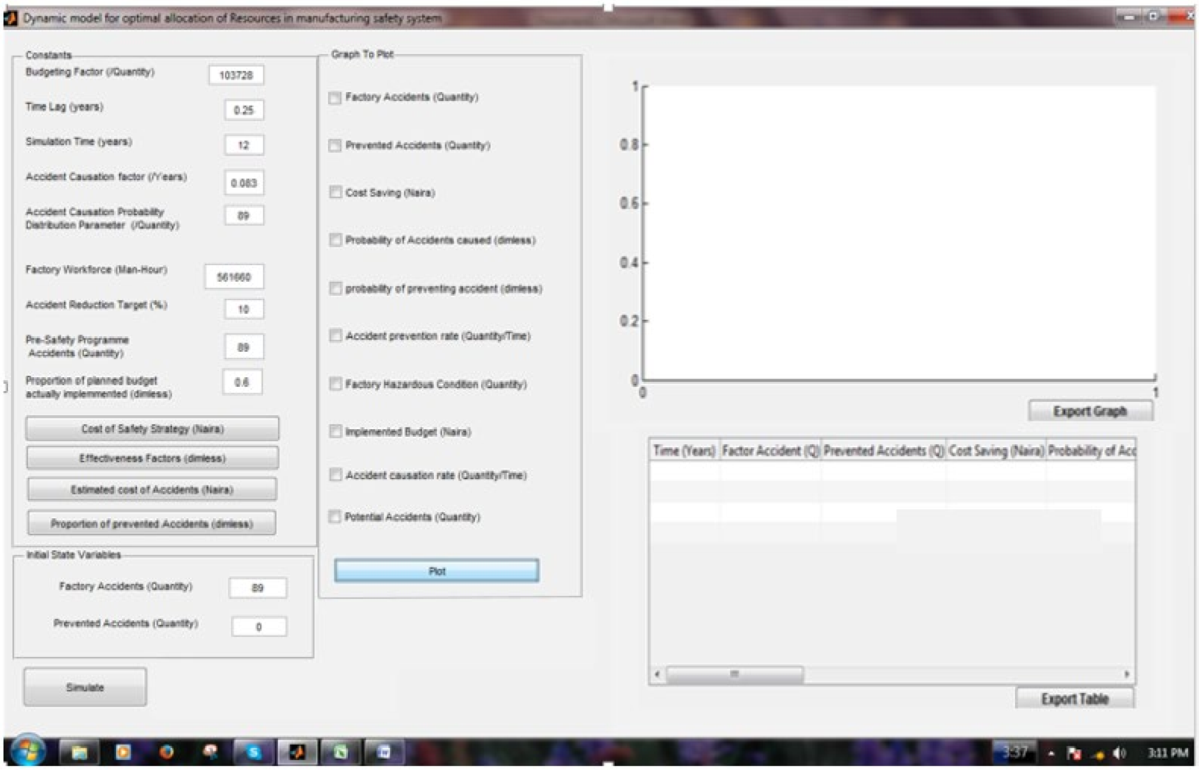

FIGURE 6
THE SIMULATOR, SHOWING THE VALUES OF THE CONSTANT

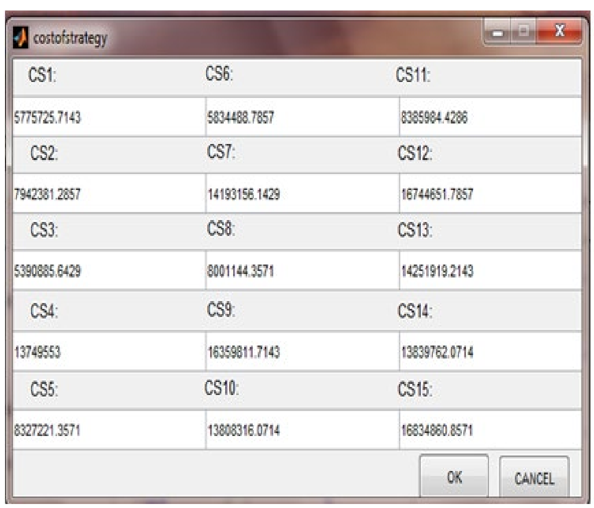

FIGURE 7
COSTS OF SAFETY STRATEGY

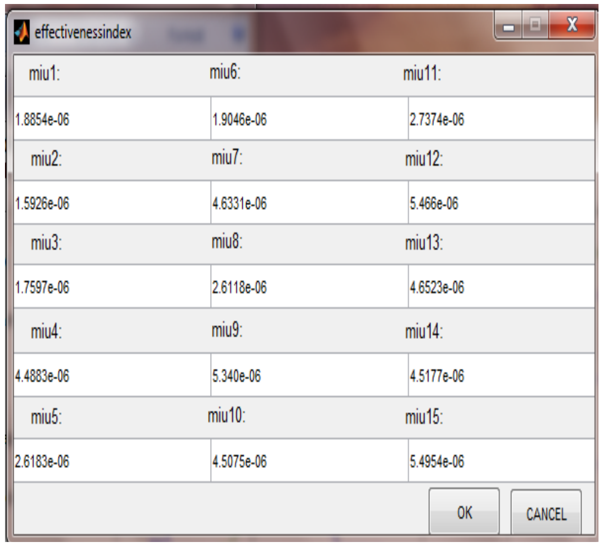

FIGURE 8
EFFECTIVENESS INDICES OF THE SAFETY STRATEGIES

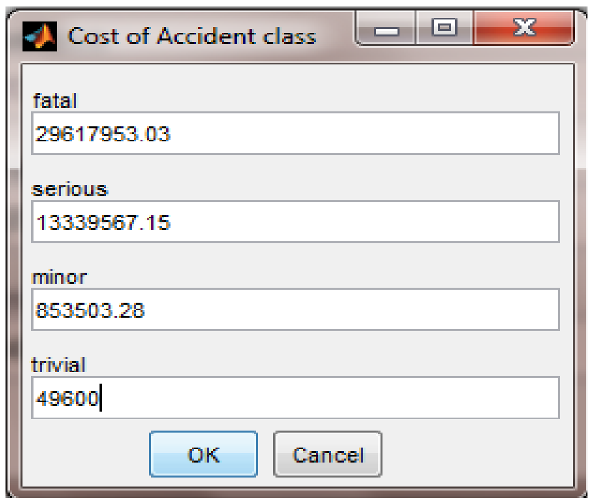

FIGURE 9
COST OF ACCIDENT CLASSES

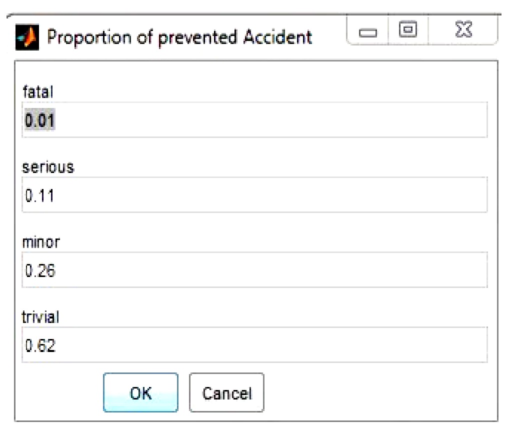

FIGURE 10
PROPORTION OF ACCIDENT CLASSES

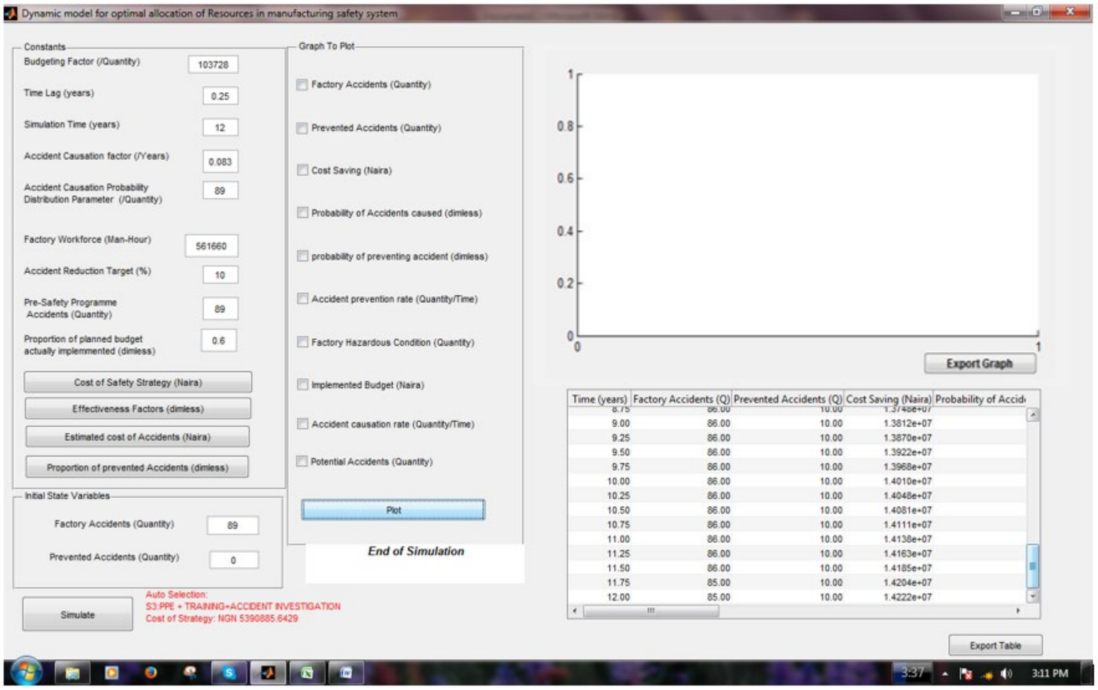

FIGURE 11
THE OUTPUT OF THE SIMULATION

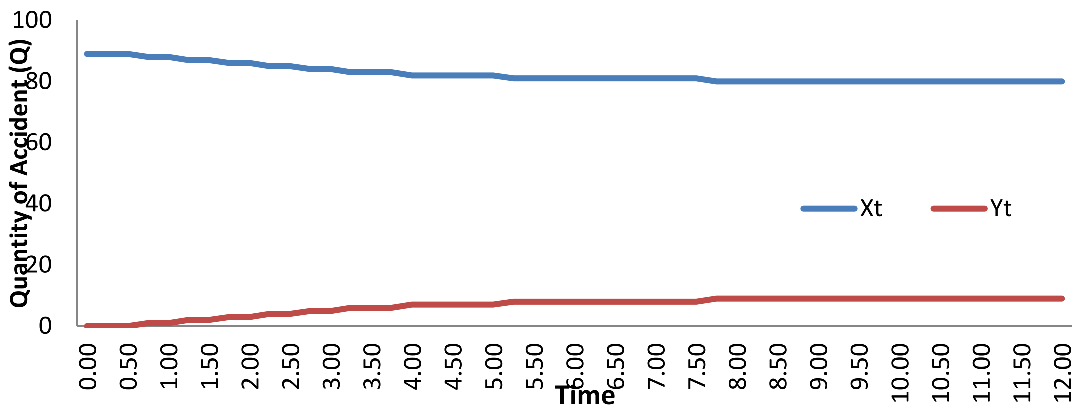

FIGURE 12
EFFECTS OF P = 0.6 AND T = 10% ON THE FACTORY ACCIDENTS AND PREVENTED ACCIDENTS

This is also reflected in Figure 13, where the probability of accidents caused reduced as the probability of accident prevented increased with time. The stepwise nature of the plots of the accident caused and prevented is expected as accidents are known to occur in discrete terms. The number of factory accidents decreased as the probability of accident occurrence approaches zero. Correspondingly, the number of prevented accidents improved as potential accidents reduced (Figure 14). There was a sharp decline in the number of accidents within the first 4 years of safety strategy implementation with accidents reducing by 8 within this period (from 89 to 81). A much slower trend is observed over the next 3.75 years; between the 4th and the 7.75th year of safety strategy implementation. Given the accident reduction target and proportion of the budget, the quantity of accidents remained constant from the beginning of the last quarter of the 8th year to the 12th year of the simulation period with a potential factory accident standing at 80.

This constant trend was set to continue except investment is made on the safety programme, the investment will however bring about a further reduction in the number of accidents witnessed. For safety managers, it will interest them to know the year of redundancy of their safety programme. This can be read off from the graph of the factory hazardous condition (FC) over the simulation period (Figure 15), which was 3 years and 3 months i.e. from the third quarter of the 8th year to the 12th year.

CONCLUSIONS

An effective and sustainable safety programme is a key factor for the healthful economy and growth of any industry. Thus, this study developed a CPS interactive interface which serves as a useful tool for predicting and achieving factory accident, prevented accident, cost, setting and achieving accident reduction targets. Consequently, the CPS helps the safety managers to proactively make some safety decisions. Also, the outputs of the simulations show that the aims of reducing accidents in all the values of P and T supplied and the cost of accidents is achievable.

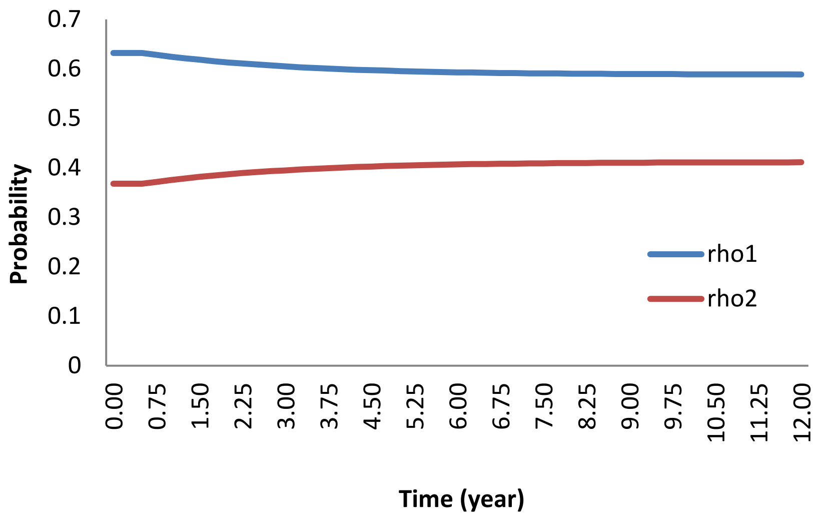

FIGURE 13
EFFECTS OF P = 0.6 AND T = 10% ON PROBABILITY OF PREVENTED ACCIDENT AND ACCIDENTS CAUSED

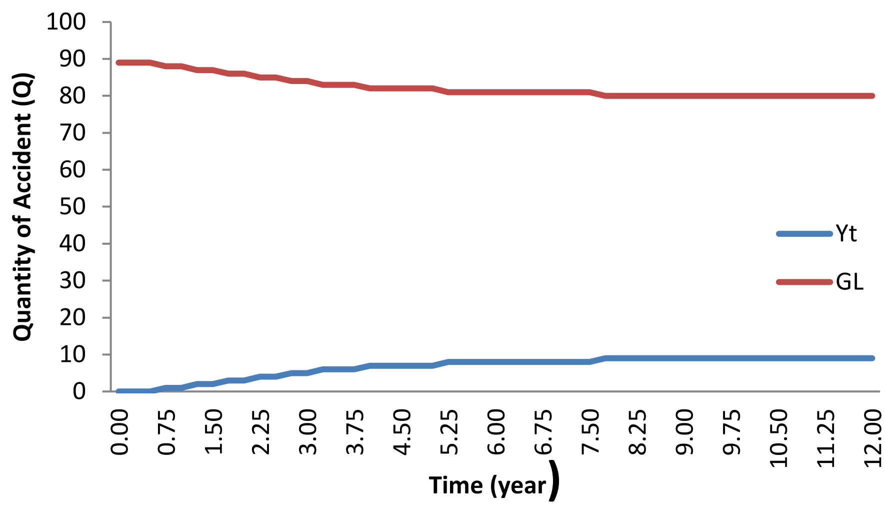

FIGURE 14
EFFECTS OF P = 0.6 AND T = 10% ON PREVENTED ACCIDENTS AND POTENTIAL ACCIDENTS

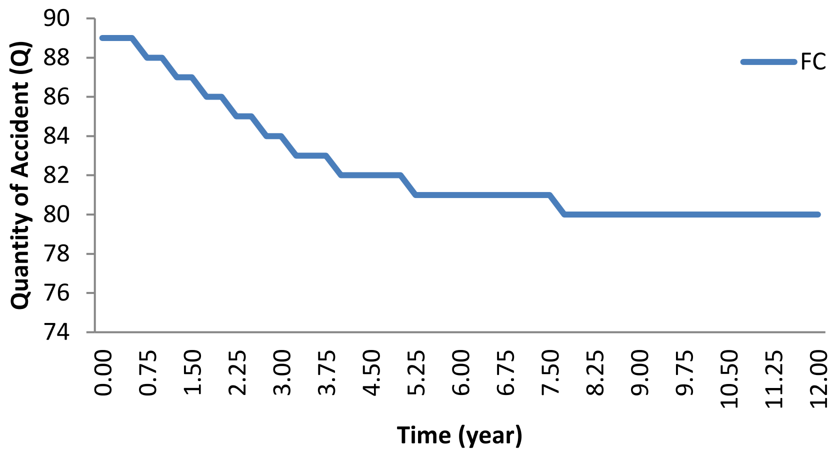

FIGURE 15
EFFECTS OF P = 0.6 AND T = 10% ON FACTORY HAZARDOUS CONDITION

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