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RESEARCH PAPER

Development of System Dynamics Based Simulation Models for Runway Safety Planning

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ABSTRACT

Safety has been established in maintaining and improving the productivity level of the aviation industry with derivable benefits in terms of wealth and reputation. Despite high investments in aviation, safety is generally recognized as an incurred cost, leading to a compliance approach. This may be due to the dearth of literature on a generally agreed proactive safety performance indicator to justify the huge investment. This study, therefore, developed predictive models that evaluate runway safety investment strategies and predict the overall performance of the aviation system using System Dynamics stock and flow diagram. An interactive computer programme of the models was written using Java programming language. A set of dynamic equations for predicting a number of runway accidents, preventions, monetary savings/losses, and safety programme breakeven period are the safety performance measures. The runway safety intervention effectiveness factor and level of budget implementation are system policy parameters used to control the mechanism of the runway safety system. Relevant data were obtained from Federal Aviation Authority, Nigeria to validate the models. Twenty-nine runway safety quantities were identified. The dynamic equations for a number of runway accident preventions and monetary savings/losses exhibited exponential growth, while the number of runway accidents exhibits exponential decay. The results of the simulation runs showed no significant difference between the former and real-life situations; thus, the models can serve as useful tools to effectively and efficiently manage the behavior and performance of the runway safety programme.

KEYWORDS: *Runway safety, runway accident, runway hazards, predictive models, system dynamics.*

1. Introduction

Despite the numerous national and international aviation risk and safety monitoring bodies, hazardous practices and conditions still persist. The prevalence of aviation losses of lives and man-hours of labor is attributable to insufficient investment in safety, whereas the associated cost accrued due to accident for the individuals, governments, aviation organizations, or communities through compensation cost, insurance cost, legal cost, and so on is detrimental to the economic value of the nation. Unfortunately, the paid passenger transport class of aviation holds a lackluster safety report, accounting for 94% of civil aviation fatalities [1].

Runway safety has long been a concern for the aviation industry with runway incursions and runway excursions identified as significant threats [2]. Runway accidents are low-probability, high-consequence (lp/hc) events. These runway accidents are most often result from the loss of situational awareness (Air Traffic Controllers, Pilots and Airside vehicle drivers), which can also be exacerbated by worker fatigue (Air Traffic Controllers and Pilots), unfamiliar and complex airports, or even a lack of clear marking and signage on taxiways, among other reasons. Moreover, the growing international business with the associated air traffic increase has put runway incursions on the rise [3].

However, runway excursion has been recognized to consist of 96% of all runway accidents, 80% of deadly runway accidents, and 75% of associated fatalities [4]. Investing in the proactive runway protection programme is essential in order to mitigate the occurrence of runway accidents with

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high consequences. Despite the fact that these accidents have been the focus of a few studies, the quantity has been surprisingly insignificant and the recommended preventive measures have been especially few in comparison with numerous programmes devoted to runway incursions [4, 5]. As a consequence, with the anticipated increase of air traffic and increasing complexity in airport operations, it is believed that the dedication to runway safety programme has to additionally be addressed via a greater systemic and systematic technique to ensure the constant and harmonized application of ICAO provisions with clear goals and commonplace know-how shared by all stakeholders [6].

Bala et al. [7] mentioned that aviation safety has been based totally on the lively investigation of past mishaps and the acquaintances of restorative moves, which preclude the repeat of the aforementioned occasions. They similarly said that aviation safety was constructed upon the reactive evaluation of past accidents and the introduction of corrective moves to prevent the reoccurrence of these events. With extremely low accident rates in these days, it is far increasingly more difficult to make additional enhancements to the level of safety through this method. Clarios et al. [8] advocated that a proactive approach was more robust than historical analysis since safety issues continue to exist with the absence of accidents. Therefore, it thus becomes sufficient to develop predictive models that will take into consideration the system as an entity and might assist in making rational investment selections concerning the runway safety programme.

Many methods have been employed through the years to expand several quantitative and qualitative safety performance assessment models that range from classical statistics through risk assessment system analysis, engineering economic factor, price deflation, and system analysis to system theory, data mining, and artificial intelligence [9]. In particular, literature is replete with risk and safety modeling in civil aviation [7- 8, 10- 12]. Adebiyi et al. [9] reported the safety models that were advanced and consisted of accident rate model, frequency coefficient and severity coefficient models, efficiency index, justification model, safety sampling version, safety productivity, and system theoretic accident model process (STAMP). System analysis and system theory accident models view the accident as resulting from chains or outcomes of occasions. However, Leveson [13] stated that by focusing on the events that precede accidents, event chains deal with systems as a static, unchanging structure. However, systems and organizations constantly experience change and adaptation to present situations. System dynamics is one way to explain the dynamic change in the system and has been used to study the capability of undesired results of organizational choice-making [13].

A number of system dynamics applications in both instructional studies and consulting contain a quantitative assessment of the cost and advantages of numerous programmes, both retrospective and potential. It has found applications in the management of large production projects, management of software program development, and simulation of complicated biological, biophysical, and social structures [14]. Other comparable works on the utility of system dynamics consist of Marais and Leveson [15], Yu et al. [16], Manataki and Zografos [17], Suryani et al. [18], Mehrjerdi and Alipour [19], Mehrjerdi and Dehghanbaghi [20], Mehrjerdi [21], Nasirzadeh et al. [22], and Pourhossein et al. [23]. Whilst Charles-Owaba and Adebiyi [14] applied system dynamics to evaluate the performance of manufacturing safety programmes, there are rarely any research work on aviation safety programme evaluation, in particular on the comparison of the programme's feasible benefits in terms of economic savings and selection of effective safety programme investments. The development of a system dynamics based predictive model for evaluating the performance of runway safety is the subject of this study.

2. Previous Studies On Aviation Safety and Risk Assessment

A number of the research studies have been reported within the literature on safety and risk assessment in general and aviation safety specifically. This includes a study reported by Janic [24] involving the use of two methods for evaluating aviation risk and safety, namely the causal technique and statistical method. The causal technique makes use of the number of accidents, deaths, and accidents per unit of air transport output over the years as a safety level indicator. The system output is described as a wide variety of aircraft kilometres (km), passenger-km, and/or aircraft departures over a given period. The statistical method uses the Poisson method to model the occurrence of air accidents through the years [24].

Luxhoj et al. [25] developed the Aviation System Risk Model (ASRM) for National Aeronautics Space Administration (NASA). The ASRM is a risk-based decision support system prototype designed to evaluate the impacts of new safety technologies/interventions. The process utilizes an analytic generalization framework to develop an integrated approach to model complex interactions of causal factors using an influence diagram. Bayesian probability theory was used for model qualification, and Bayesian decision theory provided an analytical method to evaluate the possible impact of new technologies. The entire process was supported by expert judgments and the analytical mythology was encoded as a Probabilistic Decision Support System (PDSS) [12, 25]

In structuring critically successful elements of airline safety control, Hsu et al. [26] developed a hybrid model that incorporates Grey Relational Analysis (GRA), Decision Making Trial Evaluation Laboratory (DEMATEL), and Analytic Network Process (ANP). The GRA was used to group and detect critical components of a safety management system (SMS). Both DAMATEL and ANP were later used to examine and map out all varieties of interactions among important elements and dimensions systematically. After an empirical study, an organization was found to be the most essential dimension in SMS that started off with guidelines that brought to all personnel the top manager's vision on safety. Shyur [27] developed an analytic technique that used statistics of each accident and safety indicators to the aviation risk, which might be caused by human errors. The technique makes use of a proportional risk model evolved by Cox [28] to investigate the non-linear outcomes of aviation safety elements and flexible evaluation of aviation risk [27].

2-1. System dynamics analysis of organization accidents

Most modern accident evaluation techniques are primarily occasion-based and no longer effectively capture the dynamic complexity and non-linear interactions that represent accidents in complicated structures. Organizational accidents are being increasingly studied using system dynamics (SD) tools. However, compared to social research of organizational accidents, most of the SD research studies carried out to this point lack grounding in actual records. Tropically, organizational accidents normally have available records in the form of inquiry reviews and different public reports.

Goh et al. [29] identified eight relevant SD literature pieces that summarized the application of SD tools for analyzing and theorizing organizational accident (Table 1). Out of the eight articles, four used the handiest qualitative technique and the other four used mainly stock and flow simulation. Three of the four articles that used stock and flow simulation extensively utilized CLD to symbolize dynamic hypotheses. Despite the fact that Rudolph and Repining [31] did not use CLD to explain its hypothesis, the article explained its theoretical propositions textually prior to simulation. The four qualitative papers used a mixture of reference models (or behavior through the years charts), CLD, and influence diagrams (or root cause analysis). As an entity, five of the eight papers modeled real cases, even as Rudolph and Repining [31], Cooke and Rohleder [33], and Marais et al. [34] created their models primarily based on existing literature.

Surprisingly, research works done by Yu et al. [16], Charles – Owaba and Adebiyi [14], and Adebiyi and Charles – Owaba [37] were not stated in the research by Goh et al. [29]. Yu et al. [16] developed a system dynamics model for evaluating the organizational and human elements in a nuclear plant that make a contribution to nuclear safety. Charles – Owaba and Adebiyi [14] evolved a safety program simulator to look at the organizational accidents during pre-safety and safety periods in manufacturing industries. Moreover, Adebiyi and Charles –Owaba [37] used SD simulations to assess the overall performance of safety programme investments in manufacturing industries. These papers explore the implementation of theorizing the technique of SD study due to the fact that they establish theories deductively, i.e., primarily based on real system records [29]. This approach was used for this research.

Tab. 1. A summary of relevant system dynamics literature on organizational accidents [29]

Author –Date	Title	Tool	Aim	Methods Description
Tsuchiya et al. [30]	An analysis of Tokaimura nuclear criticality Accident: A system dynamics approach to	Influence diagram/root cause analysis	“partial root cause analysis of the event using a systems approach”	Qualitative; case specific analysis; single case
Rudolph and Repining [31]	Disaster: Understanding the role of quality in organizational collapse.	Stock and flow simulation	“development of a general theory of how an organizational system responds to an on-going stream of non-novel interruptions to existing plans and procedures”	Simulation theory based on literature case
Cooke [32]	A system dynamics analysis of the Westray mine disaster	Causal loop diagram, CFD stock, and flow simulation	“the application of a simplified model of the Westray mine system to illustrate how the methodology of system dynamics can be useful for understanding the behaviors of complex safety systems	Simulation; are specific; single case
Cooke and Rohleder [33]	Learning from incidents: from normal accidents to high reliability	Stock and flow simulation	“providing a theoretical basis for incident learning systems and injecting motivation to managers to consider learning systems implementation.”	Simulation; model based on literature
27 Marais et al. [34]	Archetypes for organizational safety	Archetypes (causal loop diagrams)	“proposition of an initial set of six archetypes that model common dynamic organizational behaviors that often lead to accidents”	Qualitative; archetypes
Salge and Milling [35]	Who is to blame, the operator or the designer? Two stages of human failure in Chernobyl accident	Causal loop diagram and stock and flow simulation	”Analysis of the causes of Chernobyl power plant accident”	Simulation: case specific: single case; two separate simulation models used.
Lauge et al. [36]	The dynamics of crisis lifecycle for emergency management	Qualitative analysis of reference modes	“identification of the characteristics of each phase by analyzing real cases through the development of reference modes”	Qualitative reference modes; multiple cases.
Goh et al. [29]	Applying systems thinking concepts in the analysis of major incidents and safety culture	Reference modes and causal loop diagram	“demonstrating the use of systems thinking and causal loop diagrams through a case study on Bellevue hazardous waste fire in Western Australia”	Qualitative; case-specific analyse; single case.

2-2. Critique of the approach

The increasing complexity of rather technological structures along with aviation, maritime, telecommunications, nuclear power plant life, space missions, chemical and petroleum enterprise, and health care and patient protection is leathering to doubtlessly disastrous failure modes and new varieties of protection troubles. Each of the strategies said above addressed one region of safety considerations or the other. Meanwhile, traditional accident modeling approaches are not adequate to analyze accidents that occur in cutting-edge socio-technical systems, in which accident causation is not the end result of human error or individual component failure. However, there exists some room for development in those extensively used procedures. In using a statistical method, Janic [24] made use of measurement indicators, such as the number of accidents, loss of life, and injuries, in line with the unit of air traffic output through the years to determine whether or not aviation safety was enhancing. This does not screen the cost implication of the safety programme.

Moreover, it was stated that the model that predicted risk and number of accidents was needed in cutting-edge socio-technical systems [7, 29]. Luxhoj et al. [25] and Luxhoj [39] applied Human Factor Analysis and Classification system (HFAC) and Bayesian Belief Network (BBN) to broaden an aviation safety model that predicted the best risk related to technological interventions in the aviation safety system. The model is based totally on the conditional probability of causality and is also reactive and lagging in nature. Moreover, Luxhoj [12] applied analytics method to probabilistic safety risk model for the complex aerospace system. However, Leveson [13] argued that the risk assessment strategies were firmly rooted in the probabilistic evaluation of failure occasions and were disappointing in utility to control cognitively complex human managing activities. The system analysis is synonymous with risk assessment. It employs the hazard analysis and hazard operability technique. Shyur [27] applied proportional risk model to increase an analytical method that made use of statistics on each accident and safety indicators to qualify aviation risk susceptible to human errors. Even though Shyur [27] focused on the single causal element (i.e., human errors), the emphasis was typically dedicated to the work system design with consciousness on figuring out the contribution of causal factors to general system risk. Hsu et al. [26] used Grey Relational Analysis, GRA with Decision Making Trial Evaluation Laboratory (DEMATEL), and Analytic Network Process (ANP) to group and discover key components of airline safety management system (SMS) and examine and map out all sorts of interactions amongst crucial components and dimensions systematically. This research determines the degree of interplay amongst components, but ignored the dynamic nature of Safety Management System. Consequently, it cannot be used to predict safety programme performance. All in all, the financial implications of technological interventions were not investigated in evaluating the actual gain/loss of such investment.

Moreover, during safety programme implementations, different decisions are involved such as the amount of resources to be expended, accident prevention strategy to adopt, accident-prone factors, and prediction of the number of accidents and performance of safety programme in the context of the general interaction of safety programme's causing and prevention variables and parameters. However, the common attribute of previous studies on aviation safety performance evaluation is that of the static and reactive approach. Thus, a hybrid of the system dynamics approach and fault tree analysis will be employed in this research work to develop a time-based predictive model that will overcome the shortcomings of the above-mentioned methods

3. Methodology

3-1. Identification of runway safety components/quantities

System Dynamics methodology was used to identify runway safety components. The fault tree analysis was used in identifying causes of runway accidents. The runway accident prevention components were identified through an extensive review of previous work, interviews of safety personnel of Federal Aviation Authority, Nigeria (FAAN), Nigeria Civil Aviation Authority (NCAA), Accident Investigation Bureau (AIB), and Nigeria Airspace Management Agency (NAMA). The components were found to come from three (3) basic defenses of aviation safety: training, technology, and regulations. By extracting both categories of activities, the system variables, parameters/inputs, and outputs were identified and presented in Table 2.

It should be noted that forty-four runway accident hazards were identified in the work done by Akinyemi and Adebiyi [2] using the principles of fault tree analysis (FTA).

Tab. 2. Specification of the set of runway safety components and notations

S/N	Symbol	Description	Dimension
1	X_t	Runway Accidents	[Q]
2	α_t	Runway accident causation rate	$[Q][T]^{-1}$
3	X_p	Pre-safety programme runway accident	[Q]
4	ρ_1	Probability of runway accident occurrence	Dimensionless
5	λ	Runway accident causation prob. distr. Par.	$[Q]^{-1}$
6	β	Budgeting factor	$[N][Q]^{-1}$
7	B	Programme Budget (Planned)	[N]
8	h	Runway accident factor	$[T]^{-1}$
9	B_a	Implemented Runway Safety programme budget	[N]
10	P	Proportion of programme budget actually Implemented	Dimensionless
11	GL	Potential Runway Accidents	[Q]
12	R	Runway Accident Prevention goal	[Q]
13	μ_k	Safety programme intervention effectiveness factor	$[Q][N]^{-1}$
14	γ	Runway accident prevention rate	$[Q][T]^{-1}$
15	T	Runway Safety time lag	[T]
16	Y_t	Runway accidents prevented	[Q]
17	ρ_2	Probability of preventing Runway accidents	Dimensionless
18	U_k	Ratio of actual expenditure on runway safety Activities	Dimensionless
19	B_k	Implemented budget on safety activities	[N]
20	g_k	Accident prevention target through runway safety Interventions k (Maintenance program, Safety management system (SMS), Training,	[Q]

		Wildlife programme, Fire Fighting programme, Standard Operating Procedures, Runway End Safety Areas, Safety policy, and Technology improvement)	
21	n_{1-3}	Proportion of runway accidents prevented viz. Fatal Serious and Minor runway accidents	Dimensionless
22	y_{1-3}	Fatal, Serious, and Minor runway accidents prevented respectively	[Q]
23	C_{1-3}	Estimated cost of Fatal, Serious and Minor Runway accidents	$[N][Q]^{-1}$
24	$V_{.y}$	Total value of accident prevented	[N]
25	SBL	Runway Safety Benefit/Loss	[N]
26	$f_{.k}$	Decreasing runway accident hazard value brought about by runway safety intervention k	Dimensionless
27	$e_{.k}$	Effective runway accident hazards value to be mitigated by runway safety intervention k	Dimensionless
28	e_{1-44}	Weights of Runway accident hazards	Dimensionless
29	z_i	Runway accident hazards reducing multiplier	Dimensionless

3-2. Developing stock and flow diagram (SFD) of runway safety

An SFD, which depicts the dynamic relationship of the elements of a system, was developed to quantify the model. The SFD for the runway safety system was adapted from previous work done by Charles–Owaba and Adebiyi [14]. The adaptation to this model was in the basic events (runway accident hazards, Table 3) obtained from fault tree analysis study by Akinyemi and Adebiyi [2], integrated as system dynamics parameters in the SFD of runway safety.

Runway accident hazards are imparted upon by the runway safety interventions that simultaneously reduce the effect of the probability of runway accident occurrence and, also, bring about the effect of the implementation of runway safety interventions. Luxhoj [30] asserted that the overall relative risk reduction of a consequence may not be as high as the relative risk reduction of a particular causal element or a set of causal elements. Therefore, one runway safety intervention may additionally impact a single and/or multiple causal elements and that multiple runway safety interventions might also affect a single and/or multiple causal elements. Table 4 shows all of the runway safety interventions and the corresponding runway accident hazards impacted upon. A Venn diagram was developed (Figure 1) from Table 4 to elucidate the runway safety interventions and runway accident hazards interactions and/or relationships. Figure 2 shows the resultant stock and flow diagram for runway safety performance evaluation.

Ten (10) runway safety interventions were identified: Maintenance programme, Safety management system (SMS), Training, Wildlife programme, Fire Fighting programme, Standard Operating Procedures, Safety Briefing/Awareness, Runway end safety areas, Safety policy, and Technology improvement.

Tab. 3. Runway accident hazards

S/N	Runway accident hazards notations	Description of runway accident hazards
1	e_1	Ground controls untimely intervention
2	e_2	Pilot loss of situation awareness
3	e_3	Departure runway not verified prior to take off
4	e_4	Communication loss between Ground Control and Taxing crew
5	e_5	No condition monitoring of aircraft during taxing
6	e_6	Delay in information sharing between Ground Control and other runway users.
7	e_7	Work pressure on pilot
8	e_8	Level experience in situation management
9	e_9	Yieldedness to training on the prevailing condition
10	e_{10}	Negligence of safety signal marking by taxing crew
11	e_{11}	Use of non-standard signals
12	e_{12}	Lack of coordination between taxing crew

13	e_{13}	Delay in runway condition information sharing with appropriate quarters
14	e_{14}	Loss of situational awareness by the maintenance crew
15	e_{15}	Indecisiveness of pilot to act
16	e_{16}	Poor crisis management by pilot
17	e_{17}	Emergency response of the departure controller
18	e_{18}	Momentary confusion clearance issued
19	e_{19}	Working condition of airline and airport personnel
20	e_{20}	Flight engineer error in data not corresponding to prevailing runway condition
21	e_{21}	Error in weather reportage and weather data analysis
22	e_{22}	Runway allocation error due to incorrect runway assignment and data upload
23	e_{23}	Runway maintenance crew negligence
24	e_{24}	Use of ambiguous terms to describe the prevailing condition
25	e_{25}	Limitation of aqua-planning
26	e_{26}	Lack of appropriate runway condition description: Wet/Contamination/Low friction: standing water, rubber, oil, slush, snow, ice, and paint
27	e_{27}	Runway surface measurement device error, parallax error
28	e_{28}	Runway surface tolerance error of measuring device
29	e_{29}	Bird strike
30	e_{30}	Other wild-life strikes
31	e_{31}	Wrong diversion/sign and markings
32	e_{32}	No diversion/sign and markings
33	e_{33}	Loss of required separation
34	e_{34}	Low visibility, Low ceiling
35	e_{35}	Wind shear, Tailwind, Strong wind, Freezing rain, Turbulence
36	e_{36}	Delay in order to abort a take-off in case of an obstacle
37	e_{37}	Take-off rejected at high speeds
38	e_{38}	Defaulting SOP (Standard Operating Procedure)
39	e_{39}	Long touch-down zone/high speed during approach
40	e_{40}	Approach below flight path, Approach above flight path
41	e_{41}	Pilot error in over-speeding (high speed and/or low speed)
42	e_{42}	Un-optional wheel-braking force/brake
43	e_{43}	Tires
44	e_{44}	Hydraulic Power

Source: Akinyemi [40], Akinyemi and Adebiyi [2]

Tab. 4. Runway accident hazards and the corresponding runway safety intervention

Runway safety intervention	Runway safety intervention notations	Runway Accident Hazards
Maintenance programme	g_1	e_{14}, e_{23}, e_{26}, e_{27}, e_{28},
Safety management system (SMS)	g_2	e_1, e_2, e_3, e_4 e_5, e_6, e_8, e_9, e_{10}, e_{12}, e_{13}, e_{16}, e_{17}, e_{18},e_{34},
Training	g_3	e_1, e_3, e_5, e_6 e_7, e_9, e_{12}, e_{13}, e_{16}, e_{17}, e_{18}, e_{20}, e_{21},e_{22}, e_{34},
Wild-life programme	g_4	e_{29}, e_{30}
Fire Fighting programme	g_5	e_{35}, e_{37}, e_{38}, e_{39}, e_{40}, e_{41}, e_{42}
Standard operating procedures	g_6	e_1, e_2, e_3, e_6, e_{11}, e_{24}, e_{36}
Safety Briefing/Awareness	g_7	e_{31}, e_{32}
Runway end safety areas	g_8	e_{35}, e_{37}, e_{38}, e_{39}, e_{40}, e_{41}, e_{42} , e_{43}, e_{44}
Safety policy	g_9	e_8, e_{13}, e_{17}, e_{19}, e_{20}, e_{34},
Technology Advancement	g_{10}	e_{14}, e_{15}, e_{20}, e_{21}, e_{26}, e_{37}, e_{38}, e_{39}, e_{39}, e_{40}, e_{41}, e_{42}

Source: Akinyemi [40]

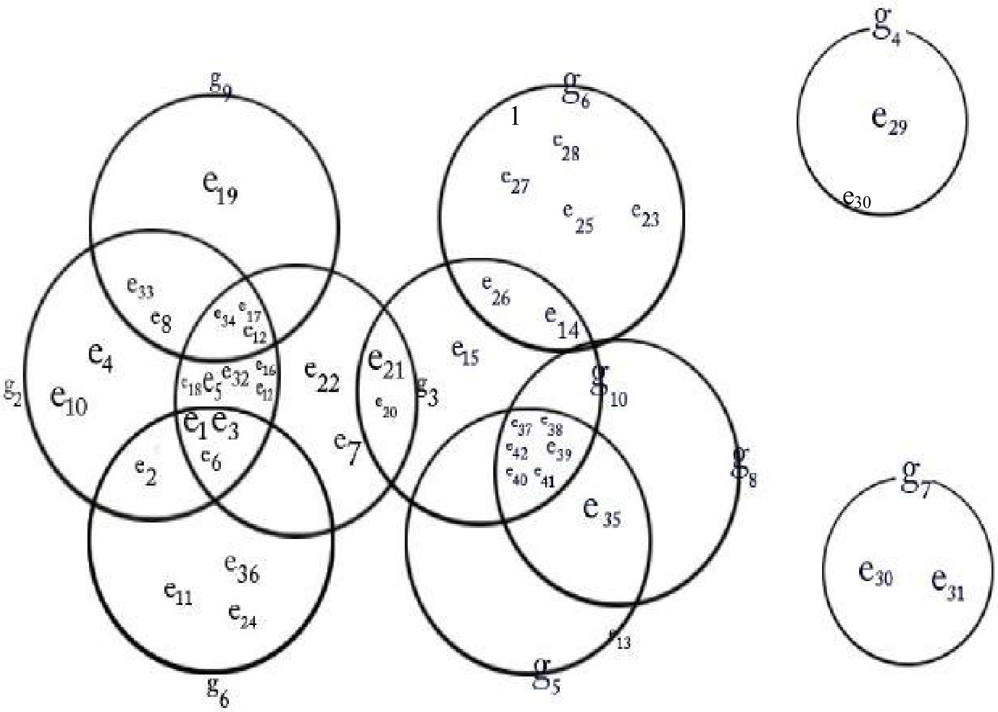


Fig. 1. Venn diagram showing runway safety intervention and runway accident hazards relationships [40].

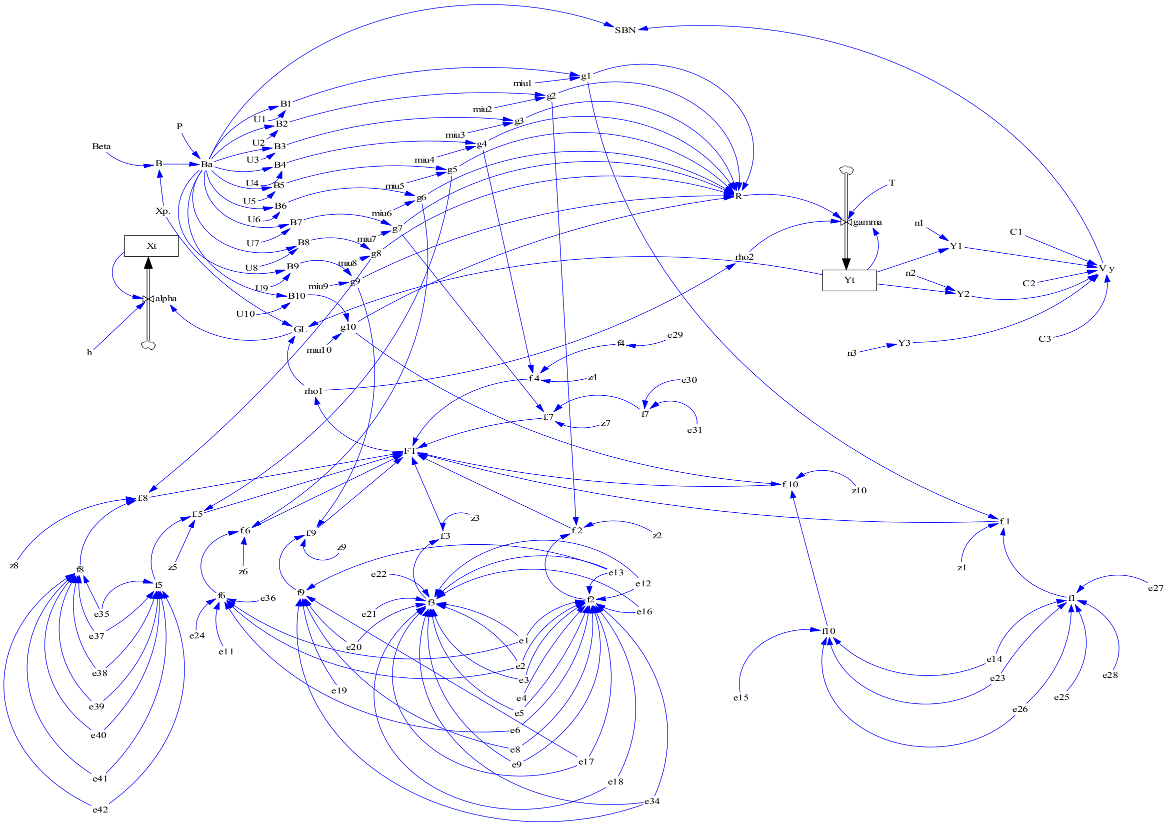


Fig. 2. SFD for system dynamics based simulation model for performance evaluation of Runway Safety

3-3. Development of runway safety predictive models

1. Predictive model for the number of runway accidents caused

From Fig. 2, the differential equation for the rate of runway accident causation is given as follows:

$$\frac{dX_t}{dt} = \left[\left(X_p - Y_t\right) - X_t\right]\left(\sum_{k=1}^{10} f_{.k}(g_k, e_{.k})\right) h \qquad (1)$$

The System Dynamics differential equation for runway accident causation (X_t) is solved using the integrating factor method:

$$X_t = \left(X_p - Y_t\right)\left(1 - e^{\left[\sum_{k=1}^{10} f_k(g_k, e_k)\right]ht}\right) + X_o e^{\left[\sum_{k=1}^{10} f_k(g_k, e_k)\right]ht} \qquad (2)$$

The predicted number of runway accidents caused was compared with the real-life situation data using the null hypothesis statistical testing (t-test statistic). The null hypothesis for runway accidents caused in pre-safety and safety periods is as follows:

H_o: $U_1 = U_2$
H_1: $U_1 \neq U_2$

where U_1 is the mean of predicted runway accidents caused, and U_2 is that of the experienced runway accidents caused.

2. Predictive model for the number of runway accidents prevented

Runway accident prevention rate is:

$$\gamma_t = \left(\frac{R - Y_t}{T}\right)\rho_2 \qquad (3)$$

$$\frac{dY_t}{dt} = \left(\frac{X_p \beta P \sum_{k=1}^{m} U_k \mu_k - Y_t}{T}\right)(1 - \sum_{k=1}^{10} f_{.k}(g_k, e_{.k}))) \qquad (4)$$

Solving the differential equation, we have:

$$Y_t = X_p \beta P \sum_{k=1}^{m} U_k \mu_k \left[1 - e^{-\frac{\left(1 - \sum_{k=1}^{10} f_{.k}(g_k, e_{.k})\right)t}{T}}\right] + \left[Y_0 e^{-\frac{\left(1 - \sum_{k=1}^{10} f_{.k}(g_k, e_{.k})\right)t}{T}}\right] \qquad (5)$$

3. Runway safety performance measure

The runway safety performance measure is the difference between the value of runway accidents prevented and the planned budget implemented:

$$SBL = V.y - B_a \qquad (6)$$

$$SBL = n_i Y_t C_i - P\beta X_p \qquad (7)$$

Substituting and simplifying Eq. 7, we have:

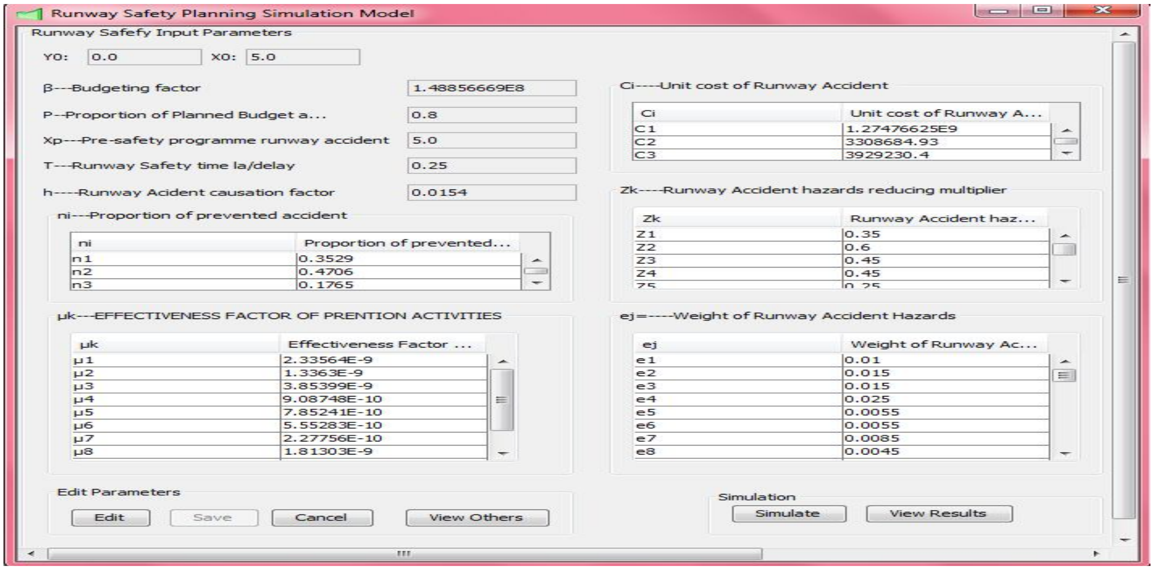
$$SBL = X_p \beta P\left[\left(\sum_{k=1}^{M} U_k \mu_k \sum_{i=1}^{N} n_i C_{i1}\right)\left(1 - e^{\frac{-(1 - \sum_{k=1}^{10} f_{.k}(g_k, e_{.k}))t}{T}}\right) - 1\right] + Y_0 \sum_{i=1}^{N} n_i C_{i1}\, e^{\frac{-(1 - \sum_{k=1}^{10} f_{.k}(g_k, e_{.k}))t}{T}} \qquad (8)$$

3-4. The development of the computer code

In developing the computer code, the following conditions are noted:

1. The boundary conditions for a number of runway accidents caused and runway accidents prevented are considered.
2. The initial values of the number of runway accidents caused and prevented are assumed.
3. The values of the residual for the number of runway accidents prevented and the number of runway accidents caused are calculated through the respective equations and the estimated values.
4. As period t changes, a new residual must be calculated.
5. This continues until the residual approaches zero.

Based on the above conditions, the developed runway safety planning model was coded using Java programming language. The simulation model is used to carry out a predictive evaluation of cost-saving/loss of runway safety and effect of runway safety parameters on the performance of runway safety. Figures 3 and 4 show some interfaces of the simulation model.



Runway Safefy Input Parameters

YO: 0.0 XO: 5.0

β---Budgeting factor: 1.48856669E8

P--Proportion of Planned Budget a...: 0.8

Xp---Pre-safety programme runway accident: 5.0

T---Runway Safety time la/delay: 0.25

h----Runway Acident causation factor: 0.0154

ni---Proportion of prevented accident

ni	Proportion of prevented...
n1	0.3529
n2	0.4706
n3	0.1765

µk---EFFECTIVENESS FACTOR OF PRENTION ACTIVITIES

µk	Effectiveness Factor ...
µ1	2.33564E-9
µ2	1.3363E-9
µ3	3.85399E-9
µ4	9.08748E-10
µ5	7.85241E-10
µ6	5.55283E-10
µ7	2.27756E-10
µ8	1.81303E-9

Ci----Unit cost of Runway Accident

Ci	Unit cost of Runway A...
C1	1.27476625E9
C2	3308684.93
C3	3929230.4

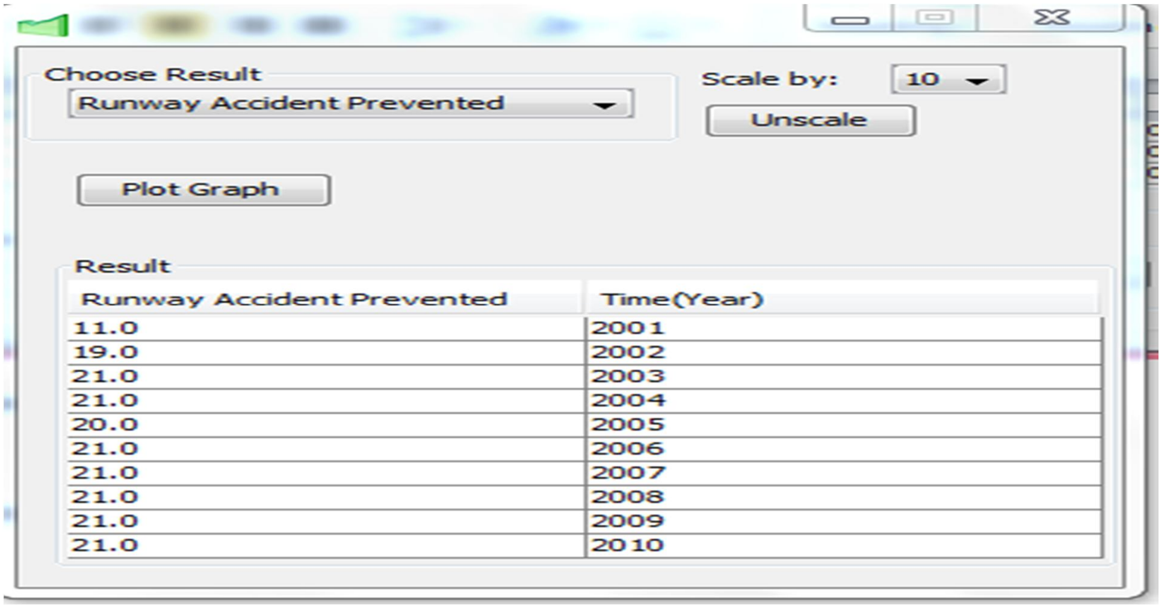
Zk----Runway Accident hazards reducing multiplier

Zk	Runway Accident haz...
Z1	0.35
Z2	0.6
Z3	0.45
Z4	0.45
Z5	0.25

ej=----Weight of Runway Accident Hazards

ej	Weight of Runway Ac...
e1	0.01
e2	0.015
e3	0.015
e4	0.025
e5	0.0055
e6	0.0055
e7	0.0085
e8	0.0045

Fig. 3. Simulation model interface



Choose Result: Runway Accident Prevented

Scale by: 10

Result

Runway Accident Prevented	Time(Year)
11.0	2001
19.0	2002
21.0	2003
21.0	2004
20.0	2005
21.0	2006
21.0	2007
21.0	2008
21.0	2009
21.0	2010

Fig. 4. Output dialog box for displaying graphs and tables

4. Results and Discussion

4-1. Model validation

The system dynamics based simulation models, termed Runway Safety Planning simulation models, were run based on the rendition that the model must have the ability to emulate the real-life situation being modeled within equal parametric conditions. Endogenous variables of airport that represent the runway safety system's behavior (Tables 5 and 6) are used to validate the model over a 10-year planning horizon. In the first run of the simulation, it was found that the change in runway accidents caused was infinitesimal.

This is because aviation accidents have a low probability but high consequences of occurrence; hence, the simulation model was scaled to the proportion of 10 for ease of analysis of results. For instance, the pre-safety runway accident is 5; after scaling, it becomes 50.

The evaluation of the model outputs with past accident records over the identical time period presents the specified validation. The predicted and experienced runway accidents during pre-safety and safety periods are presented in Tables 7 and 8. The mean percentage deviation of predicted runway accidents and experienced runway accidents caused was estimated as 1.4%, indicating an error of 1.4%. Consequently, the t-test (Table 9) showed that there was no significant difference at a 5% level of significance between the experienced and the predicted runway accidents. According to Table 9, the simulation model replicates system fairly well.

Tab. 5. Estimates of runway safety planning model parameters

S/N	Runway safety input parameters	Symbol	Estimated Values
1	Budgeting factor	β	₦ 148, 856, 669 (₦ /Accident)
2	Proportion of Planned Budget available on Prevention activities	P	0.8
3	Effectiveness factor of Prevention activities	μ_k	Maintenance programme (2.3356×10^{-9} Accident/₦), Safety management system (SMS) (1.3363×10^{-9} Accident/₦), Training (3.85399×10^{-9} Accident/₦), Wild life programme (9.08748×10^{-10} Accident/₦), Fire Fighting programme (7.85241×10^{-10} Accident/ ₦), Standard Operating Procedures (5.55283×10^{-10} Accident/₦), Safety Briefing/Awareness (2.27756×10^{-10} Accident/₦), Runway end safety areas (1.81303×10^{-9} Accident/₦), Safety policy (4.46869 × 10-10 Accident/₦) and Technology improvement (2.33564×10^{-9} Accident/₦).
4	Unit cost of Runway accident	C_{1-3}	Minor (₦ 3, 929, 230.4), Serious/Major (₦ 3, 308, 684.93) and Fatal/Aircraft destroyed (₦ 1, 274, 766, 250)(Akinyemi and Adebiyi, 2016).
5	Pre-safety programme runway accident	X_p	5 accidents
6	Runway Safety time la/delay	T	3 months
7	Proportion of prevented accidents as minor, serious/major and fatal/aircraft destroyed	n_{1-3}	Minor (0.1765), Serious/Major (0.4706) and Fatal/Aircraft destroyed (0.3529)
8	Runway Accident causation factor	h	0.0154 [T^{-1}]

Tab. 6. Estimates of weight of runway accident hazards

S/N	ID	Description of Event	Probability
1	e_1	Ground controls untimely intervention	0.003
2	e_2	Pilot loss of situation awareness	0.0095
3	e_3	Departure runway not verified prior to take-off	0.0085
4	e_4	Communication loss between GC and Taxing crew	0.0055
5	e_5	No condition monitoring of aircraft during taxing	0.0055
6	e_6	Delay in information sharing between GC and other runaway users.	0.0055
7	e_7	Work pressure on pilot	0.0085
8	e_8	Level experience in situation management	0.0045
9	e_9	Yieldedness to training on the prevailing condition	0.0055

10	e_{10}	Negligence of safety signs and marking by taxing crew	0.008
11	e_{11}	Use of non-standard signals	0.006
12	e_{12}	Lack of coordination between taxing crew	0.0045
13	e_{13}	Delay in runway condition information sharing with the appropriate quarters	0.0055
14	e_{14}	Loss of situational awareness by the maintenance crew	0.0085
15	e_{15}	Indecisiveness of pilot to act	0.003
16	e_{16}	Poor crisis management by pilot	0.003
17	e_{17}	Emergency response of departure controller	0.0055
18	e_{18}	Momentary confusion clearance issued	0.0033
19	e_{19}	Working condition of airline and airport	0.0025
20	e_{20}	Flight engineer error in data not corresponding to the prevailing runway condition	0.005
21	e_{21}	Error in weather reportage and weather data analysis	0.0085
22	e_{22}	Runway allocation error due to incorrect runway assignment and data upload	0.0085
23	e_{23}	Runway maintenance crew negligence	0.0085
24	e_{24}	Use of ambiguous terms to describe the prevailing condition	0.0035
25	e_{25}	Limitation of aqua-planning	0.009
26	e_{26}	Lack of appropriate runway condition description: Wet/Contamination/Low friction: standing water, rubber, oil, slush, snow, ice, paint	0.0085
27	e_{27}	Runway surface measurement device error, parallax error	0.006
28	e_{28}	Runway surface tolerance error of measuring device	0.0035
29	e_{29}	Bird strike	0.0085
30	e_{30}	Other wild-life strikes	0.008
31	e_{31}	Wrong diversion/sign and markings	0.0035
32	e_{32}	No diversion/sign and markings	0.0085
33	e_{33}	Loss of required separation	0.0085
34	e_{34}	Low visibility, Low ceiling	0.012
35	e_{35}	Wind shear, Tailwind, Strong wind, Freezing rain, Turbulence	0.0035
36	e_{36}	Delay in order to abort a take-off in case of an obstacle	0.0055
37	e_{37}	Take-off rejected at high speeds	0.006
38	e_{38}	Defaulting SOP (Standard operating procedure)	0.009
39	e_{39}	Long touch-down zone/high speed during approach	0.009
40	e_{40}	Approach below flight path, Approach above flight path	0.006
41	e_{41}	Pilot error in over-speeding (high speed and/or low speed)	0.0035
42	e_{42}	Un-optional wheel braking force/brake	0.009
43	e_{43}	Tires	0.009
44	e_{44}	Hydraulic Power	0.005

Tab. 7. Comparison of experienced and predicted runway pre-safety programme accidents

Year	Predicted (expected) Runway Accidents	Experienced Runway Accidents
1991	50	50
1992	50	70
1993	50	30
1994	50	20

1995	50	80
1996	50	30
1997	50	30
1998	50	70
1999	50	50
2000	50	30
Mean	50	46

Tab. 8. Comparison of experienced and predicted runway safety programme accidents

Year	Predicted Runway Accidents	Experienced Runway Accident	% Deviation of Predicted from the Experienced
2001	50	50	0.00
2002	50	30	66.67
2003	50	70	-66.67
2004	49	50	-2.00
2005	48	120	-60.00
2006	47	50	-6.00
2007	47	20	135.00
2008	46	50	-8.00
2009	45	20	125.00
2010	44	70	-37.14
Mean	48	53	14.44
		% error	1.44

Tab. 9. Summary of t-test results for predicted and experienced runway accidents at a 5%level of significance.

Source of Variation	t-test value Calculated	t-test value Critical	Remark
Pre-Safety Runway Accident Caused	0.59	2.31	No Significance Difference
Safety Programme Runway Accident Caused	-0.58	2.31	No Significance Difference

4-2. Runway safety planning (RSP) simulation models

Twenty-nine (29) runway safety components (parameters and variables) were identified. In adapting the SFD developed by Charles-Owaba and Adebiyi [14], a relationship was established between runway accident hazards and runway safety prevention activities (Table 4). A Venn diagram was developed that showed inter-relationship existing among runway accident hazards and runway safety prevention activities (Fig. 1). Consequently, the resulting adapted SFD is shown in Fig. 2.

In developing the RSP simulation models, two sets of dynamic differential equations were formulated and solved. On the one side, the predictive model of the number of runway accidents (X_t) was developed in terms of runway accident factor (h), potential runway accidents (GL), runway accident hazards (e_j), runway accident hazards reducing multiplier (z_i), runway safety interventions target (g_k), and a number of runway accident prevented (Y_t). On the other side, the predictive model of the number of runway accident prevented (Y_t) was developed in terms: β, P, U_K, μ_k, X_P, e_j, and T. These two predictive models were combined to develop a runway safety performance measure, namely runway safety programme benefit/loss (SBL) in terms of β, P, U_K, μ_k, X_P, e_j, Y_t, n_i, C_{i1}, and T.

In the runway safety planning simulation models, Java Oracle programming language was used to develop a graphical user interface and menu-driven environment to drive the models. The equations are based totally on the runway safety system and the syntax of JAVA programming language. The simulation model consists of two major sectors: the GUI (graphical user interface) where model parameters are inputted and the output/result interface where graphical and tabular outputs are displayed.

In terms of performance, RSP simulation model has some similarities with the work done by Luxhoj [39] and Luxhoj *et al*. [25]. Luxhoj *et al*. [25] and Luxhoj [39] developed an aviation system risk model (ASRM) that provided a computer code for the performance of technological interventions in terms of risk reduction of the occurrence of runway incursions. The risk model developed was static and reactive in nature. In the RSP simulation model, SD was employed to evaluate the dynamic interactions of runway safety system performance. In addition, the model provides insights into monetary benefit /losses obtainable from the implementation of runway safety interventions. The RSP simulation model user interface is very usable in the first attempt.

4-3. Model behavior

The RSP simulation model is tested to make certain that it has the ability to copy the actual existence of eventualities being modeled. The behavioral plots of the model output are provided in Figures 3 to 10. It incorporates the standard run of model outcomes for the ten-year simulation period for a different proportion of budget and level of runway safety intervention effectiveness factor.

Unlike the safety programme in the manufacturing sector where factory accident follows a positive exponential decay [14], the number of runway accidents decreases following an exponential decay (parabolic trend) and is followed by an exponential increase within the number of runway accidents prevented as shown in Figures 5 and 6. The exponential decay (parabolic trend) behavior of runway accidents is a sign of the impact of types of runway accident hazards and the role of runway safety interventions in lowering runway accident risks. The proportion of budget (P) and the runway safety intervention effectiveness factor (μ_k) control the mechanism of the runway safety system. In addition, this system parameters seek to achieve a maximum target that reduces the chance for runway accident occurrence.

For the first successful simulation run at a 80% proportion of budget and a 100% level of runway safety intervention effectiveness factor, the predicted runway accident commenced lowering from pre-safety stage of 50 to 48 (a 4% reduction) in 2003 to 2005 (Fig. 7). A safety climate period of 3 years was experienced between the year 2001 to 2003 at a pre-safety runway accident level (50) and another safety climate period of 1 year from 2005 to 2006 with runway accidents at 48. There was a further downward trend from 48 to 44 from 2006 to 2010, representing another 8% reduction. It should be noted that the experienced runway accident displayed the random nature of runaway accidents (periodically up-and-down runway accidents), while the predicted runway accident displayed step and exponential graph. However, the means and standard deviations of the predicted runway accident and the experienced runway accident were 48 and 2.17 and 53 and 29.46, respectively. It should be noted also that, at the expiration/end of each safety climate period, there was a corresponding reduction in runway accidents caused.

Luxhoj et al. [25] developed the Aviation Safety Risk Model (ASRM) to evaluate the performance of technology interventions in reducing aviation accidents using relative risk reduction as a safety precursor. The ASRM developed is reactive and lagging in nature. The implementation of these technologies yields a 24% relative reduction in risk. The RSP simulation model developed in this research is proactive and dynamic in nature. It used a number of runway accidents caused, a number of runway accidents prevented, and runway safety benefits/losses as the safety precursors. In the number of runway accidents caused, a 12% reduction was achieved with the implementation at 80% proportion of budget and 100% level of runway safety intervention effectiveness factor.

The graph/behavioral plots of the number of runway accidents prevented show exponential growth. Considering Fig. 8, the number of predicted runway accidents prevented started with 8 in 2001, grew exponentially to 13 in 2002 and 14 in 2003, and stabilized till 2010. The mean number of predicted runway accidents prevented was calculated as 14. Since the predicted runway accidents prevented show exponential growth, the experienced runway accidents prevented exhibit the random nature of runway accidents prevented. Quantitatively, the means and standard deviations of the predicted and experienced runway accidents prevented were 14 and 3.12 and 19 and 18.53, respectively. Since the number of runway accidents prevented increases, the runway accident prevention rate (activities) decreases and approaches zero, as shown in Fig. 9. That is the further validation of the runway safety planning simulation model.

The graphs/behavioral plots of runway safety benefit show exponential growth (Fig. 10). Fig. 10 shows a monetary loss of ₦265 million in 2001, notwithstanding the runway safety programme break even at the end of 2003. The monetary saving increased to ₦25 million at the end of 2004; however, it reduced to ₦2 million at the end of 2005. The monetary savings later increased to ₦30 million at the end of 2008. This could be the safety gains as a result of the safety climate period of 2006 to 2007.

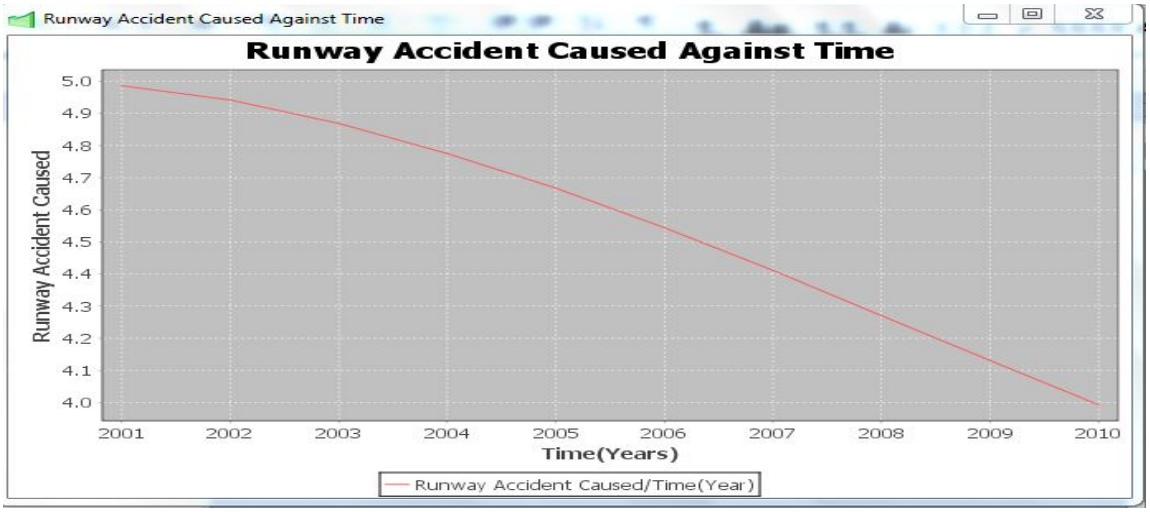


Fig. 5. Exponential (parabolic) decay of runway accidents caused

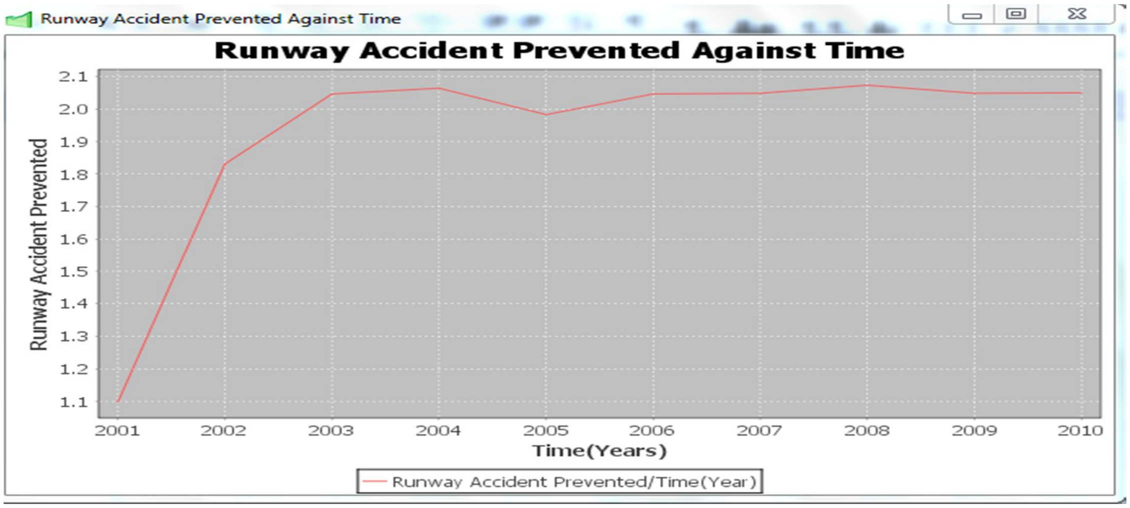


Fig. 6. Exponential growth of runway accidents prevented

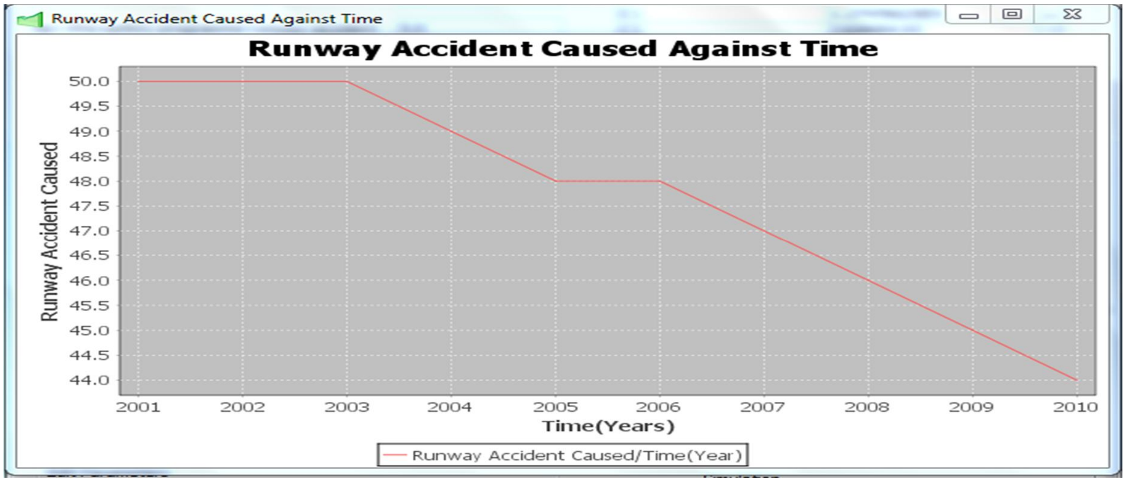


Fig. 7. Behavioral plot of runway accidents at P= 0.8 and μ = 100% level

Fig. 8. Behavioral plot of runway accidents prevented at P = 0.8 and μ= 100% level

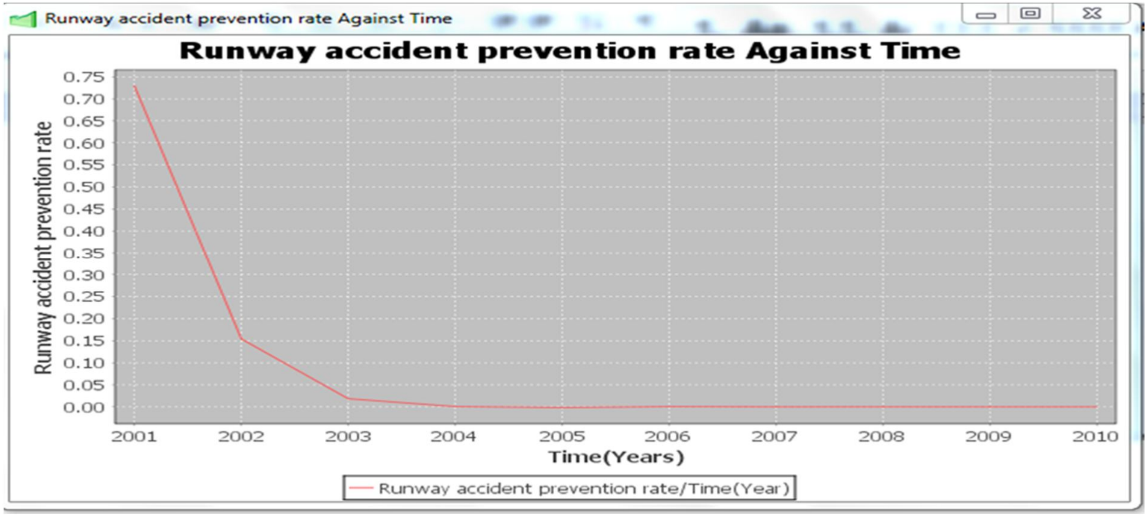


Fig. 9. Behavioral plot of the runway accident prevention rate

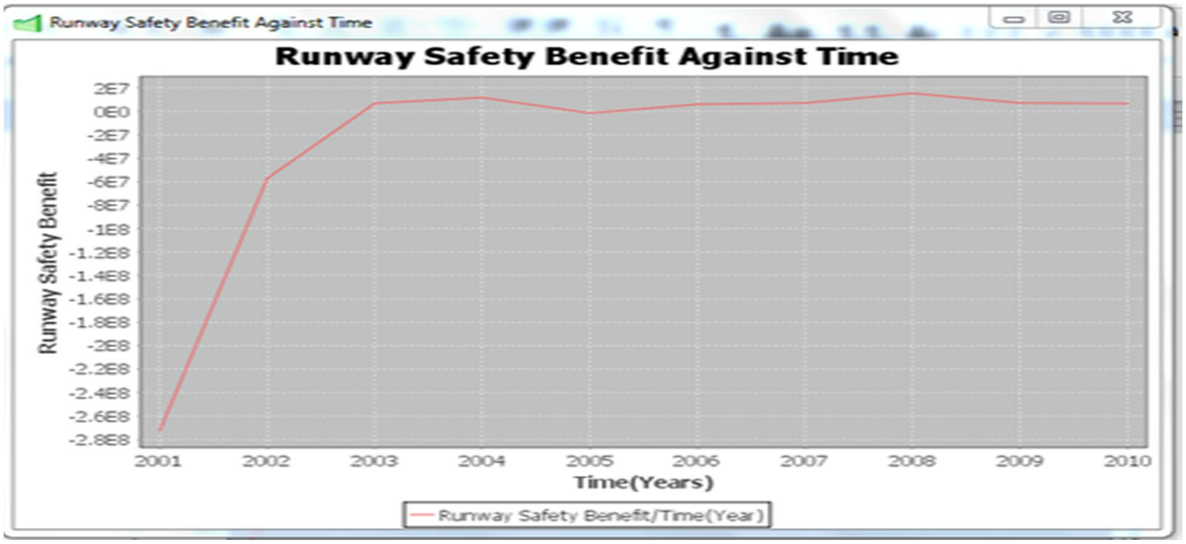


Fig. 10. Behavioural plot of runway safety benefit at P = 0.8 and μ = 100% level

4-4. Sensitivity analysis

Runway safety intervention effectiveness factor (μ) and level of implementation (P) control the time required for the system to grow. The number of runway accidents caused decreases with an increase in the level of implementation (P) and the level of runway safety intervention effectiveness factor (μ). Conversely, the number of runway accidents prevented increases with an increase in the level of implementation (P) and the level of runway safety intervention effectiveness factor (μ).

Furthermore, it is expected that the level of implementation controls the amount of runway safety benefit/loss for an effective runway safety programme, while the runway safety benefit/loss (SBL) reveals the breakeven point of runway safety policy. As P and μ increase, runway safety benefits increase proportionally, while the breakeven points decrease from 3 years to as low as 15 months. Interestingly, at P=2.0 and μ =150%, the runway safety benefits reach break-even at the end of the fourth year, i.e., it took four years for the runway safety benefit to manifest (Fig. 11). This shows the limit to which the implementation level of the runway safety budget can be raised so as to achieve a better result. Further implementation will lead to waste. At low μ and high P, runway safety benefit never reaches breakeven throughout the implementation period. Fig. 12 shows the runway safety benefit at P=0.8 and μ=90%. By increasing P to 2.0 and maintaining the value of μ at 90%, the runway safety runs at a loss throughout the safety periods (Fig. 13). Therefore, maintaining the runway safety effectiveness factor below the 100% level for any given P will result in a runway safety loss in the range of ₦125 million to ₦992.5 million. The runway safety benefits decrease with a decrease in µ for any given P, and vice versa.

One of the fundamental factors militating against the effectiveness of runway safety activities is the depreciation of runway facilities/ infrastructures/ technologies and/or lack of maintenance resulting in a decrease in the runway safety effectiveness. The effect of runway safety intervention effectiveness factor was examined vis-à-vis the runway accidents and runway accidents prevented. The behavioral plot is presented in Fig. 14. It is observed that the runway accident increases with a decrease in the level of runway safety intervention effectiveness factor. Conversely, the number of runway accidents prevented decreases when the level of runway safety intervention effectiveness factor decreases. In other words, the runway safety programme is capable of achieving better results (in terms of an increased number of runway accidents prevented and decreased number runway accidents caused), provided that the level of runway safety intervention effectiveness factor is not below 100%. However, at a lower level of the runway safety intervention effectiveness factor, runway safety programme would not be able to cope with runway accident hazards. It should be noted that, for this investigation, the budgeting factor and level of implementation of budget are kept constant.

The strategic planning implication of this is that the effectiveness of maintenance activities of airport facilities/infrastructures/technologies and all other runway safety activities must not drop below the 100% level. This can be achieved through constant reliability tests of runway safety activities. It should be noted that, in Nigeria, maintenance activities of airport facilities, infrastructure, and technologies are carried out by FAAN, while the appraisal of other runway safety activities is carried out by NAMA and NCAA.

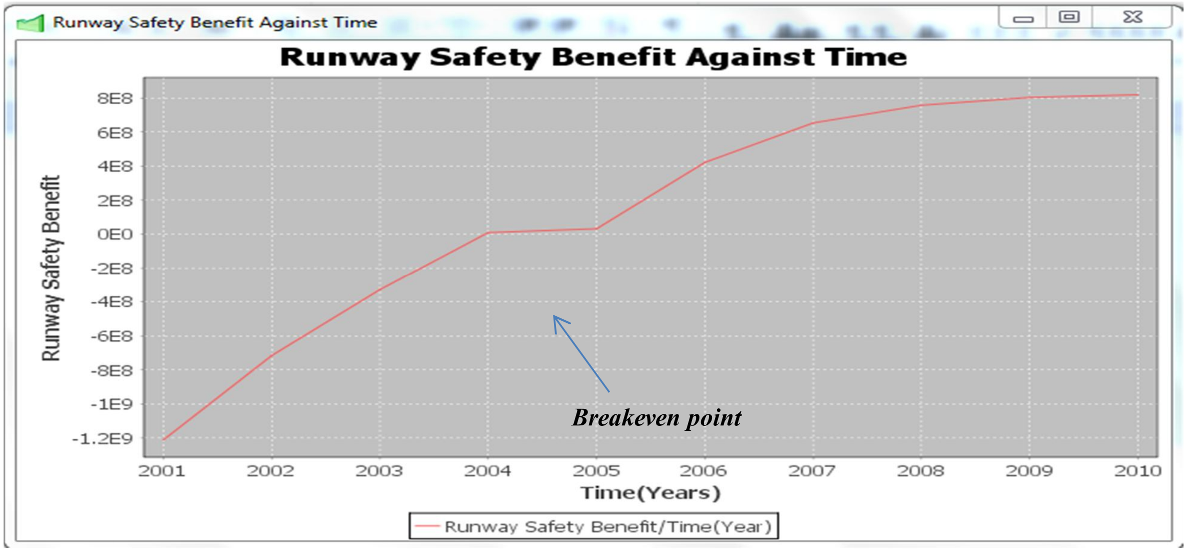


Fig. 11. Behavioural plot of Runway Safety benefit at P= 2.0 and µ at 150% level

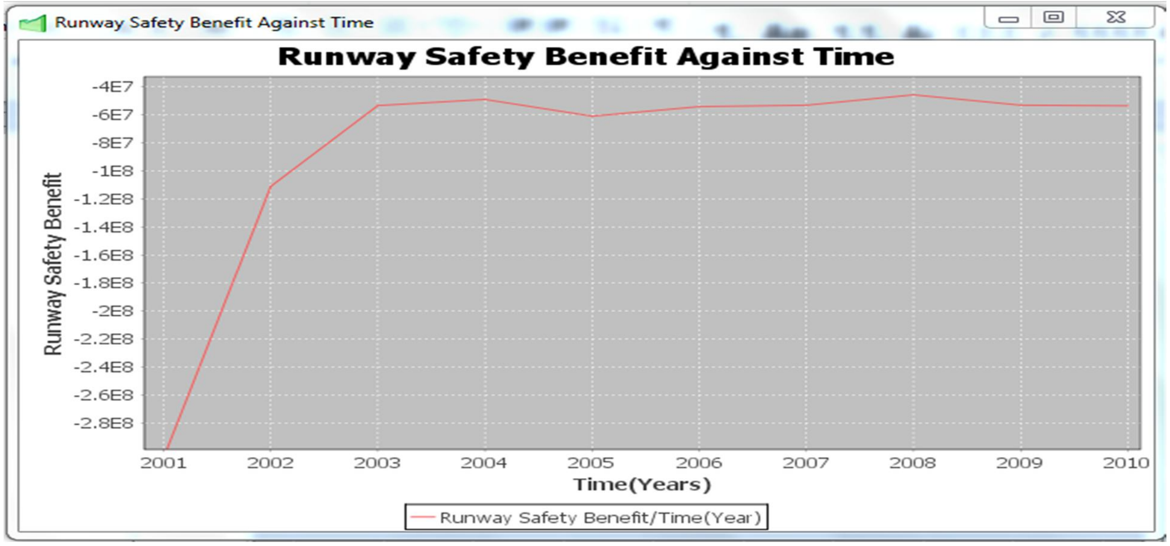


Fig. 12. Behavioral plot of Runway Safety benefit at P= 0.8 and μ at 90% level

Fig. 13. Behavioral plot of runway safety benefit at P= 2.0 and μ at 90% level

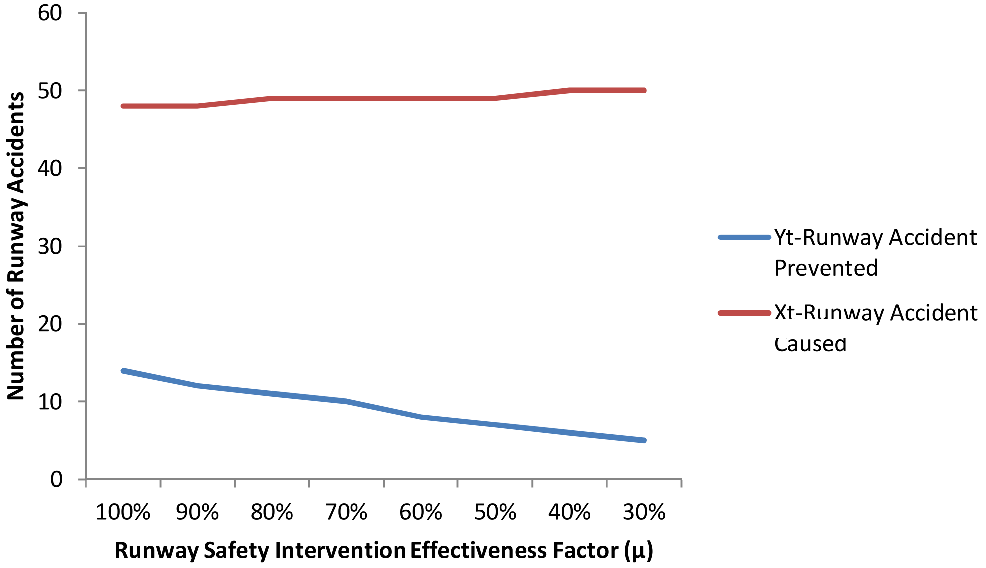


Fig. 14. Behavioral plot of the effect of runway safety intervention effectiveness factor on runway accidents

5. Conclusions

This study managed to develop the system dynamics models and the associated computer programme for proactive planning and managing of the runway safety programme. The simulation models enjoy the capability of evaluating the potential undesired consequences of organizational decision-making on runway safety programmes. It is believed that the study will provide a veritable tool for stakeholders in not only runway safety but also the aviation industry for economic justification of investments in aviation safety programme.

Specifically, the results of our study identified twenty-nine runway safety system components and forty-four runway accident hazards for runway safety system database. The system dynamics models developed included the number of runway accidents, the number of runway accidents prevented, and runway safety benefit/loss (SBL) performance function. A computer code was developed for these models for scenario experimentations. The computer code developed is flexible and can be adapted for further modifications and updating. In our scenario experiments, the effectiveness of runway safety interventions and the level of implementation of budgetary allocations were the runway safety system policy parameters. For a sustainable runway safety system and zero runway accident target, constant reliability tests and the full implementation of budgetary allocation of all runway safety interventions are recommended.

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