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Safest and Shortest Exit Algorithm for NPP Fire Evacuation

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Abstract: Fire safety in nuclear power plants (NPPs) is very important for realizing a high level of safety which investigate achievement reasonably protection for persons and the environment since fire can cause core melts thus emergency fire evacuations are concerned in NPPs. In this research, a new algorithm for Emergency fire evacuation is developed to minimize evacuation time for limiting the evacuee's exposure to fire hazards products. The developed algorithm is a Safest Shortest Exit algorithm (SSE) which consists of three techniques: a rules-based to recognize the safest route, Distance Vector Hop (DV-Hop) localization to determine evacuee's location, and Dijkstra to produce the shortest route. The developed SSE is simulated for protecting the persons inside NPP buildings through three stages. Validation of the developed SSE algorithm is realised through simulation fire scenario inside a standard Main Control Room (MCR) in a Nuclear Power Plant as realistic fire scenario using the Consolidated Model of Fire Growth and Smoke Transport (CFAST) as fire zone model. CFAST produces output fire data that used by SSE to create the exit map for safest and shortest route for evacuees. The Results of the simulation represent that the developed algorithm can produce the safest and shortest evacuation route within minimum evacuation time in form of a clear tree graph.

Keywords: Emergency Fire Evacuation, a Standard Main Control Room, Safest and Shortest Route, NPP Fire Evacuation, DV-Hop Localization Technique, CFAST Model, Dijkstra Algorithm

1. Introduction

Fire accidents are very deadly in NPP since the safety principles must be achieved. Fire evacuation is very important for NPP, so the main goal of this research is identifying the suitable Safest Shortest exit route in the fire emergency evacuation, by developing a Fire Evacuation algorithm that can be load and run in any evacuee's watch to produce safest and shortest route form his/her location in minimum time to reduce the evacuation time.

The core of fire safety is protecting Spirits and Property from Hazards. Fire safety in nuclear power plant NPP aims to existence a high level of safety, investigates achievement reasonably protection for persons and the environment. To reach a safe State fire must not affect systems and operators that their functions are required for operating and protecting the plant [1]. Identifying the suitable shortest and safest routes in NPP during fire emergency evacuation is very important. Evacuation management for nuclear power fire accident involves manifold processes and factors that must be taken in concern through evaluation criteria. Determining Safest routes and shortest routes in clear forms and in smallest time during fire accidents must be considered as the most important evaluation criteria [2].

Fire evacuation models are suited as a portion of performance-based analyses to assess the level of life safety. Fire evacuation computer models realize a more pragmatic evacuation estimation to assess evacuee's life safety and diminish the predicted evacuation time [3]. Emergency fire evacuation models categories: simulation models, dynamic programming models, and approximation, and heuristic technique. The computational model [4] uses prediction data on smoke propagation inside a structure obtained from Fire Dynamics Simulator to identify evacuation fastest escape route by A* algorithm [5]. The evacuation model simulates the proper shortest and safest route [6] and dynamic road network model by implementing the Dijkstra Algorithm [7]. Most of the previous works in Emergency fire evacuation are obtaining the optimal route of buildings or public places and minimizing the total predicted evacuation time only.

In this paper, a new hybrid Safest Shortest Exit algorithm is developed for protecting evacuees through combination of three techniques that are applied into three stages. In the first stage, a rules-based technique is applied through IF-Else algorithm to find the safest route in suitable method [8]. In the second stage, the DV-Hop localization technique establishes the evacuee's location since, it is the most appropriate than other techniques through counting the average hop in minimum time [9]. In the third stage, the shortest route is determined depending on the Dijkstra technique which is a graph search algorithm that solves the single-source shortest path problem in a smallest time and in clear form (tree) [10]. The devloped SSE is validated using CFAST [11] as fire zone model to simulate fire ignition scenario in a Main Control Room (MCR) in NPP. In the fire simulation process, CFAST produces fire products data used by the developed algorithm (SSE) to estimate the safest shortest route for operators, workers, and public evacuees. The SSE can be used for any other high-risk building just by change the input geometry data.

Fire safety in NPPs required more essential to evacuate evacuees from fire danger locations to safe places in smallest time especially, for evacuees who are unfamiliar with the NPPs buildings since they need to follow the guide and escape safely to overcome the evacuee problem through finding the safest and shortest routes in a clear form. Therefore, in this research, the mean goal is producing an independent evacuation preparedness algorithm for exit route SSE in a clear form to guide evacuees to discharge from the NPP building safely.

2. The Developed Safest Shortest Exit Algorithm

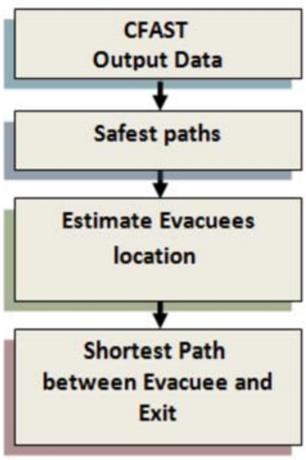


Figure 1. *The simulation of developed Safest Shortest Exit algorithm (SSE) block diagram.*

The Safest Shortest Exit Algorithm (SSE) is developed to determine the safest shortest suitable exit route for each evacuee which can be implemented in evacuee’s watch. For validation SSE, fire simulation is performed to imitate emergency fire evacuation state in NPP. A fire scenario inside a standard Main Control Room (MCR) in NPP is ignited and simulated using CFAST fire zone modeling to produce fire products which are generated during any fire accidents such as HCL, CO, CO_2 and so. After that, SSE runs to identify the Safest Shortest Exit route for the evacuees (as the operators, workers, or Public) through determining the safest paths, evacuees’ location and the Shortest Exit route. The simulation of Safest Shortest Exit algorithm block diagram is shown in Figure 1.

2.1. CFAST Fire Simulation

CFAST as a fire simulation zone model is applied to simulate a fire scenario inside the MCR in cabinet as shown in Figure 2. The fire modeling CFAST separates the MCR into two zones, commonly referred to as the upper and lower layers. These layers are based on the physics, and dynamics of fire ignition inside of an enclosure, which includes the fire plume, combustion products, and air entrainment [12]. The time for fire detection from fire ignition in the CFAST model is about 44 sec [13]. The temperature and gaseous products from fire events have the main effect in the emergency evacuation [14]. The fire products especially toxic& hazard fire gases imitation from fire sensors are simulated using the CFAST model in Excel format.

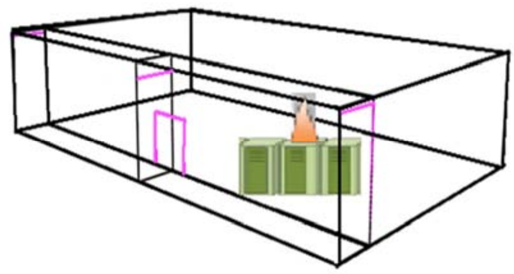


Figure 2. *Fire ignition in MCR.*

2.1.1. Fire Ignition Scenario in the Standard MCR

The CFAST simulation fire ignites in a cabinet in the MCR, which contains control cables [15]. The door of the standard MCR is open and ventilation conditions are the place condition at the fire started. The ambient parameters of the simulation are temperature (20°C) and presser (101300 Pa), fire ignition parameter fire grows according to the t-squared curve with a maximum value of (702 kW) and source of fire with a heat of combustion (10,300 kJ / kg) [16] during simulation time 2000s. In the fire scenario, the fire grows to arrive at three other cabinets. Fire is described as a source of heat placed at a specific point, within cabinets inside standard MCR that generates combustion products according to specified combustion chemistry.

2.1.2. Fire complete Scenario in the Standard MCR

The fire simulation scenario used the previous fire input parameters of MCR, such as temperature, pressure, water vapor to estimate the results of the fire scenario from different fire gasses emissions such as smoke CO_2, CO, HCL and determines the percentage of O_2 and toxic species in both of two layers [17, 18]. The HRR curve is shown in Figure 3. Based on a physical assessment of the cabinet, it is determined that the exterior panels of the burning cabinets do not open before or during the fire [19]. The smoke, heat, and flames are exhausted from an air vent in the side of the cabinet. The top of the air vent is 0.3 m below the top of the cabinet. The air vent is 0.6 m wide and 0.2 m high. The cabinet is 2.4 m tall. The jacket and insulation material of the cables are taken as an equal-parts mixture of polyethylene (C_2H_4) and neoprene (C_4H_5Cl), with an effective chemical formula $C_3H_{4.5}C_{l0.5}$. The heat of combustion and product yields for XPE/neoprene cable are shown in Table 1. The t-squared fire grows as the formula of time squared as flowing:

$$\dot{Q}(t) = \dot{Q}_{peak}(t)\left(\frac{t}{t_{peak}}\right)^2 \quad (1)$$

Where: $\dot{Q}(t)$ is the Q point of fire with time, $\dot{Q}_{peak}(t)$ is the Q point at fire peak, t is the simulation time and t_{peak} is the time at fire peak.

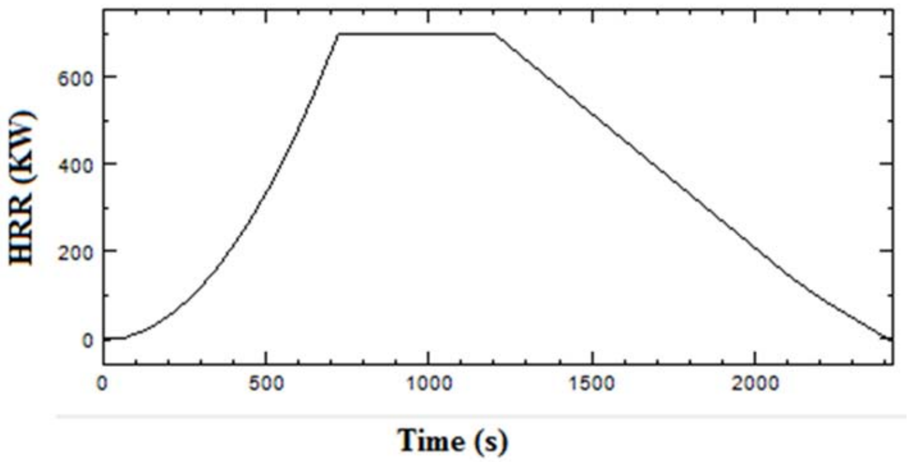


Figure 3. *Fire Heat Release Rate in the standard MCR.*

2.2. Defining the Safest Rout Using Rule-based Technique

In the first stage of SSE, the safest route is defined by using the import fire products data matrix of the CFAST fire model to avoid more danger routes that have hazard gases, high toxic fire radiated or high temperatures. In this stage, the rule-based algorithm [20] is used to generate the safest routes. The Rules typically take the form of an {IF: THEN} expression. Therefore Rule-based technique in SSE typically comprise a set of rules that dependent on the CFAST collectively through the calculation output model to release the safest routs. The Rule-base flowchart is shown in figure 4.

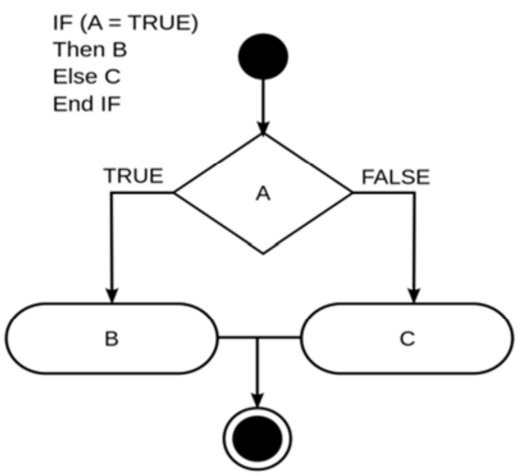


Figure 4. *The Rule-base flow chart.*

2.3. Estimating the Evacuee's Location Using the DV-Hop Technique

Distance Vector Hop (DV-Hop) localization algorithm is widely used in localization techniques, and that uses the routing exchange protocol to help evacuees obtain beacon node information which is used during locations calculations [21]. During emergency fire evacuations, the evacuee's location must be determined to estimate the safest and shortest route for evacuating from the building that depended on the evacuee site.

In the second stage of the developed SEE, the evacuee's location is estimated to involve and import the localization matrix of data based on the DV-Hop technique. The DV-Hop is simulated through considered the evacuees are nodes randomly distributed as shown in Figure 5. The evacuation region is simulated in the NPP building through assumed to be a square area with a fixed size of 100 x 100 m^2, the radio range (R) is set to 50 meters contains fifty nodes as evacuees, that are randomly deployed with 5 anchors nodes. The mean square localization error is chosen to evaluate the performance of localization in the developed algorithm. The error calculated by:

$$error = \sum_{n=1}^{N} \frac{\sqrt{(X_n - X'_n)^2 - (Y_n - Y'_n)^2}}{N \times range} \quad (7)$$

Where: (X_n, Y_n) are the estimated coordinates of unknown evacuee's node N, (X'_n, Y'_n) are the actual coordinates, the range is the communicate radius of the network and N is the total number of the nodes inside the range.

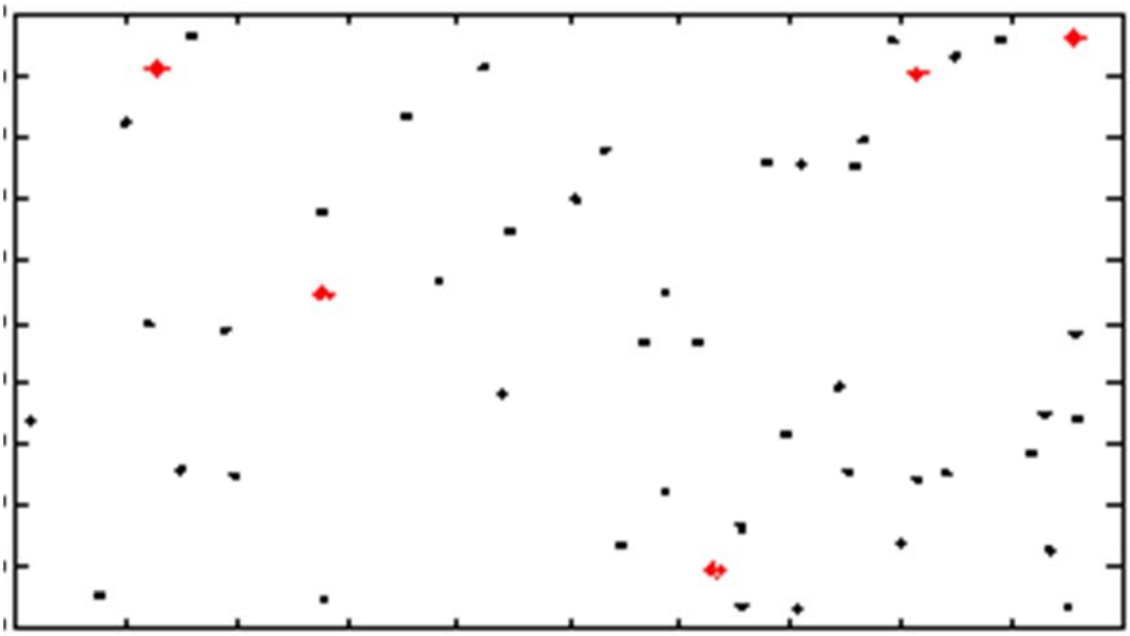


Figure 5. *Random arrange of evacuees.*

2.4. Estmaiting Shortest Route Using Dijkstra Technique

The Dijkstra's shortest route technique [22] is implemented in the third stage of the developed SSE algorithm that can be propagated in the evacuee's watch to determine the safest and shortest route, according to his//her location, during evacuated from the building through finding the shortest routes between nodes in a output graph. Dijkstra technique has been chosen not only for its effectiveness in producing the shortest route for selection of route but also, it provides an evacuation plan for the evacuee that can be represented as the shortest route tree in his/her watch.

In this technique, the source node is acting as a single fixed node and finds the shortest routes from the source to all other nodes in the graph producing the shortest route tree depend on the min-priority queue [23]. In addition, the Shortest path algorithm characterizes each evacuee node by its state and the state of each evacuee node consists of two features distance value and status label. The distance value is a scalar representing an estimate of distance from the node to the evacuee's node. The status label is an attribute specifying whether the distance value of a node is equal to the shortest distance to the evacuee node or not. The status label of a node is Permanent if its distance value is equal to the shortest distance from the evacuee node Otherwise; the status label of a node is Temporary. The algorithm maintains and step-by-step update the states of the nodes at each step one node is designated as current [22].

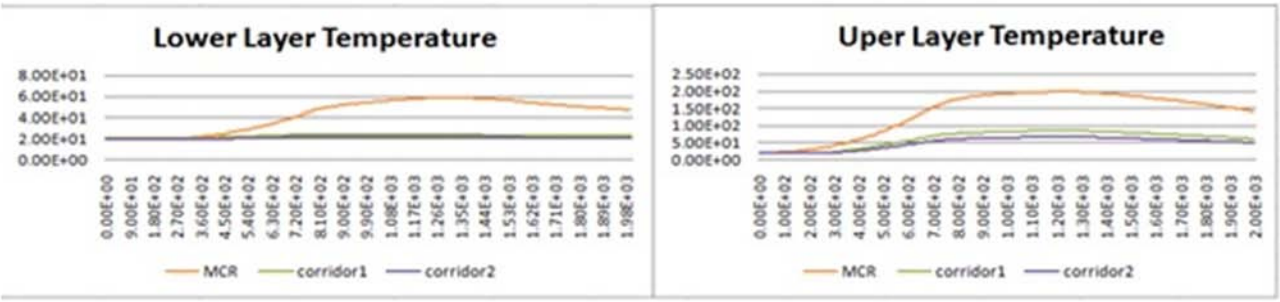
3. The Results and Discussion

Results consist of two parts. In the first part, the fire scenario output data from CFAST model are represented through the concentration of hazard fire gasses emissions such as CO2, CO, HCL, and toxic. In the second part, the results of the developed Safest Shortest Exit algorithm (SSE) used three stages a rules-based to recognize the safest route, the DV-Hop technique determining the evacuee's location, and the Dijkstra technique to produce the shortest route tree.

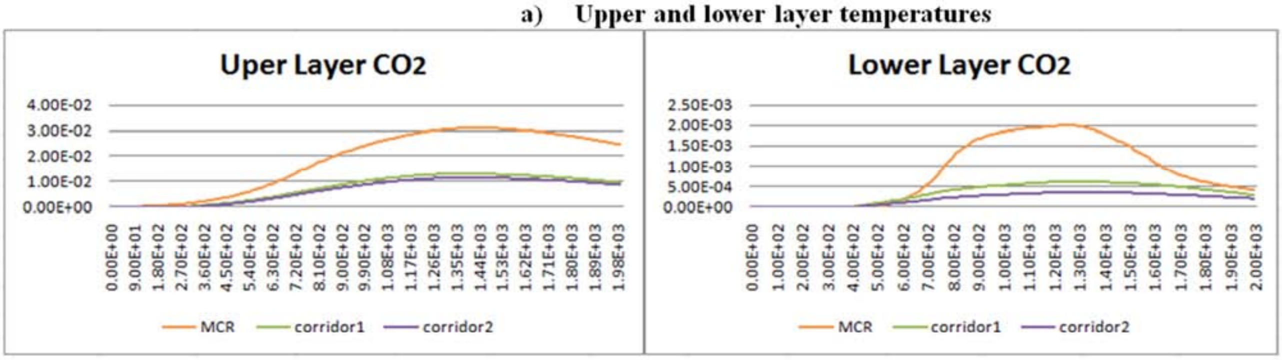
3.1. The of CFAST Simulation

Heat and toxic gases produced by combustion have fire hazard effects since the exposure for a certain time to certain quantities of toxic gases can cause death, thus it is very important to measure the temperature and amount of output fire toxic gases to safe the evacuation process. The resulting from CFAST Simulation are temperatures and gases that produced due to the simulation fire in the cabinet, are graphically represented in Figure 6.

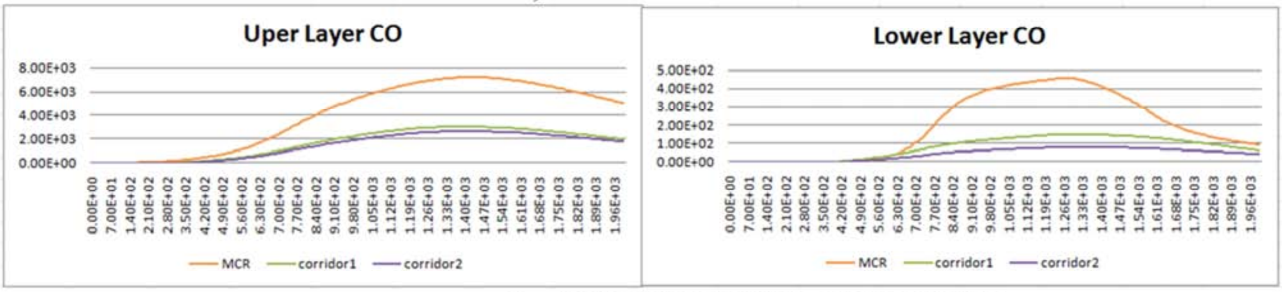
The temperature of fire effects on the human body due to heat transfer from the high-temperature fire, thus it must be relatively low temperature [24] therefore, measuring the temperature during the fire very important. Figure 6a temperatures of the standard main control room (MCR) and two corridors depends on the flux flow response. The product gases are emitted due to burning internal cables and components of the cabinet are shown in figure 6 (b-e). Figure 6b Concentration of carbon dioxides CO_2 in mol fraction at both upper and lower layers. Figure 6c Concentration of carbon monoxide CO in mol fraction. Figure 6d Concentration of hydrogen chloride HCL causes significant fire hazards in part per million (ppm). Figure 6e Concentration of toxic species fire releases in g min/m^3. The product gases carbon dioxide CO_2, carbon monoxide CO and hydrogen chloride HCL as shown in graphs look similar but they have different values. The output result data of CFAST saved in an Excel sheet that used in the next part to determine the safest and shortest route.



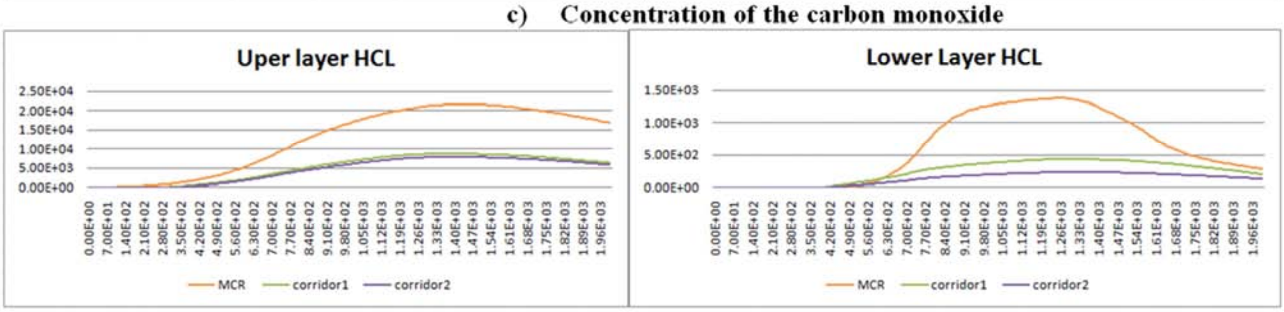
a) Upper and lower layer temperatures



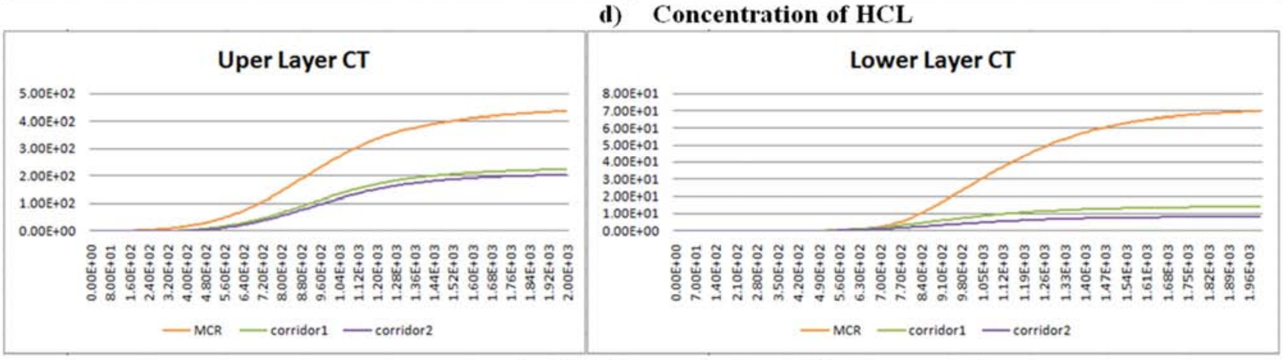
b) Concentration of the carbon dioxide



c) Concentration of the carbon monoxide



d) Concentration of HCL



e) The Concentration of the toxic species

Figure 6. *(a-e) The results of CFAST Simulation in the MCR & two corroders.*

3.2. The Results of the Second Part

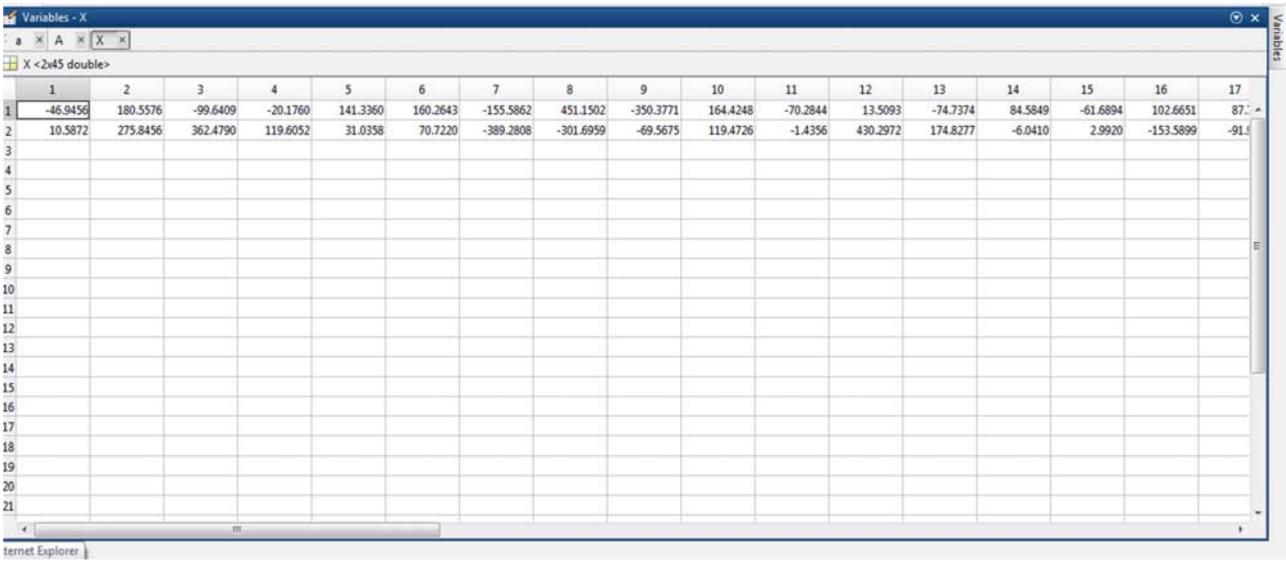
In this part, the results of the developed Safest Shortest Evacuation algorithm (SSE) are represented which determine the safest shortest suitable exit route for each evacuee. SSE algorithm is implemented for determining the Shortest and Safest Exit route per his/her evacuees' location. The results of the SSE are divided into three results stages. In the first stage, the safest routes are detected using a rule-based technique. In the second stage, the location of evacuee's determination is based on the Wireless Localization DV-Hop technique. In the third stage, the shortest route is based on the Dijkstra technique.

3.2.1. The Results of the First Stage

In this stage, the safest route is determined for evacuee by using the Rule-Based technique, to assist in generating the Safest Route utilizing the CFAST Output Data. The CFAST output data imports in the Excel sheet format simulated the concentration of output fire gasses emissions like CO2, CO, HCL, and toxic species and temperatures. The safest route used CFAST output data to remove the danger routes that contain more toxic and hazardous gases such as CO & HCL or have high temperatures in a visibility graph of safest routes.

3.2.2. The Results of the of Second Stage

In this stage, the result from determining the evacuee's location using DV-Hop localization technique for evacuating from the NPP building according to the evacuee's site are represented. The evacuee's node location coordinate is determined in Excel sheet as shown in Figure 7. The Mean square error for each evacuee node is small and it isn't exceeding 12% as shown in Figure 8.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	-46.9456	180.5576	-99.6409	-20.1760	141.3360	160.2643	-155.5862	451.1502	-350.3771	164.4248	-70.2844	13.5093	-74.7374	84.5849	-61.6894	102.6651	87.
2	10.5872	275.8456	362.4790	119.6052	31.0358	70.7220	-389.2808	-301.6959	-69.5675	119.4726	-1.4356	430.2972	174.8277	-6.0410	2.9920	-153.5899	-91.

Figure 7. *Evacuees' node location coordinates.*

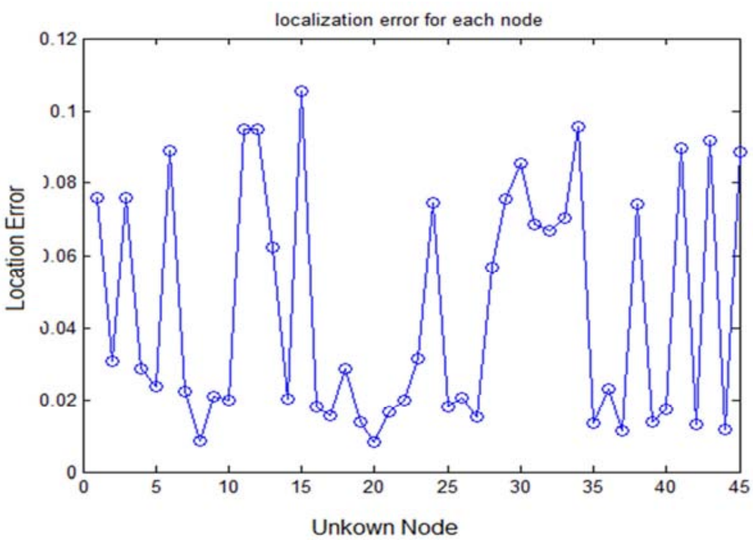


Figure 8. *Mean square errors for each evacuee node localization.*

3.2.3. The Results of the Third Stage

Finally, results of the shortest route are generated between the evacuee location node and Exit based on the Dijkstra technique. The final Safest and Shortest Route generates in this stage, and displays in the visibility graph as a tree is shown in Figure 9 where, the two colors of the node to distinguish between the Safest and Shortest Route (suggested to take) and the dangers routs (untack). The red nodes are a taken route and the otherwise is an untaken route.

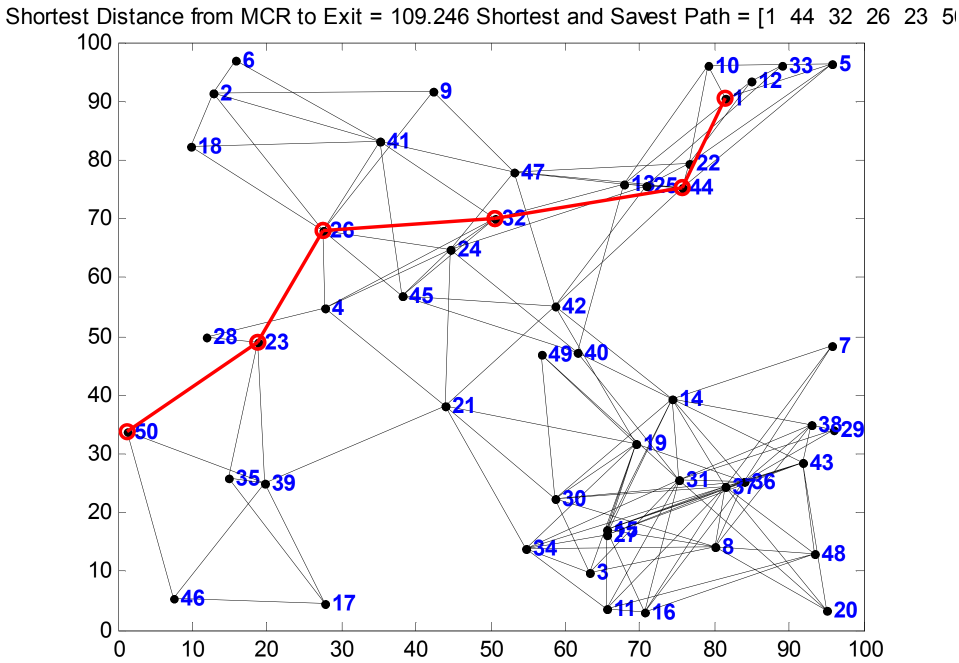


Figure 9. *The plan of the Safest and Shortest Route.*

The developed SSE plots the matrix data in a Visibility graph. The Visibility graph represents the route as it can be understood by displaying the relationship of nodes and edges. The relationship is connected way based on the weight from the matrix data. The distance calculation of the shortest route has been carried out between MCR and Exit node. The developed SSE as evacuation algorithm has a unique color to provide the evacuees with the safest shortest evacuation rout for Exit from NPP building. The result of the safest and shortest route calculated in the SSE algorithm embedded the Dijkstra Algorithm as shown in table 1.

Table 1. *Safest Shortest Route.*

Source ID	1
Destination ID	50
Distance	109.246
Path	1 44 32 26 23 50

3.3. Evaluation of the Developed SSE

Evaluation of the developed SSE is realized by calculating the Required Safe Escape Time (RSET), that consists of CPU time takes by the CFAST model to simulate and generate fire data, and the time taken by SSE algorithm to estimate the safest and shortest route. The Required Safe Escape Time (RSET) result is in the above simulation is 50.98 sec about one minute, which is very small to produce the safest and shortest route in a clear tree.

4. Conclusion

The fire safety principles in Nuclear power plants (NPPs) must be accomplished so, fire accidents must be avoided or minimized the exposer to fire products if they happen. Consequently, fire evacuation in less time is essentially required in NPPs. The main goal of this research is minimizing the fire emergency evacuation time by developing Safest Shortest Exit route (SSE) algorithm. The developed SSE is a Fire Evacuation algorithm that can be propagated in the evacuee's watch to produce a tree graph of safest and shortest route from his/her location in less predicted evacuation time. In this research, fire scenario in MCR inside NPP is simulated to validate the developed algorithm SSE. In SSE, the fire products produced from simulated fire ignition in standard MCR, that is imitated by a fire zone model CFAST and the developed SSE is executed to determine the safest shortest exit evacuation route for operators, workers, and visitors in NPPs.

The developed SSE consists of three stages, in the first stage, CFAST output data used to remove the danger route for producing the safest route using a rule-based technique. The CFAST outputs data are formed in Excel sheets to represent, the concentration of fire gasses emissions as CO_2, CO, HCL, toxic species and upper and lower room temperatures. In the second stage, the evacuation location is estimated based on DV-Hop localization technique. In the third stage, the input evacuee's location node and Exit node is used to determine the shortest route for evacuee to exit from the NPP building using Dijkstra Technique. The total distance is calculated based on the route from the location of the evacuee to exit then, the Safest Shortest Route is generated. The escape time takes by the developed SSE to estimate the safest and shortest route as a tree is a very small time. The developed SSE can be used for emergency fire evacuation in any high-risk buildings.

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