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# A mathematical model and application for fire risk management in commercial complexes in South Africa

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A R T I C L E I N F O

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A B S T R A C T

The successive event of fire mishaps in business buildings has been a significant issue. Accurately quantifying fire risks had been a complicated process due to its stochastic behaviour. Existing fire risk assessment applications are models dedicated to industrial fire hazards and wildfires. They are less suitable for fire risk analysis for the built environment. Also, most of these software require high rate subscriptions. More often than not, they require a highly-skilled programmer to use them. The development of a quantitative means for assessing the inclination of commercial complexes to a purported risk of "market fires" was done using the past fire accidents' investigation reports. Some verified fire accident investigations were used to optimise the fire model; adopting the methodology highlights of the Qualitative Risk Assessment (QRA). A Visual Basic (VB) oriented computer programme for the model was developed to assess selected commercial buildings in Johannesburg city of South Africa. The model and the associated computer programme showed the accuracy of the developed fire risk model in forecasting fire hazards. The estimated fire risks correlated with the fire incident histories of the evaluated complexes, thus validating the model. The model application could be a useful tool for predicting fire accidents for stakeholders.

## 1. Introduction

Fire accident in Commercial Complexes has been an incessant and ageless source of concern to business investors [1]. Commercial buildings' fire hazards have a non-negligible negative economic impact. The hazard of fire accident in commercial domains poses a high risk on huge investments that can be wiped out in a flash [2]. Fig. 1 shows the economic impact of fire losses according to different sectors in South Africa. Accurately quantifying fire risks had been a complicated process due to its stochastic behaviour [3]. Generally, quantitative risk analysis is a useful tool for the identification and quantification of an impending risk which otherwise helps in the control and management of such risk [4,5]. Fire risk can be defined as a measure of the feasibility of the fire danger and its consequences on objects and people [6]. The process involves the determination of a level of permissible fire risk. This level is referred to as one at which, the possibility of destruction, losses and other involved socio-economic implications is deemed negligible [7]. The most common quantitative analysis methods are statistical, analytical, and expert's estimates [8]. The quantitative risk assessment is undoubtedly a set of tools that can be used to predict fire accidents [9].

The outcome of the risk assessment is used to determine the magnitude of allocation of financial commitments towards the investment agreement in insurance [11] and also used by other stakeholders to develop a Fire Prevention Plan (FPP) [12]. The risk analysis tool is for accurately quantifying fire risks in the built environment for small and medium scale enterprises providing everyday services to the public. These business locations are characterised with small and average size shops, office spaces, departmental stores, restaurants, cafes, garages and workshops usually being clustered together as a commercial building [2]. Fig. 2 shows the commercial buildings fire incidences by these categories mentioned in South Africa.

The continuous event of fire mishaps in business structures, shopping centres, and markets is a high risk belonging to public liability insurance cover. For the insurer servicing a client in such a commercial community, it is a deal involving the risk for the entire commercial complex rather than the risk of a single shop/warehouse/apartment [14–16]. Very high prepaid premiums had been a source of discouragement to small and

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**Nomenclature**

| | |
|---|---|
| A | Fire Ignition-source Factor |
| B | Fire Load Factor |
| C | Fire Accessibility Factor |
| N | Total number of user's identified units in the examined building |
| I | operational index |
| m | the total number of user's identified ignition-source |
| n | the total number of identified Fire Load factor |
| q | the index numbers of identified ignition-source factors; that is q = 1,2,3 … m |
| j | the index for the units in the complex; that is j = 1,2,3 … n |
| $P_{Ai}$ | Attributed Probability for ignition-source component "i" causing a fire. |
| $P_{Bi}$ | Attributed Probability for sustainable component "i" sustaining an ignition-source |
| $M_{ij}^{A}$ | (t) the intensity of factor $A_i$ |
| $M_{ij}^{B}$ | (t) the intensity of factor $B_i$ |
| $P_{Aj}$ | Probability of an ignition-source in unit "j" |
| $P_{Bj}$ | Probability of an ignition-source being sustained in unit "j" |
| $P_{Aij}$ | Probabilistic Magnitude of ignition-source factor component "i" in unit "j" |
| $P_{Bij}$ | Probabilistic Magnitude of Accessibility factor component "i" in unit "j" |
| $P_{Fj}$ | Probability of fire occurring in unit j |
| $P_F$ | Probability of a fire occurring in the complex |
| $A_{xy}$ | Fire Accessibility loop from one unit to another; the ability of a fire to reach a unit "x" from another unit "y" |
| $F_j$ | Fire Risk for individual unit |
| F | Fire Risk quotient for the building |

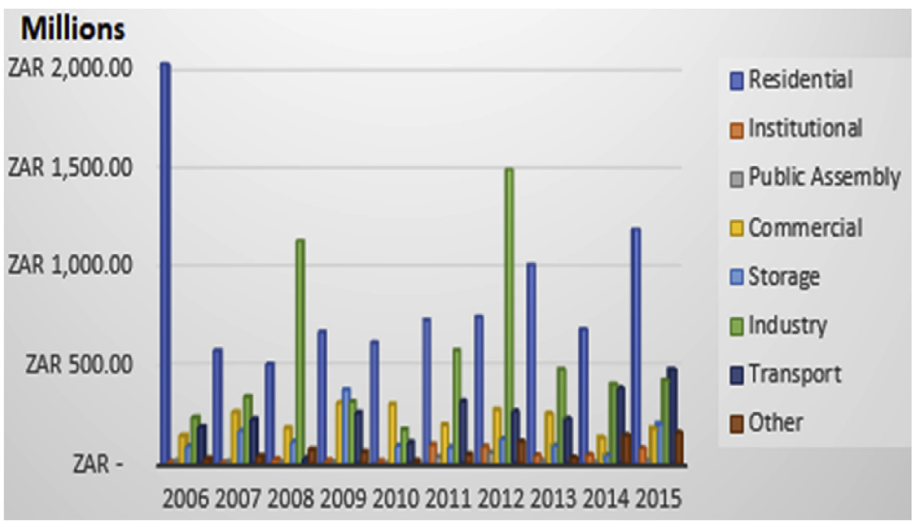


**Fig. 1.** South African Economic Impact of Fire Losses by Categories (2006–2015**)** [Data extracted from Ref. [10]].

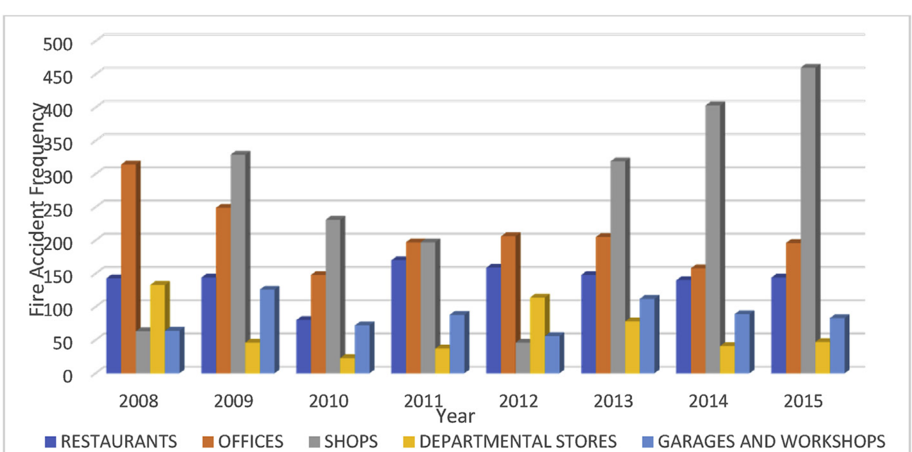


**Fig. 2.** South African Commercial Buildings Fire Incidences by Categories (2008–2015) **[**Data accessed from Ref. [2,10,13]].

middle scale merchants and artisans. Consequently, many such businesses are without adequate insurance cover [17]. At the slightest occurrence of a fire hazard, the numerous casualties are being rendered jobless intensifying the issue of poverty [18].

Conducting fire risk analysis with follow up actions to break the fire triangle is a means of increasing fire safety [19]. A fire risk analysis demonstrates the susceptibility to a flame episode and spread of flame. Risk analysis applications can be used to determine the inclination of a complex to fire hazards using some predetermined key performance indicators (KPI) for hazard identification and appraisal. The analysis is a procedure which incorporates both subjective and quantitative assurance of risks and their rated assessment [8]. Viable fire risk management for a built facility involves perceiving all the potential dangers related to the premises and carrying out an appraisal of the ampleness of the measures in place to avoid the hazard. The report of such audit could be used to give appropriate courses of action to protect individuals and businesses in the built environment from the dangers of a fire accident or reducing the additional danger of the flame spreading to do more damage [7]. Any validated fire risk analysis models have the abilities to indicate the risk exposure level of units or collectively the whole building to identify, eliminate (if possible) or monitor the risk factors identified [20].

## 2. Fire hazards quantitative models

Generally, hazard study models are classified into two types: qualitative and quantitative strategies. Qualitative methods of risk assessment are aimed at raising awareness of purporting dangers and the risk position of a system under study using some particular computational methods [21,22]. Quantitative research, which is the focus of this work, depends mostly on measures requiring a more prolonged exposure of the hazard assessment models which consists of one or more of the three corresponding phases; a recognisable level of evidence, level of notation and hierarchical level [23,24]. As a general rule, it must be a combination of a recognisable stage of detection, identification and evaluations [22, 25]. Regardless of the philosophy used to assess the hazard the general performance information and the related data available (history) determines the method of assessment to be chosen [26,27].

### *2.1. Brief survey on some computer program fire risk models*

Quite many Computer programs had been developed for effective and efficient fire hazard risk reduction in buildings [28]. These computer programs have its fundamental base in theoretical and real-life data premises using codes to interconnect their operations towards an optimised risk analysis [29]. Traditionally, many mathematical models and applications had been used to predict fire behaviour and quantify the risk of fire. Such models are either deterministic or non-deterministic. Computer program deterministic models include Computational Fluid Dynamics (CFD) models based on scientific theories and experimental results. Many computer programs use CFD models to simulate and visualise the pattern of smoke growth and heat transfer to analyse fire risk for built environments [30]. Non-deterministic models are generally based on actual fire data used to address the reliability of fire safety measures. They are presented in statistical, stochastic or probabilistic simulations of fire spread and damage [31]. In all cases, uncertainties which are caused by critical factors in fire development forecasting, building user behaviour during a fire, and/or fire protection system should be components evaluated in the model [9]. Some selected computer program fire risk models were with this succinctly discussed.

COMPBRN is an old computer package widely used to predict the time to failure of critical components. COMPBRN is a deterministic computer package specially designed for fire risk analysis for nuclear power plants [21]. Since the input parameters used in fire simulations in a room have many uncertainties, the evaluation of the damage time of the specified components is of a significance [32]. Ho and Apostolakis in 1992 present an updated version of the code called COMPBRN III, which highlights the importance of parameter uncertainty propagation by integrating functions to provide a probability distribution for component damage times [33]. FIRE-RISK (formerly known as CESARE-Risk) and FiRECAM are among the earliest computer program for fire risk assessment. The two risk assessment models are based on the cost of the fire accident if it happens [34]. Both programs are often used for the evaluation of multiple scenarios over relatively short periods using event tree assessment (ETA) [35]. FRAMEworks is closely related to FIRE-RISK and FiRECAM's fire risk and cost assessment model [36]. The computer-based quantitative model combines fire accident effects for the evaluation of a specific class of products in a specified occupancy, including fire hazard scenarios, with a statistical value of associated fire deaths, in order to establish a rate of fire mortality for these specified scenarios [37]. FRAMEworks was developed in collaboration with the National Institute of Standards and Technology (NIST), the fire analysis and research division of NFPA and a private consulting firm. They developed FRAMEworks to be a comprehensive but general fire risk assessment application for products that are used in buildings [36,38].

Another computerised fire risk assessment model developed by the fire research arm of the United Kingdom Building Research Establishment is CRISP (Computation of Risk Indices by Simulation Procedures) [36]. This model is also similar to Beck's project in that it provides a Monte Carlo simulation (MCS) of complete fire scenarios, but in an object-oriented format, as against state transition method used by Beck. The main aim of the CRISP approach is that the Building-Contents-People system is treated as a set of objects presented in a program that defines the behaviour of objects in response to stimuli (input data) [39]. Objects can interact in different manners depending on the information exchange between them, without affecting each other. However, the data related to an object can not be modified by another object. The associated object definition and input parameters can only be modified by changing the code for a particular object. The categories of objects modelled in CRISP includes cold and hot gas layers, alarms, walls, vents, furniture, rooms, occupants and firefighters [36]. The behaviours of objects are controlled by physical relationships such as fire growth and rule tables. For each execution, various contents, conditions and characteristics of the occupants are selected and assigned them probabilities [34]. The simulation starts predicting the evolution of a risk scenario over a period an occupant is in any risk situations. The simulation purportedly ends when the occupants have escaped, rescued, died or the fire is extinguished. CRISP was used to identify the trade-offs between a fire alarm system and the need to argue the passive fire protection for such building. Nevertheless, it was not recommended for modelling buildings complex than two-story residential [34].

Consolidated Fire and Smoke Transport (CFAST) model, O-Zone (Ozone) model and Fire Dynamic Simulator (FDS) fire models are among the widely used deterministic model to determine the state of fire by modelling the evolution of smoke and fumes. CFAST is a two-zone fire model based on the ideal gas law and combustion modelling, defined in a differential equation format for solving homogeneous upper and lower gas and temperature layers [40]. Ozone is one of the fire zone model digital tools that often evaluate changes in the temperature of gases in a compartment during a fire [21]. Based on a limited number of assumptions, Ozone is easy to use and provide a proper assessment of the situation [32]. The OZone computer code is designed to help engineers design structural elements exposed to fire in the compartment [41]. The code is based on the aggregate inferences drawn from the harvested recent developments. It incorporates a single-chamber shot model combining a two-zone model and a one-zone model [32]. One-zone is for modelling of fire compartments and the other on the impact of localised fires on structures. CFAST and OZone are the most widely used programs to simulate fires in compartments [31]. FDS fire models is a slow-moving large eddy simulation (LES) code focused on transporting smoke and heat from fires to describe the evolution of fire. FDS is primarily a tool to study the fundamental dynamics of fire and combustion; and it has been widely used to solve fire problems related to fire protection technology [31].

@RISK is compiled as a "plug-in" program that can be installed in a spreadsheet such as Microsoft Excel spreadsheet among others. @Risk is mainly used as a probabilistic model to predict a possible state of operation for each agent using MCS. The main feature is to provide an estimate of the probability distribution of the possible outcomes for each selected output cell in the worksheets. The software uses simulation to

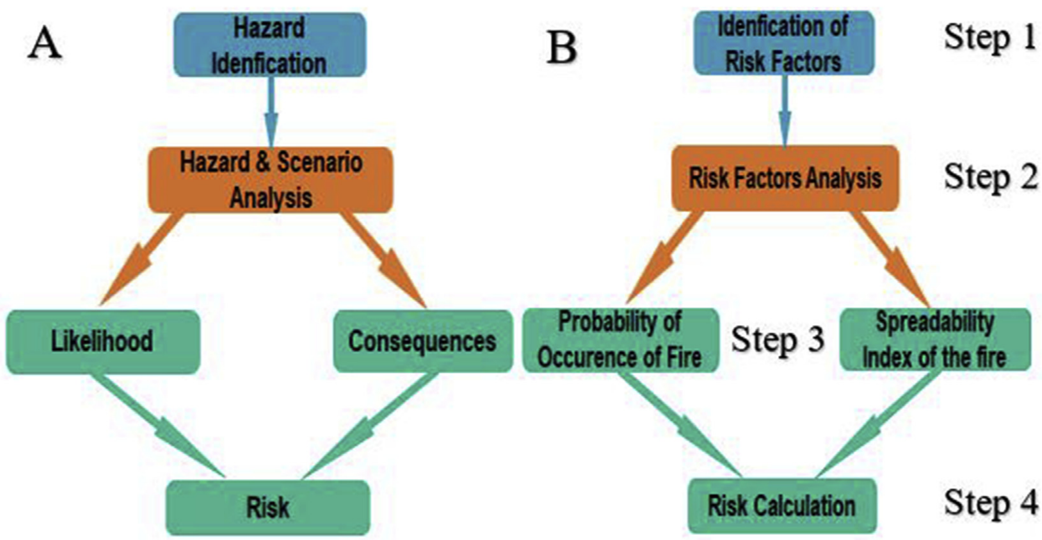


**Fig. 3.** (**A**): Process of the QRA [9] (**B**): The risk analysis process (present study).

combine uncertainties and risks and allow easy graphical analysis [42]. In the past, business modelling was based primarily on spreadsheets, with individual variables being manually modified to examine their impact on the project. Indeed, analysing the impact of two or more variables moving on a model required a lot of time and jobs. @RISK can be used to vary the reliability values of fire protection systems. @RISK is a useful modelling tool for analysis under uncertain and risky conditions [23]. FIREHARM (FIRE HAzard and Risk Model) is another computer fire safety research model, which calculates the typical dimensions of fire behaviour, fire risk and fire effects in space and uses them as variables for

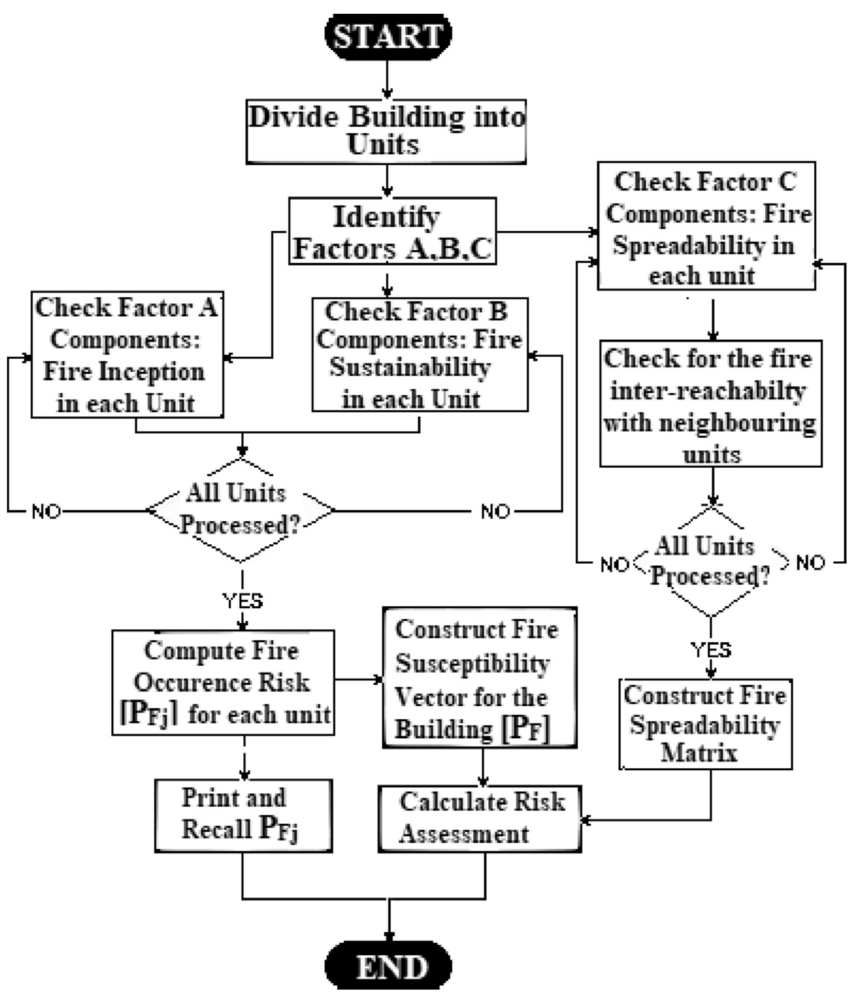


**Fig. 4.** The flow chart for the risk analysis.

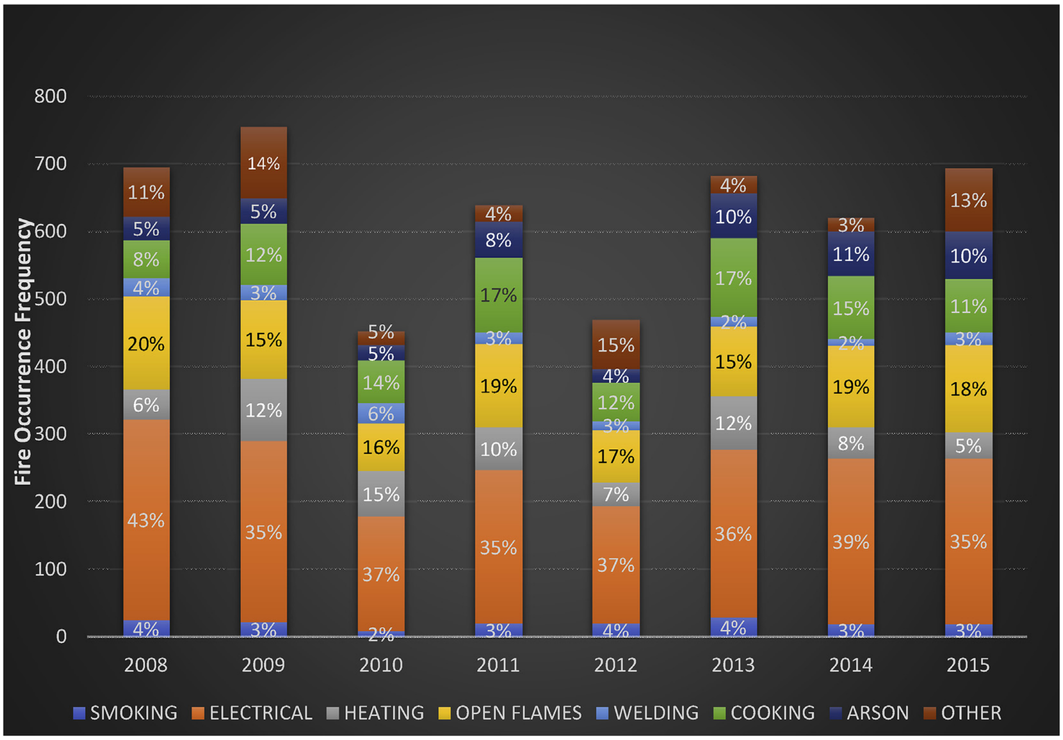


**Fig. 5.** Fire Statistics for South African Commercial Complexes showing Causes by Percentage per Year (2008 and 2015) [Data accessed from Refs. [2,10,13]].

the spatial representation of the fire risk. The fire risk is then calculated using a daily simulation of fuel moisture over 18 years to calculate fire measures over time. The digital hazard and risk maps are being used for fire protection planning and real-time forest fire operations [3].

Most of the fire risk assessment applications in existence, including the above discussed are specialised models for either industrial and forest fire risk control and monitoring. They are found less appropriate for the commercial built environment. Apart from the fact that most of the applications are not freeware, they mostly require a high level of skill in programming to be able to put them to use. These project a need for a fire hazard risk management/analysis specifically for the built environment being utilised for commercial purposes.

### *2.2. The fire risk model*

The new model consolidates the modularisation process of the Quantitative risk assessment (QRA) but notwithstanding, it was modified to a distinctive and more specific intended approach. QRA is a systematic hazard analysis method for assessing the vulnerability of a facility, operation or system to risks [43]. The QRA is a fundamental tool for understanding the risk exposures, the nature of such risk, the assets at risk, and the prominence of the risk [23]. The primary aim of QRA usually is to improve productivity through a reduction in losses to hazards and minimises threats throughout the lifecycle of an asset. It has also been found to be most useful in the Risk analysis in process activities for high-risk production companies like Oil and Gas and Chemical Industries [23,36]. Fig. 3 represents the relationship between the developed fire risk analysis and QRA.

The developed Fire Risk model practical consists of four steps [44].:

i) Identification of Risk Factors,
ii) Analysis of the Identified Risk Factors,
iii) Quantification/Combination of the Risk Occurrence,
iv) Risk Calculation.

## 3. The Methodology Fire Risk Model

The model consists of five main steps shown in Fig. 4 as adopted from Ref. [45]. The highlights of the steps include (i) Segmentation of the building into divisible units, (ii) Determination of the factors that can cause a fire accident in individual unit, (iii) Quantification of fire Load factors existing in each unit, (iv) Quantification of fire Accessibility factors; that is what makes it possible for the fire to spread from one unit to another and (v) Calculation of the risk index. The building of interest is segmented into units such that a unit is physically and/or operationally unique. For example, a typical South African trading complex typically consists of an array of stores; a unit can be made from a block of shops in a row. For multi-story buildings, each floor can stand as separate units. The segmentation is to improve the convenience of using the model without meddling things up.

Generally, risk-related "occurrence" is usually the projection of the frequency of a hazard or failure happening [46]. The occurrence of fire requires a combination of a spark, oxygen and fuel [47]. For a fire initiation, to occur, two main factors A and B must be present. Fire ignition-source was tagged factor A while "fire load" as factor B. Possible ignition-source factors for a fire are activities, elements or measures that can initiate fire. However, fire load factors include anything that can sustain a spark or an explosion of burning flames [48]. Fire load are any combustible material accessible by the heat and flame during a fire incident [49]. The fire load can be summarily referred to as any material (solids, liquids and combustible gases) that serve as fuel to aid the fire occurrence and growth. After initiation, the flames initially spread slowly on flammable surfaces in abundant of air usually containing oxygen that combusts the sparks. It progressively becomes exponentially faster if there is no substantial impedance or suppressant along the path of the spread [50]. This combination process and ease of the fire spread is referred to as the factor C in the developed risk model. The heat and radiation from the flames and hot gases as a chain reaction ignites another potential fuel nearby to escalate the fire growth in the magnitude of the fire load [51].

For each unit, fire occurrence is the interactions of the factors A and B, which is the fire outbreak probability for the individual units. The fire accessibility factor C projects, at each unit level, the intra and inter domino effects of the spread. This produces a fire accessibility matrix to determine the fire propagation quotient for the building. The accessibility matrix, follows a function of the building architectural structure, the materials of the walls and the nature of the fire. The resultant value of all the factors, using relevant mathematical relationships quantifies the fire risk for each unit. Subsequently, for the whole building, the risk analysis estimates the probability of a fire accident, mathematically resolving all the risks in all the units together. The final classification of the results of the risk analysis is, as shown in Table 1.

### 3.1. The mathematical background for the model

The following are the mathematical background for the developed model. The model parameters are as interpreted in the nomenclature.

Given; $A = \{A_1, A_2, A_m\}$ 1

and

$B = \{B_1, B_2, \dots \dots \dots \dots, B_q\}$ 2

Also

$$M^A_{ij} = \{0; Otherwise 1; If\ ignition - source\ factor\ component\ "i"\ is\ present\ in\ the\ unit\ at\ a\ time\ "t." \quad (3)$$

And

$$M^B_{ij} = \{0; Otherwise 1; If\ accessibility\ factor\ component\ "i"\ is\ present\ in\ the\ unit\ at\ a\ time\ "t." \quad (4)$$

$$P_{Aij} = P_{Ai} \times M^A_{ij}(t) \quad (5)$$

$$P_{Bij} = P_{Bi} \times M^B_{ij}(t) \quad (6)$$

Fire at given time t, such that

$$P_{Aij}\begin{cases} P_{Aij} : If \quad M_{ij} = 1 \\ 0; Otherwise \end{cases} \quad (7)$$

$$P_{Bij}\begin{cases} P_{Bij} : If \quad M_{ij} = 1 \\ 0; Otherwise \end{cases} \quad (8)$$

$$P_{Aj} = \sum_{i=1}^{m} P_{Aij};\ 0 \le P_{Aj} \le 1 \quad (9)$$

$$B_{Bj} = \sum_{i=0}^{m} P_{Bij};\ 0 \le P_{Bj} \le 1 \quad (10)$$

This implies that:

$$\sum_{i=1}^{m} P_{Ai} = \sum_{i=1}^{m}\left(P_{Ai} \times M^A_{ij}(t)\right) = 1; \text{if all the 'm' components of factor A are present in unit j} \quad (11)$$

$$\sum_{i=1}^{m} P_{Bi} = \sum_{i=1}^{m}\left(P_{Bi} \times M^B_{ij}(t)\right) = 1; \text{if all the 'q' components of factor B are present in unit j} \quad (12)$$

Therefore,

$P_{Fj} = P_{Aj}$ x $P_{Bj}$ $0 \le P_{Fj} \le 1$ 13

Once there is a fire in any unit then the building has a fire occurrence.

Applying a reliability model and treating the units as a parallel type that is, $P_{F1}$, $P_{F2}$ …. ….$P_{FN}$ are in parallel connection.

PF=1- [ (1-PF1) (1-PF2) …...(1-PFN)] = measurement (in probability) of the fire occurrence risk factor, for the whole building 14

The particular assumption made for the fire spread as follows [9]:

(i) Non-explosive fire will spread to other units interconnected by any form of combustible material.
(ii) Non-explosive fire spreads to units at a 4 m radius reach without any interconnectivity because of firearms.
(iii) Explosives fire source spreads to units around a 10 m radius reach.

The accessibility matrix A measures the ease of propagation of the fire

**Table 1**
Risk Level Classification.

| Probability | The Risk Level |
|---|---|
| 0.70 - 1.00 | Critical |
| 0.50 – 0.69 | High |
| 0.31 – 0.49 | Medium |
| 0.00 – 0.30 | Low |

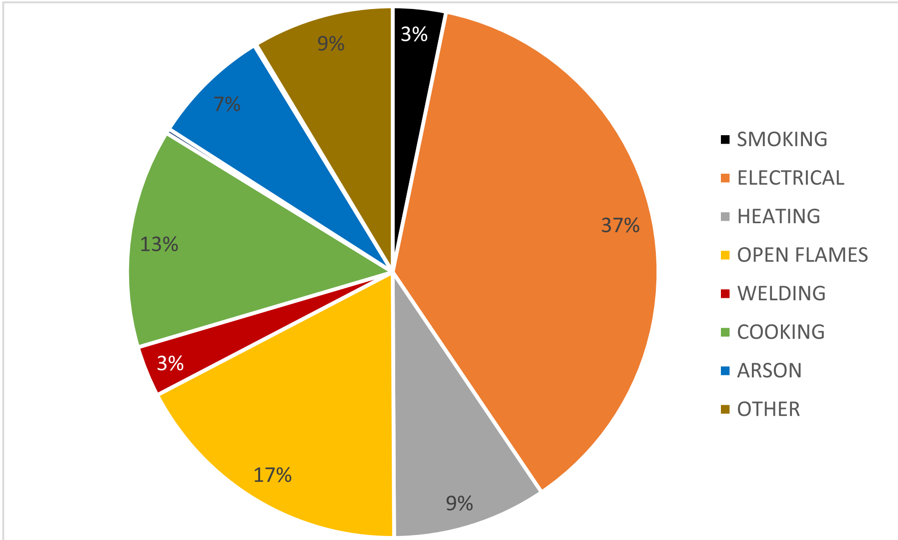


**Fig. 6.** Fire Causes for Commercial Buildings in South Africa by Percentage of Average for 2008 to 2015 [Data extracted from Ref. [2,10,13]].

**Table 2**
Showing the assigned probabilities for each component of the Fire Incidence factor (Factor A).

| Potential Fire Causes | Probability of Occurrence ($P_{Ai}$) |
|---|---|
| Naked Fire | 0.17 |
| Welding Activities | 0.03 |
| Gas- Fired Activities | 0.11 |
| Heating and Hot Bearings | 0.09 |
| Electrical Sources (Faults) | 0.37 |
| Cigarettes Smoking | 0.03 |
| Sparks as a result of rapid moving metals | 0.03 |
| Static Discharges | 0.03 |
| Activities involving Smokes | 0.05 |
| Hot Surfaces and Chips | 0.09 |
| $\sum \mathbf{P_A} = 100$ | |

in the complex.

The fire spread factor is notified with an accessibility causal loop, which is the ability of the fire to reach a unit “x” from another unit “y”. The assignment is such that each cell contains elements $A_{xy}$ defined as follows:

$$Axy = \{0; Otherwise 1; If\ Fire\ will\ spread\ using\ the\ stated\ condition\ statements\ assumptions \quad 15$$

Where, such that: $1 \geq x \leq \alpha$; $1 \geq y \leq \mu$ (but note that it is usually a square matrix, thus, $\alpha = \mu = N$). Such that x ranging from 1 to α, and y ranges from 1 to μ, thus producing an accessibility causal loop matrix as follows:

Given: Risk Factor, $F = A \times PF = Axy \times PFj$ 16

Moreover, recall that the fire occurrence Vector, $P_{Fj}$.

The susceptibility of the building to fire accident can be determined using the probability of occurrence [31].

Susceptibility to a fire occurring in a unit “j” is $P_{Fj}$ then vector $P_F$ is the susceptibility to fire occurrence of the whole building.

$$P_F = \begin{bmatrix} P_{F1} \\ \vdots \\ P_{FN} \end{bmatrix} \quad 17$$

$$F = \begin{bmatrix} R_{11} & \cdots & R_{1\mu} \\ \vdots & \ddots & \vdots \\ R_{\alpha 1} & \cdots & R_{NN} \end{bmatrix} \times \begin{bmatrix} P_{F1} \\ \vdots \\ P_{FN} \end{bmatrix} \quad 18$$

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_n \end{bmatrix} \quad 19$$

$$F_i = \begin{bmatrix} \frac{F_1}{N} \\ \vdots \\ \frac{F_n}{N} \end{bmatrix} \quad 20$$

If $A_{xy} = 0$ or 1 and $0 \geq P_{Fj} \leq 1$ then $0 \geq \frac{F_j}{N} \leq 1$.

In Summary, Overall Fire Safety of the Complex under investigation becomes:

$$FR = \frac{\sum_{j=1}^{N} F_i}{N^2} = \text{Fire Index for the whole of the Commercial Complex}$$
21.

### 3.2. Computer application development

The software implementation was performed with Microsoft Visual Basic® with the source code for the package is available in [52]. The user interfaces have been designed to be easy to use. As the user follows the instructions, some essential guides prompt up through the risk assessment process by allowing the user to interact with background source codes by specifying simple numbers and browsing the checklist for each unit. At the end of the process, an in-depth evaluation will be conducted for each unit. The results presented are treated in the background to display the risk factors for each unit, then the risk assessment of the entire

**Table 3**
The complex X's Factor A characteristics.

| S/N | Fire incipience factor | Assigned Probability (PAi) | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Naked fire | **0.17** | | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 |
| 2 | Welding activities | **0.03** | | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 |
| 3 | Gas-fired activities | **0.11** | | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 |
| 4 | Heating and Hot Bearings | **0.09** | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| 5 | Electrical sources | **0.37** | | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| 6 | Cigarettes and/or matches | **0.03** | | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| 7 | Sparks from rapid of metals | **0.03** | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| 8 | Static discharges | **0.03** | | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| 9 | Activities involving Smokes | **0.05** | | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 |
| 10 | hot surfaces and chips | **0.09** | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| | $\sum_{i=1}^{m}$PAi = 1 | 1.00 | $\sum_{i=1}^{m}$PAij | 0.63 | 0.78 | 0.80 | 0.89 | 1 | 0.63 | 0.78 | 0.37 |

It was planned to be for demarcation of the matrix components. The unbold figures are the matrix components, while the bold is the corresponding multiplier. It does not have any negative implication if removed.

**Table 4**
Complex X's Factor B characteristics.

| S/N | Fire sustainable factor | Assigned Probability PBi | Units | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Abundant air | 0.20 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | Loose or packed paper | 0.20 | | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 |
| 3 | Furniture or wooden material | 0.20 | | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | Debris and dried solid waste | 0.10 | | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |
| 5 | plastic and rubber material | 0.10 | | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 6 | Clothes and foam | 0.10 | | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| 7 | Flammable liquids/gasses | 0.10 | | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 |
| | $\sum_{i=1}^{m}$PBi = 1 | 1.00 | $\sum_{i=1}^{m}$PBij | 0.8 | 1 | 0.6 | 0.9 | 0.9 | 0.8 | 0.9 | 1 |

complex by clicking on "Calculate". Procedures in the model algorithm described earlier were followed. The computer programme is integrated with user interfaces in which any intended user will supply all the necessary information by either inputting a value or just some few clicks as a way of providing the inputs. The software programme calculates the risk for the commercial building immediately after the necessary checkboxes had been checked the button "Finish" had been pressed. This eliminates possibilities for errors, and more so the processes to get to the final result can be saved as a "project". The project can be revisited for amendments, at any point in time, after which the re-calculation takes effect within seconds. The step by step instruction about the usage and operations of the software application is in the Appendix.

The data used as a pilot to the probabilities assigned to each factor analysed in Figs. 5 and 6. Deriving probability from fire statistics had been an established method [28]. The DayoFRA (software) was developed using fire accident statistics for South Africa. However, the Fire risk Analysis Software can be deployed in some other countries as well. Better still another set of probability assigning can be reprogrammed for specific countries, area or environment once the fire statistics analysis had been effectively carried out. For this application, there are ten (10) distinctively identified causes highlighted by the authors as possible fire risk initiators which are as shown in Table 2. The assigned probabilities were guided by the fire accident statistics of determining causes as discovered by detailed investigation's reports for eight (8) years (Fig. 6). The probability assigning was done classifying all identified causes under smoking, electrical (faults), heating, flames, welding, cooking and the "other" cause represented in Fig. 6 were discovered to be such like static discharges, metals under friction and the rest of them. Arson was taken not to be a fire cause associated with the physical features, and facility usage as it is as an intentionally induced incidence and as such was not included. The assigned probabilities were used for the mathematical computation as the inbuilt weight to the given potential fire causes; when the evaluator chooses the corresponding components.

## 4. Result and discussion of the fire risk analysis

The complex was divided into eight units numbered from 1 to 8. The complex is a two-storey building; the modularisation was carried out in

**Table 6**
Complex X's fire reachability: Factor C (reachability of fire from one unit to another).

| FROM UNITS | TO UNITS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| **1** | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | Rxy |
| **2** | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | |
| **3** | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | |
| **4** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | |
| **5** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | |
| **6** | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | |
| **7** | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | |
| **8** | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | |

**Table 5**
The Fire occurrence risk for each unit for complex X.

| | Probability of fire occurrence for each unit, PFi | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Units | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| $\sum_{i=1}^{m}$PAij | 0.63 | 0.78 | 0.80 | 0.89 | 1.0 | 0.63 | 0.78 | 0.37 |
| $\sum_{i=1}^{m}$PBij | 0.8 | 1.0 | 0.6 | 0.9 | 0.9 | 0.8 | 0.9 | 1.0 |
| PFi | 0.504 | 0.78 | 0.48 | 0.801 | 0.90 | 0.504 | 0.702 | 0.37 |

**Table 7**
Result presentation from the software package.

October 10, 2018 9:49:17 a.m.
Fire Risk Analysis Engine
************************************************************************************************

The Fire Occurrence for each unit in the complex.

| | Prob. for Fire Factor A | Prob. for Fire Factor B | Prob. of Fire occurrence in the complex |
|---|---|---|---|
| For Unit One: | 0.63 | 0.8 | 0.504 |
| For Unit Two: | 0.78 | 1 | 0.78 |
| For Unit Three: | 0.8 | 0.6 | 0.48 |
| For Unit Four: | 0.89 | 0.9 | 0.801 |
| For Unit Five: | 1 | 0.9 | 0.9 |
| For Unit Six: | 0.63 | 0.8 | 0.504 |
| For Unit Seven: | 0.78 | 0.9 | 0.702 |
| For Unit Eight: | 0.37 | 1 | 0.37 |

Fire Spreadability result (Factor C)
All units in the complex are inter-connected with Brick
Units are separated by distances in meters: 0.3
************************************************************************************************
Final result
Risk Estimate = 0.4876 (Mild Risk)

such a way that there were three units on each floor, including the ground floor. Each unit has at least ten (10) stores. The commercial activities in the building range from the sale of engine parts, plastics and household utensils, fabrics, mattresses, furniture, stationery, confectionery, etc. The building also accommodates service businesses such as tailoring, cybercafés, fast foods, and some other consulting firms.

### *4.1. The mathematical computation and risk analysis of a commercial complex X in the city of Johannesburg, South Africa*

The factors A, B and C found in each unit of the commercial complex were presented in Tables 3 and 4. Table 5 displays the Fire occurrence probability for each unit of Case study complex X. In the same vein, Table 6 shows the result of calculated fire accessibility (reachability of fire from one unit to another) according to the model user's inferences using the models' guide yardsticks (assumptions). Tables 3–6 follows the principal of the mathematical model described above. Table 3 is the presentation of worked equation (7) while Table 4 is a presentation of derived equation (8). Horizontal computation of all the units 1 to 8 gives the values of equations (9) and (10) from Tables 3 and 4, respectively.

Table 5 is the computations of equation (13) using the results of equations (9) and (10) gotten from Tables 3 and 4, respectively. Summarily, Table 5 presents $P_{Fi}$ for all the units 1 to 8; using $\sum_{i=1}^{m} P_{Aij}$ and $\sum_{i=0}^{m} P_{Bij}$ derived from Tables 3 and 4 respectively for all the units. Table 6 was derived for units 1 to 8 using the reliability factor of equation (15); thus, the matrix for factor C was derived.

Table 6 transforms to the reachability matrix, $R_{xy}$

$$R_{xy} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

Using extracted values of Table 5 in equation (17); the Fire

$$\text{Occurrence Vector, } P_{Fj} = \begin{bmatrix} 0.50 \\ 0.78 \\ 0.48 \\ 0.80 \\ 0.90 \\ 0.50 \\ 0.70 \\ 0.37 \end{bmatrix}$$

From equation (18); The combined Risk Factor for all units = $R_{xy} \times P_{Fj}$

$$\text{The building Fire Risk Factor} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} 0.50 \\ 0.78 \\ 0.48 \\ 0.80 \\ 0.90 \\ 0.50 \\ 0.70 \\ 0.37 \end{bmatrix}$$

The product of 8 × 8 and 8 × 1 matrix produces an 8 × 1

$$\text{Risk Factor} = \text{Fi} = \begin{bmatrix} 0.50+0.78+0.48+0.80+0.90+0+0.70+0 \\ 0.50+0.78+0.48+0.80+0.90+0.50+0+0.37 \\ 0.50+0.78+0.48+0+0.90+0.50+0+0 \\ 0.50+0.78+0+0.80+0.90+0.50+0.70+0.37 \\ 0.50+0.78+0.48+0.80+0.90+0.50+0.70+0.37 \\ 0+0.78+0.48+0.80+0.90+0.50+0+0.37 \\ 0+0+0+0.80+0.90+0.50+0.70+0.37 \\ 0+0+0+0.80+0.90+0.50+0.70+0.37 \end{bmatrix}$$

$$Thus,\ F_i = \begin{bmatrix} 4.16 \\ 4.33 \\ 3.16 \\ 4.55 \\ 5.03 \\ 3.83 \\ 3.27 \\ 3.27 \end{bmatrix}$$

From equation (20), probability of fire risk for the modularised units becomes;

$$P(F_i) = \begin{bmatrix} 0.52 \\ 0.54 \\ 0.40 \\ 0.57 \\ 0.63 \\ 0.48 \\ 0.41 \\ 0.41 \end{bmatrix}$$

From equation (21), Fire risk for the entire complex X in probability terms could be calculated as

$$FR = \frac{\sum_{j=1}^{N} \mathrm{F_i}}{\mathrm{N}^2} = \frac{31.6}{8^2} = \frac{39.35}{64} = 0.4938 \approx 0.49$$

Given the probability of fire risk FR, therefore, the complex X exhibits "a mild" fire risk, referring to Table 1.

### 4.2. The fire risk analysis results for complex X

The results of the risk analysis for the shopping mall Complex X in the city of Johannesburg, South Africa, using the developed software package - DAYOFRA is as shown in Table 7. The procedure through the process is as described in the Appendix.

It can be observed that the final results of the output for a shopping mall in the city of Johannesburg, South Africa computed by the application is approximately equal to the result obtained by mathematical computation.

## 5. Conclusions

Most existing fire risk assessment applications are specialised models for controlling and monitoring fire risks for industrial fire hazards and wildfires. They are less suited for fire risk analysis for the built environment. Aside from the fact that most of these applications (software) are expensive, they generally require a high level of programming knowledge to use them. This work produced a mathematical model for predicting the proness of commercial complexes to fire accidents. Four classes of risk levels were defined as the critical, high, medium and low. The risk analysis application has user-friendly interfaces. The interfaces were enhanced with step-by-step instructions which can be used by individuals without any high skill. The model had been validated using some identified commercial complexes in Johannesburg city of South Africa. The risk analysis model was developed into an application software using Visual Basic (VB) oriented computer programme. The application was validated using specific case studies. The model was found to have generated the best estimates for all the necessary variables. The model application could be useful for predicting fire accidents for insurance companies, governmental parastatals involved in fire safety management and other private stakeholders saddled with responsibilities of investigating and ensuring fire protection.

## Declaration of competing interest

The authors declare that there is no conflict of interest for this publication.

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## Appendix. The Outlook and Operations of The Developed Risk Analysis Software Package

The software programme has four major stages designed with checkboxes to make the application user-friendly. Instruction features such as 'next' and 'previous' make it possible for users to go through the units as a means of reassuring correct inputs. Figures A1, A2, A3 and A4 show the user input interface while figure A5 showcased the output interface. The user only needs to incorporate the appropriate information highlighted in the first three steps. In contrast, the fourth step is the computation of results which is solely done by the programme. At each click, all the mathematical computation is going on at the background using the source code for the dedicated package deposited and explained in a public domain repository: [5]. Figure A1 represented processing of factor A while Figure A2 solves for factor B. Figures A3, and A4 solves for factor C in two alternative methods, respectively. The choice depends on the preference of the user. The developed application makes the analysis more flexible for the user's convenience without compromising the quality of the assessment.

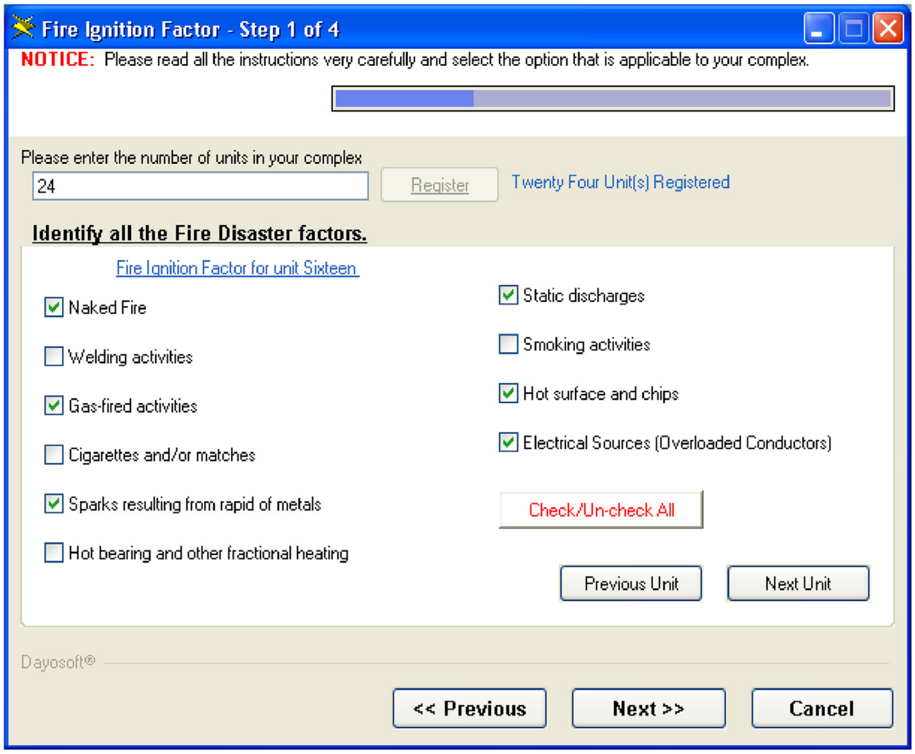


**Fig. A1.** The first user interface stage of the developed software programme.

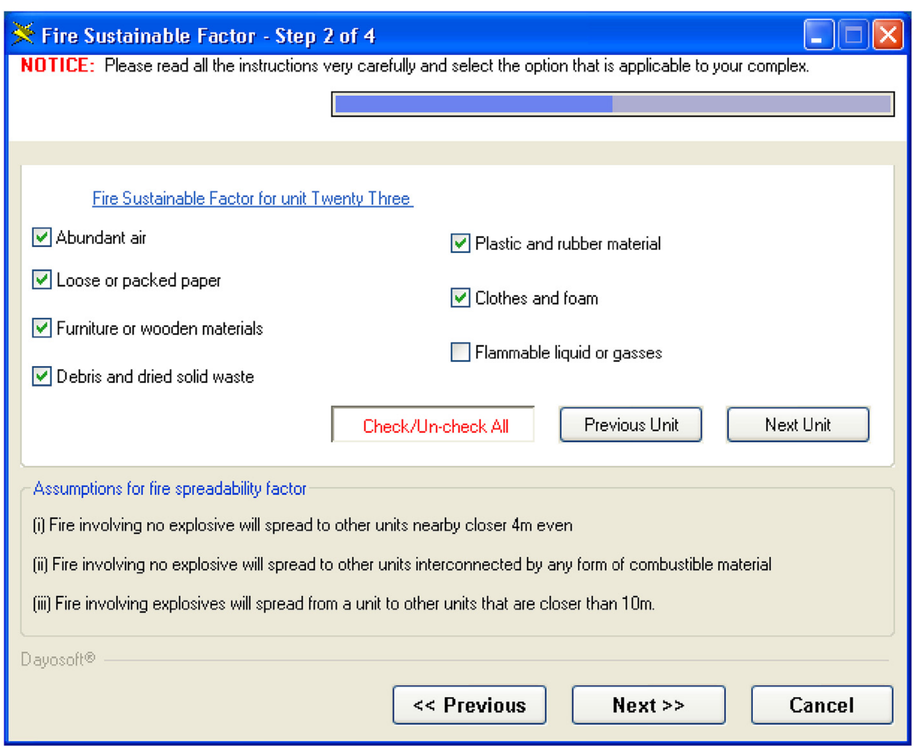


**Fig. A2.** The second stage of the developed software programme.

The third stage has two independent interfaces tagged the “fire spreadability table” and “fire spreadability options”. Only one is expected to be chosen while the other becomes inactive. The fire spreadability table requires a prepared a spreadability loop (that is an N by N matrix component). The “fire spreadability option” interface is an alternative interface. It was designed for a situation whereby it is not conducive for the user to produce the spreadability matrix. The user’s judgments about the spreadability of fire within the units of the commercial complex under investigation is either by computed fire spread assumptions already incorporated in the model or by the user’s discretion as shown in figures A4. The excel environment has been invoked into the programme, and it props up immediately the user clicks "Load Matrix" (figure A3). The N x N matrix automatically comes on the display using the number of units earlier input by the user. A click at the finish will lead to a sub-interface that will solve the loaded matrix. The interface uses a corresponding simulated inbuilt array depending on the type of connectivity characteristics specified by the programme users to adapt for the loop method. This is singularly incorporated into the programme to make the software more robust and widen its versatility. The interface is as displayed in figure A4.

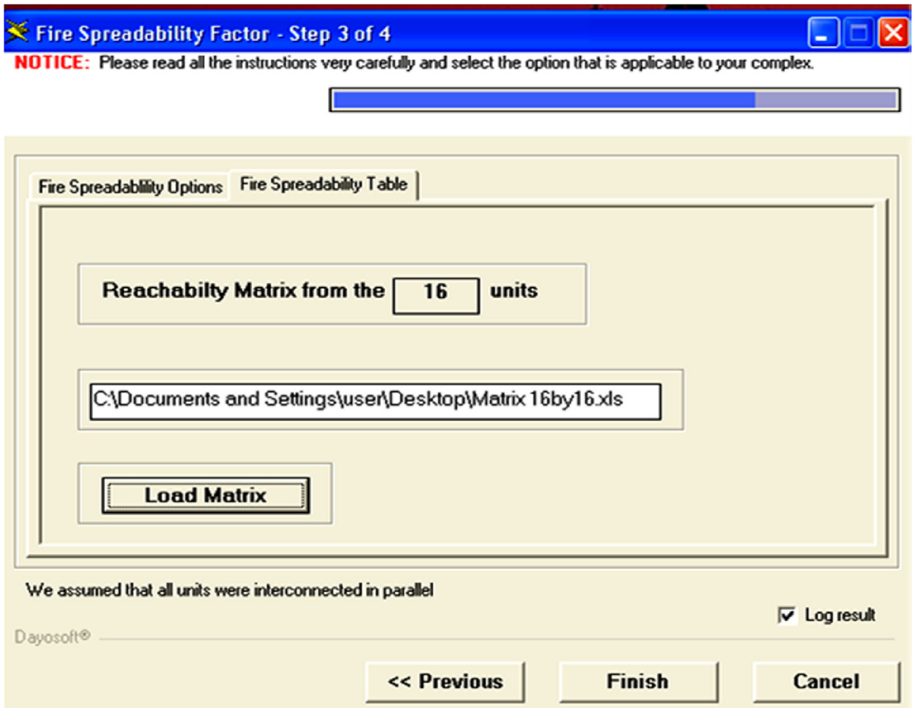


**Fig. A3.** The fire spreadability option of the third user interface stage of the developed programme

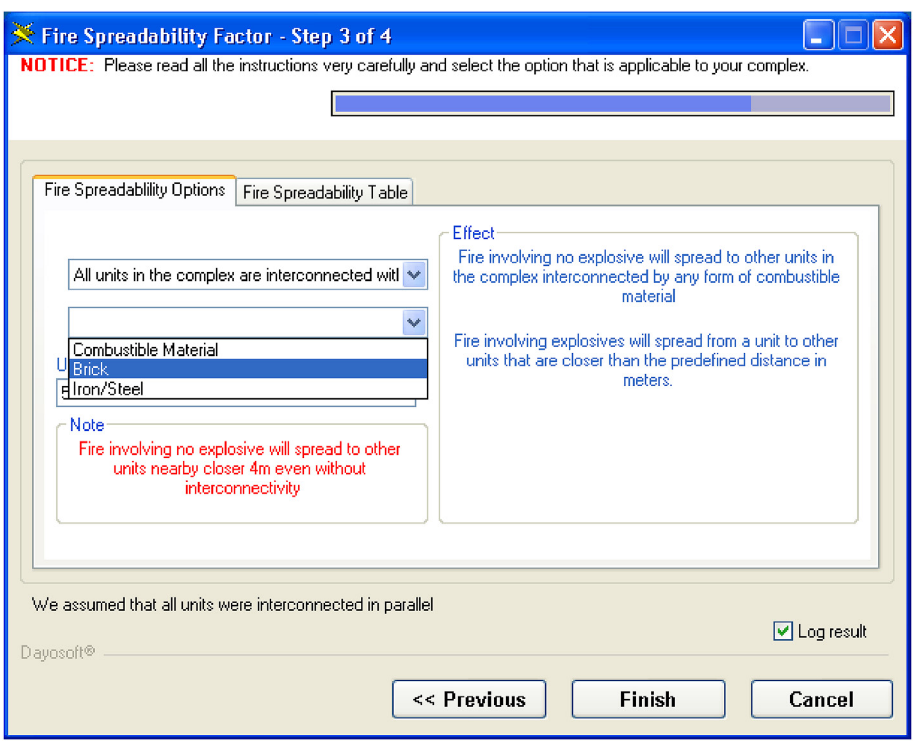


**Fig. A4.** The alternative option (b) of the third user interface stage of the developed software

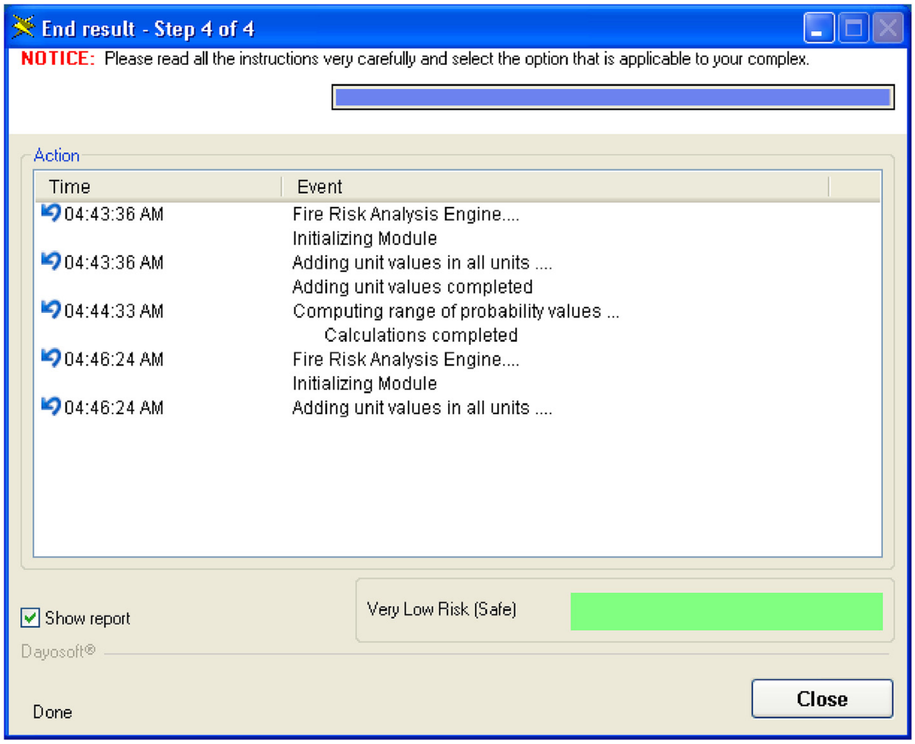


**Fig. A5.** The result processing interface of the developed software programme.

The output interface shown in figure A5, is straightforward to understand by all users regardless of the level of literacy. The output of the programme presents them in a statement form by the risk class presented in Table 1 without bothering the user with the numerical values in probability. The report showing the breakdown of the possibilities of fire outbreak in each unit can be activated by checking the box for log result and by clicking show report after the software has finished its operations. A note pad pops up with all the details as soon the application is closed. A sample of the detailed result of some of the risk analysis carried out in some commercial complexes in Johannesburg as produced by the programme developed was presented as a case study in Table 7.

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