Probabilistic Framework for Onboard Fire Safety

Societal Consequence Model (D2.3)

Ana Henriques, Cláudia Dias, Eduardo Dias Lopes

- document author -

ISQ

- organisation name -

Angus Grandison

- document approved by -

4.0

- revision number -

31 January 2011

- submission date -

PU

- distribution level -

Document history

Revision number	Date	Remarks
1.0	21/06/2010	Skeleton document
2.0	06/12/2010	First Draft
3.0	13/01/2011	Final Draft
4.0	31/01/2011	Final version of the document

Executive summary

Evacuations onboard ships do occur and they are usually the result of fire, large scale flooding (following a collision or grounding event), equipment failure or human error. In the wake of these prominent maritime disasters and also the scientific and technological advances of the past 30 years as the growth in the numbers of high density, high speed ferries and large capacity cruise ships; there is a growing interest in the marine industry on evacuation of passengers and crew at sea.

In fact, mainly motivated by those maritime disasters marine regulations have been changing recognising that an improvement in ship design and procedures is essential and necessary. However, modifications to ship configuration such as hull form, length, beam, size and location of internal compartments will have a direct impact on ship performance, namely in terms of powering, stability, seakeeping and strength. In terms of human safety, those modifications on ship internal layout or its operating procedures (e.g. changing the location, size and/or configuration of cabins, public facilities, corridor systems, stairs, assembly locations, public spaces) could also have implications on crew and passengers, namely in its ability to have a safe evacuation under emergency conditions.

In order to enforce fire safety onboard ships, regulatory bodies are responsible by formulating rules for design, construction and operations. However, those fire safety regulations have been accused of being inadequate in two ways: (i) they can be too static imposing constraints on novel designs, and (ii) novel designs can have features that do not satisfy the premise of existing rules, making approval more difficult and potentially leading to unsafe ships.

Since, this current framework for fire safety lacks on the holistic and rational approach to the assessment of fire safety, FIREPROOF project aim is to formulate a universally regulatory framework specified for marine vessels fire safety. Its general methodology will consist of generating a large number of scenarios for any given ship (traditional or novel), compute its consequences using probabilistic models, and finally aggregate the results to give rise to fire risk metrics.

This particular document, inserted into the consequence assessment, aims demonstrate the concept associated with societal consequence model and not produce a final software product. For that, two evacuation models document are analysed: **Evi** (Ship Stability Research Centre - University of Strathclyde) and **maritimeEXODUS** (Fire Safety Engineering Group - University of Greenwich), theirs methodologies and others aspects such as population and behaviour representation, and the capability to represent environmental conditions of a fire scenario (e.g. fire and smoke) are also compared.

The discussion will highlight the benefits of each evacuation model.

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1 Introduction

Over the past years, the world has witnessed fires in enclosed environments which have caused direct and indirect losses. In a maritime scene where the modern cruise ships have the capacity for carrying several thousands of people on board, fire accidents involving such large passenger ships can happen despite its remote possibility and lead to catastrophic consequences.

Therefore, in an attempt to avoid and/or reduce human fatalities, many efforts have been made to assure the occupants' safety onboard ships. IMO (International Maritime Organization) has considered societal consequences on its regulations, namely regulation II-2/28-3 and regulation II-2/13.7.4 of the Annex to the International Conference for the Safety of Life at Sea, 1974 (SOLAS, Consolidate Edition, 2004):

"*For ro-ro ships constructed on or after 1 July 1999 escape routes shall be evaluated by an evacuation analysis early in the design process. The analysis shall be used to identify (...) congestion which may develop (...) due to normal movement of passengers and crew along escape routes, including the possibility that crew may need to move (...) in a direction opposite the movement of passengers. In addition, the analysis shall be used to demonstrate that escape arrangements are sufficiently flexible to provide for the possibility that certain escape routes, assembly stations, embarkation stations or survival craft may not be available as a result of a casualty*".

Mainly motivated by IMO requirements, some efforts have been made in order to develop advanced ship evacuation simulation softwares and understand human and social behaviours of people in emergency situations. In fact, this understanding aims to lead fire engineers to input those behaviours in their models, which will result in more realistic models and outputs; and consequently an improvement on the egress strategies for fire safety.

The development of sophisticated evacuation models has allowed the attribution of fire safety issues within complex structures where the prescriptive codes, generally, do not provide clear guidance (Tavares, 2009). However, although all those attention paid in the past few years to the development of advanced evacuation models for more accurate analyses of evacuation onboard passenger ships (Lee *et al.*, 2003); less efforts have been made to include these models in a holistic framework for risk assessment. Highly motivated by this default, the FIREPROOF project aim is to formulate a regulatory framework for fire safety of marine vessels using probabilistic models.

As part of the FIREPROOF project, this particular work aims the societal consequence models within the evacuation models, i.e., estimation of the number of fatalities and injuries. Over the years, a variety of different modelling methodologies have been developed and adopted to model societal consequences for fire scenarios. However, in this particular work, this document will examine two evacuation models: **maritimeEXODUS** (Fire Safety Engineering Group - University of Greenwich) and **Evi** (Ship Stability Research Centre - University of Strathclyde), compare their methodologies and others aspects such as population and behaviour representation, capability to represent environmental conditions of a fire scenario (e.g. fire and smoke). The analysis will be made upon the commercial versions of both software tools.

2 Methodology

In the last few years, evacuation models have been largely developed and became a popular area of research within the Fire Safety Engineering community. In fact, there are today over 40 different evacuation models, which are used in different types of enclosed environments, such as: buildings, aircraft, ships and trains (Tavares, 2009). With significant differences from the old conventional hand calculations, evacuation models take into account interactions between occupants (i.e. congestion, response times, decision making, etc), and that is why they became a useful tool for the understanding of evacuation processes. Another advantageous aspect of most evacuation models is their outputs options, which allows to graphically present the information with little "avatars" moving around the space that resembles considerably the real environment. The proper use of evacuations models in a design stage allows designers, engineers and safety managers to have advance knowledge of possible problems/inconveniences (as congestion and/or confusion in an emergency event on the escape routes) and then, by using all measures at their disposal, create a safer ship.

Although the reasonable number of methods and theories developed in the building field can be directly applied to the marine sector, the evacuation models in the marine field have specific considerations that needs to be considered, like the motions and tilt of the ship in addition to a complicated mustering procedure according to the assembly points and nature of the emergency onboard. Consequently, this document is only concerned with evacuation models dedicated to the ship environment.

2.1 The classification of evacuation models

There are currently over nine evacuations models specially developed for ship scenarios. Each one of those has its own purpose, philosophy and ability. Over the past years, different evacuation model reviews have been made according to different approaches.

According to Gwynne and Galea approach (in Lee *et al.*, 2003), evacuation models can be categorized into four categories:

- **The nature of the model applications**, which refers to optimization, simulation and risk assessment;

- **Enclosure representation**: the evacuation models can use a fine or coarse network to represent their geometry. In a fine network approach, the entire floor space of an enclosure is represented in detail usually by a collection of nodes and tiles. On the other hand, in a coarse approach, only the topologies of significant structures are represented (e.g. corridors and rooms);

- **Population perspectives**: the enclosure population can be represented in either two ways: individual or global. The individual perspective allows assigning individually or randomly personal attributes whereas in the global perspective the population is represented as a homogeneous group;

- **Behavioural perspectives** represent the decision-making process of evacuees. There are five decision-making systems:
    - No behaviour system,
    - Functional analogy behaviour system,
    - Implicit behaviour system,
    - Rule-based behavioural system, and
    - Behavioural system based on artificial intelligence.

However, there is another approach which divides evacuation models into three types according to the scale of pedestrian traffic modelling: microscopic, macroscopic, and mesoscopic model (Helbing, Farkas and Vicsek; Klupfel *et al;* Vassalos *et al* in Lee *et al.*, 2003):

- On **microscopic models**, the behaviour of each individual is modelled individually. Although this approach requires more computing power than the other two models, it allows introducing different types of pedestrians with individual properties;
- **Macroscopic models** are based on the similarity of pedestrian flows with liquids or gases. In fact, the basis of macroscopic models is the continuity equation, which must be supplemented by data about the relation of density and flow. This type of model, which is the flow model advocated by the IMO Interim Guidelines, can be used for accommodation layout design purposes;
- **Mesoscopic models** combine the properties of both microscopic and macroscopic simulation models. The adoption of this kind of model may bridge the gap between the microscopic scale and the macroscopic scale.

2.2 Evacuation models for the maritime environment

2.2.1 Evi (Evacuability Index)

The passenger evacuation simulation model code-named **Evi** (**Ev**acuability **I**ndex) is a real-time interactive model developed by the SSRC (Ship Stability Research Centre at the University of Strathclyde) in collaboration with Deltamarin Ltd, RCI and Color Line. Specifically developed for maritime applications, Evi is capable of modelling large RoPax and cruise liners (Vassalos *et al.*, 2001a).

"*It [Evi] represents the state-of-art computer simulation-based capability for the prediction of passenger mustering and evacuation involving a number of escape and rescue scenarios (abandon ship, transfer to refuge centres or a combination of these) in a range of accidents (fire, collision, progressive flooding, cargo shift, foundering) whilst accounting realistically for ships motions in a sea environment*" (Vassalos *et al.*, 2001a).

As a result of shipboard experiments coupled with valuable input and feedback from owners/operator, Evi becomes a practical tool for ship designers, operators and regulators. In fact, Evi is currently used for evacuation analysis of existing and new designs of cruise liners and passenger/Ro-Ro vessels (e.g., RCI, Color Line, and Brittany Ferries) and is being systematically assessed by shipyards (e.g., Euroyards) and classification societies (e.g., Registro Italiano Navale) for use in ship design and certification (in http://www.safety-at-sea.co.uk/evi/features.htm).

Evi model is available in the computer software form that can be customised to any vessel environment. It uses routinely a virtual environment for enhanced effectiveness of evacuation performance evaluation through visualization. These visualizations can vary from very simple 3D virtual environment, to a detailed replication of the actual ship environment, allowing also the progress of the evacuation to be reviewed.

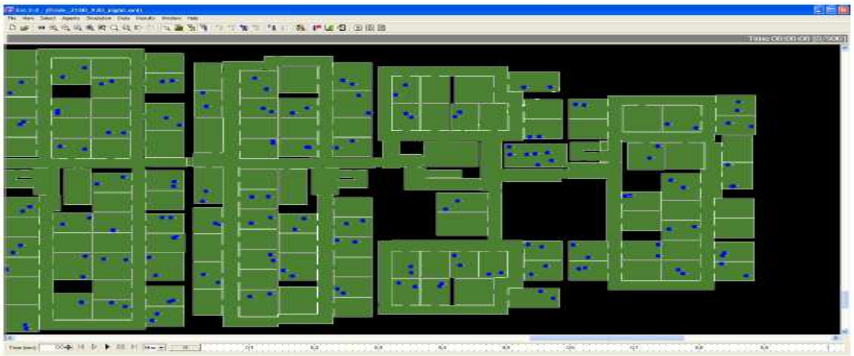

Figure 1 – Interactive 2D animated graphics on Evi (Evi – Modelling Crew Functionality and Objectives)

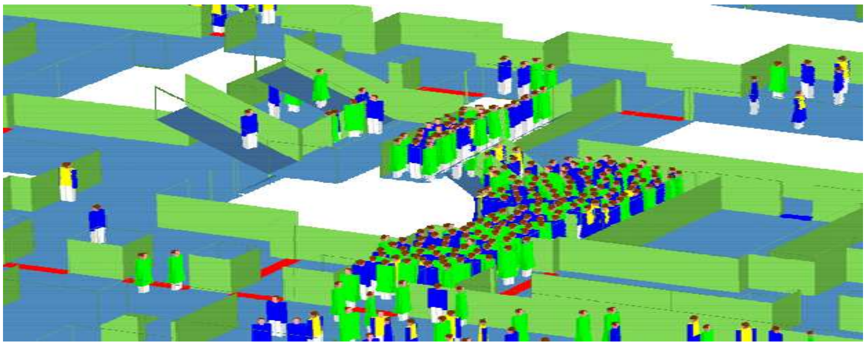

Figure 2 –Example of a detailed 3D replication of the actual ship environment on Evi software (Vassalos *et al.*, 2004)

The Evi model represents the geometry using a continuous co-ordinate approach within each coarse node defined as region. This geometry modelling uses the general arrangement (GA) of the ship which is imported into Evi through EvE (Evacuation Editor). All the ship geometric information (e.g. space categories, connections, gates, stairways) is imported in DXF format into Eve. The ship is then modelled by "drawing" the different spaces using the GA as a guide. The model is then imported into Evi in a XML format. In fact, this model is capable of representing multi-deck vessels, which can be viewed in what is referred as "2 ½ D", whereby the user is able to orientate around the structure.

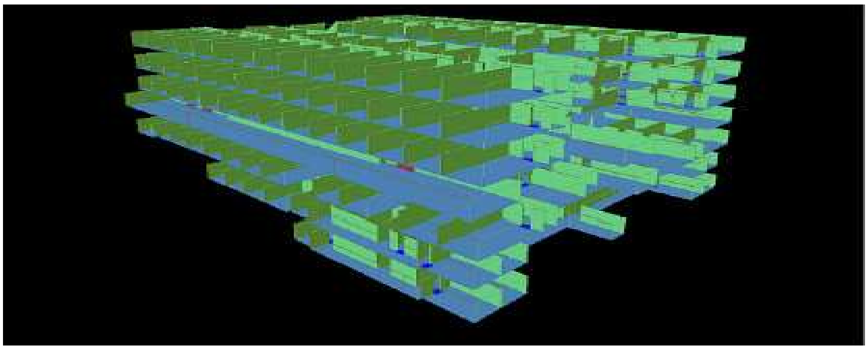

Figure 3 – 2 ½ D visualization of a ship on Evi (Evi – User Manual)

In a perspective of pedestrian traffic modelling, Evi is a multi-agent mesoscopic model, i.e. it combines macroscopic and microscopic modelling in order to provide an intelligent multi-level planning capability. It also combines personal attributes for each agent, such as: gender, age, mobility, which means that Evi incorporates an individual perspective in the population modelling. In terms of the behavioural perspective, Evi is able to use various behavioural systems on each agent, such as predefined, programmed behaviour, autonomous, rule based behaviour, guided, interactive control behaviour, and artificial intelligence style, adaptive control behaviour, which in this case has been described as mainly rule based.

It is also possible to incorporate a number of scenarios into Evi, such as passenger mustering, evacuation scenarios involving escape from emergencies (as a fire scenario) and non emergency cases. However, to simulate the evacuation process under a fire scenario it is necessary to import and distribute in time and space fire hazard data (normally imported from both zone and field fire models) into Evi software. During all simulations, Evi software has the possibility to identify potential bottlenecks, which can improve design layouts.

"*The model [Evi] includes the default IMO population.(…) Evi has successfully completed the IMO Day and Night benchmark cases, as well as the qualitative and functional validation and verification. Evi is therefore IMO compliant [IMO MSC Circular 1033, June 2002]*" (Sharp *et al.*, 2003).

Nature of original application	Maritime	x	Built Env.			
Applied to maritime cases	Yes	x	No			
Type of model	Sim.	x	Optimisation		Risk Assess.	
Geometry representation	Coarse	x	Fine		Mixed	
Behaviour Representation	Rule-based					
Population	Individually	x	Globally			
IMO populations	Present	x	Absent			
IMO test cases	Complete	x	Incomplete			
IMO benchmark	Complete	x	Incomplete			
Ability to produce data required for IMO analysis	Able	x	Unable			

Table 1 – Evi main characteristics (Sharp *et al.*, 2003)

2.2.2 MaritimeEXODUS

The Fire Safety Engineering Group (FSEG) of the University of Greenwich has developed a suite of software tools called EXODUS® specially design to simulate evacuation behaviours and pedestrian dynamics of large numbers of people within large complex structures. As a part of this suite, maritimeEXODUS is ship version of EXODUS software.

In fact, maritimeEXODUS shares many of the same principles and assumptions of the other EXODUS models (e.g. *people-people*, *people-fire* and *people-structure* interactions); however it was specially design to simulate the egress action in the maritime environment taking into consideration specific aspects of it (e.g. dynamic motion, heel and trim impact). Just like any EXODUS model, maritimeEXODUS tracks the path of each individual (individual perspective) as they make their way to the muster location, or are overcome by fire hazards during their path. In a fire scenario, this model simulates fire conditions impact upon occupants, also estimates the number of serious or minor injuries due to a fire, and whether these are caused by heat/toxic gases.

As an output, this maritime model produces interactive two-dimensional graphics, which allows the user to observe the evacuation as it takes place, allowing the user to interrogate occupants and events as they occur.

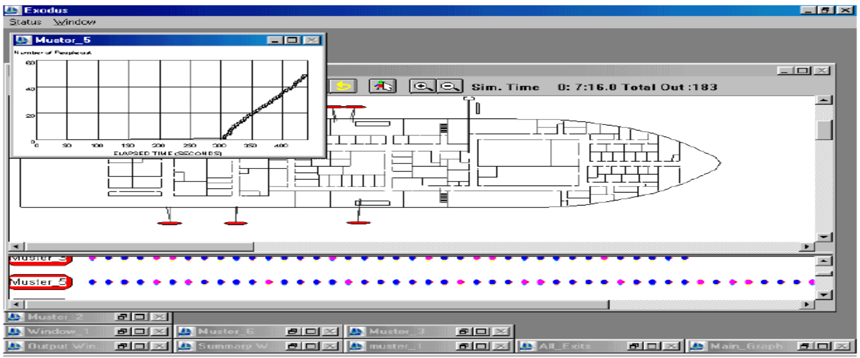

Figure 4 – Interactive two-dimensional animated graphics (Glen and Galea, 2001)

However, it has also developed a post-processor virtual-reality graphics environment know as vrEXODUS which allows creating an animated three-dimensional representations of the evacuation process.

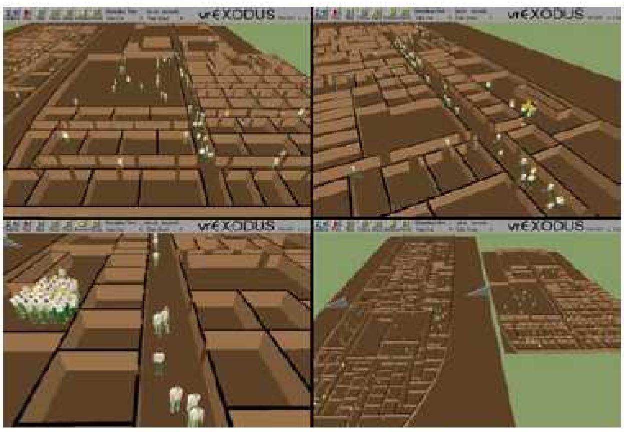

Figure 5 – vrEXODUS representation of maritimeEXODUS (Glen and Galea, 2001)

The ship layout can be specified using either a DXF file produced by CAD package, or the interactive tools provided and may even be stored in a vessel library for later use. Internally, the entire space of the geometry is covered in a mesh of nodes that are typically spaced at 0.5 m intervals. The nodes are then linked by a system of arcs. Each node represents a region of space typically occupied by a single passenger. Passengers can travel from node to node along the arcs.

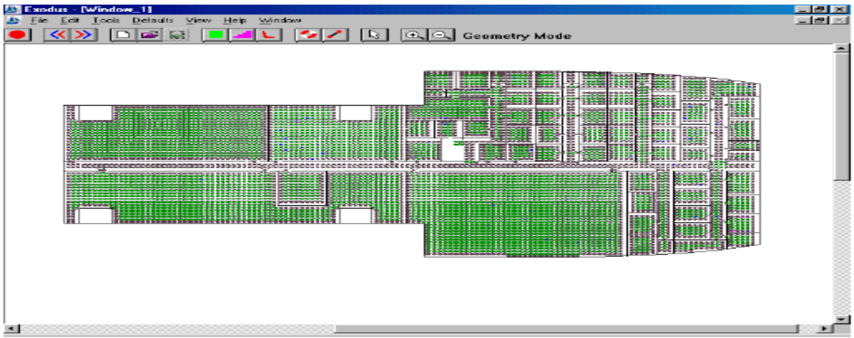

Figure 6 – Meshing of a deck plan (Glen and Galea, 2001)

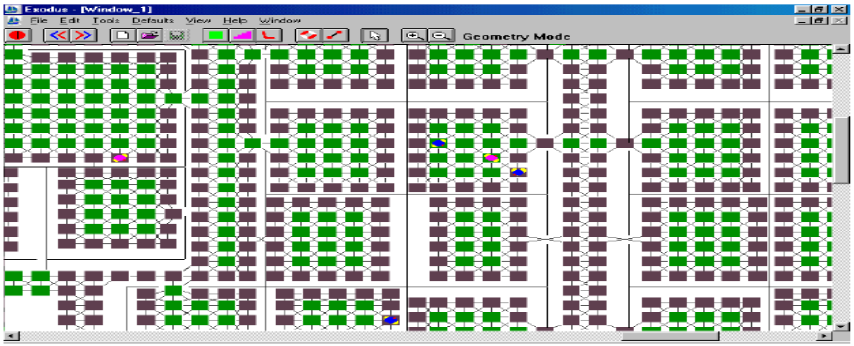

Figure 7 – Details of Arc-Node Mesh (Glen and Galea, 2001)

MaritimeEXODUS is rule-based and the progressive motion and behaviour of each individual are determined by a set of heuristics or rules (Sharp and Galea, 2003). Many of these rules are stochastic which results in slightly different outputs from the same scenario. In order to address additional flexibility these rules have been categorised into six interacting sub-models: the passenger, movement, behaviour, geometry, toxicity and hazard sub-models.

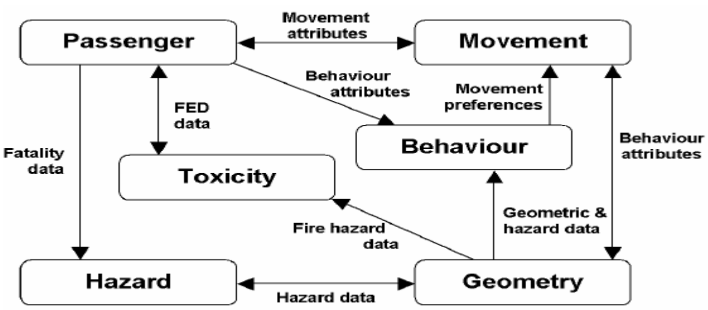

Figure 8 – EXODUS sub-model interaction (Sharp *et al.*, 2003)

- The **Passenger sub-model** allows the nature of the population of crew and passengers to be specified. It describes an individual as a collection of defining attributes and variables such as name, gender, age, maximum fast walk speed, maximum walking speed, response time, and agility.

- The **Movement sub-model** is the main simulation engine in which the physical movement of individual passengers is controlled from their current position to the most suitable neighbouring location (e.g. how individuals move around space, which includes speed, overtaking, side stepping and other evasive actions), or it is supervised the waiting period if one does not exist.

- The **Behaviour sub-model** is the most complex module of all maritimeEXODUS sub-models and incorporates adaptive capabilities that include structural knowledge, reaction to communication, affiliate behaviour, occupant motivation and reaction to fire hazards.

- The **Toxicity sub-model** determines the physiological impact of the environment (heat and toxic products) distributed by the hazard sub-model upon the occupant.

- The **Hazard sub-model** controls the atmospheric and physical environment in both spatial and temporal terms. It distributes hazards such as heat, radiation, smoke concentration and toxic fire gas concentration throughout the vessel atmosphere as a function of time and location and controls the availability of exits (i.e. opening and closing times to exit).

MaritimeEXODUS does not predict fire hazards but can accept experimental data or numerical data from other models. A software link has been established between the maritimeEXODUS and the CFAST zone model and the SMARTFIRE field model. This allows CFAST (version 6.0) history files and SMARTFIRE output files to be automatically passed to the maritimeEXODUS model.

"*Within maritimeEXODUS, the default IMO population can be specified, and has been used successfully in all of the qualitative and functional validation cases required by IMO of a marine evacuation simulation tool. (…) maritimeEXODUS is compliant with the IMO requirements [IMO MSC Circular 1033, June 2002] of a marine evacuation tool*" (Sharp *et al.*, 2003).

Nature of original application	Maritime	x	Built Env.			
Applied to maritime cases	Yes	x	No			
Type of model	Sim.	x	Optimisation		Risk Assess.	
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IMO populations	Present	x	Absent			
IMO test cases	Complete	x	Incomplete			
IMO benchmark	Complete	x	Incomplete			
Ability to produce data required for IMO analysis	Able	x	Unable			

Table 2 – maritimeEXODUS main characteristics (Sharp *et al.*, 2003)

2.2.3 Evi vs. maritimeEXODUS

Summarizing, Evi and maritimeEXODUS are both simulation tools specially developed for the maritime scene. They are also available in the form of computer software that can be readily customised to any vessel environment.

The following tables present a few comparisons between Evi and maritimeEXODUS.

- **Geometry:**

	Evi	**maritimeEXODUS**
Ship layout inputs	▪ The layout is constructed manually from DXF files using EvE, and then exported into Evi in XML format.	▪ Read from a geometry library; ▪ Constructed interactively using provided tools; ▪ Read from a CAD drawing using DXF format
Geometry representation	▪ Coarse	▪ Fine

Table 3 – Geometry representation on Evi and maritimeEXODUS

- **Population:**

	Evi	**maritimeEXODUS**
Population representation	▪ Individual perspective	▪ Individual perspective
Behaviour representation	▪ Rule-based	▪ Rule-based
IMO population	✓	✓

Table 4 – Particular aspects of human and behaviour representation within Evi and maritimeEXODUS

- **Scenario options for simulation:**

	Evi	**maritimeEXODUS**
Evacuation under non emergency scenarios	✓	✓

Evacuation under a fire scenarios	✓	✓
Contra-flow	✓	✓
Mustering	✓	✓
LSA	✗	✓
IMO day scenario	✓	✓
IMO night scenario	✓	✓

Table 5 – Scenario options for simulation on Evi and maritimeEXODUS

- **Visualization options:**

	Evi	**maritimeEXODUS**
Population density mode	✗	✓
2D animated visualization	✓	✓
3D visualization	✓	✓

Table 6 – Visualization options on Evi and maritimeEXODUS

- **Some outputs options**

	Evi	**maritimeEXODUS**
Contour map (Indicates the number of agents who have used a particular route)	✗	✓
Congestion identification	✓	✓
Total time to muster and individuals' evacuation	✓	✓
Distance travelled by individuals	✓	✓
Time wasted in congestion by individuals	✓	✓

Flow rates achieved through doors	✓	✓
Time to clear particular decks	✓	✓
Time to clear particular compartments	✗	✓

Table 7 – Some outputs from Evi and maritimeEXODUS

Section 3.9 presents more output options to be compared between the two models.

3 Toxicity assessment of the fire products

For the nowadays society, fire is an acknowledged risk that every year causes injuries to numerous people and sometimes results in a significant number of deaths. Heat, flames and toxic gases represent deadly fire products which can incapacitate humans during theirs escape from a fire scenario.

Recent investigations upon fire products have recognized heat as an important fire property which governs both fire intensity and survivability in a fire scenario (Grand in Lee *et al.*, 2003). However, according to fire statistics a large proportion of fatal and nonfatal fire casualties are usually reported as "overcoming by smoke and toxic gases" rather than "heat and burns". So, toxic smoke is considered as the greatest hazard in a fire scenario. In order to avoid and/or reduce human fire fatalities, fire safety science is combining the knowledge of chemistry, fluid dynamics, toxicology with the science of human behaviour (Robinson, 2005).

3.1 Background

Over the past decades, the research activities in the fire community have provided a substantial progress in the field of understanding how fires and its products (heat, smoke and gases) can affect people. In fact, studies of incapacitation and lethality in laboratory animals and human fire victims, resulting from exposure to thermal decomposition products from many materials, indicate doses received of asphyxiant gases, irritants concentrations, and sight obscuration by smoke and burns from radiative and convective heat are the main factors that influence peoples escape during a fire (Blomqvist, 2005).

One of the most known investigations on the field of the toxicity assessment of combustion products has been carried out by David Purser (2002). Purser's research is responsible for the development of one of the most complete human incapacitation model used to predict fire hazards in terms of exposure doses and time to incapacitation for humans. This model consists of two concepts: the *Fractional Effective Dose* (FED) and the *Fractional Irritant Concentration* (FIC).

FED has been developed based on the accumulated dose idea, i.e. the effects (incapacitation or death) of some toxic products in an atmosphere occurs when the victim has inhaled a particular $C_i t$ product dose of toxicant.

$$FED_i = \frac{Dose\ receveid\ at\ time\ t\ (C_i t)}{Effective\ C_i t\ to\ cause\ incapacitation\ or\ death}$$

Equation 1 – Fractional Effective Dose for toxicant i

In order to determine at what point in time during the course of the fire exposure the victim will have inhaled a toxic dose, it is then necessary to integrate under the fire profile curve.

$$FED = \sum_{i=1}^{n} \int_{t_0}^{t} \frac{C_i}{(C \cdot t)_i} dt$$

Equation 2 - Fractional Effective Dose

However, according to Purser (2002) there are some toxic effects that may depend only on concentration (and not concentration and time), for instance irritant gases. So the concept of *Fractional Irritant Concentration* (FIC) was developed. Analogous to FED, FIC is the sum of FICs for each irritant.

$$FIC = \frac{\text{Concentration of irritant } i \text{ to which subject is exposed at time } (t)}{\text{Concentration of irritant } i \text{ required to cause impairment of escape efficiency}}$$

Equation 3 – Fractional Irritant Concentration for irritant *i*

Note: when FED/FIC reaches unity, it is assumed that incapacitation effect occurs.

3.2 Asphyxiant Fire Products

In a fire environment, the two major asphyxiant gases are carbon monoxide (CO) and hydrogen cyanide (HCN). These gases are generally responsible for the narcosis (also known as asphyxia or suffocation) effects, i.e. depression of the central nervous systems, which may lead to a loss of consciousness and ultimately death. In addition, low concentrations of oxygen and very high concentrations of carbon dioxide (CO_2) can also lead to asphyxiants effects.

As a result of various studies of incapacitation and lethality, it is known that the effects of the asphyxiant gases depend on the accumulated dose, i.e. it depends both upon concentration and duration of exposure. So, in order to estimate the toxic effects of these gases it is common to use the FED concept.

3.2.1 CO - Carbon monoxide

Carbon monoxide is known as the most common asphyxiant gas in most fire environments. It is colourless, odourless and tasteless gas.

- **Generation of CO**

CO can be produced from both smouldering and flaming combustion. In smouldering fires, where the production of CO is quite slow, lethal concentrations of CO can be attained within 10 minutes in the immediate vicinity of the ignition (Gann and Bryner, 2008). While during a flaming combustion process, the production of CO is a gas phase process, which it is largely dependent upon the availability of oxygen in the combustion environment (Hartzell, 1996).

- **Toxicity of CO**

According to several investigations, carbon monoxide is considered the primary toxicant in many deaths due to smoke inhalation. The toxic effects of carbon monoxide are those of anaemic hypoxia (Smith in Gann and Brynner, 2008). This is due to the formation of blood carboxyhemoglobin, which results in a reduced ability of blood to transport oxygen to critical body organs, even when the arterial partial pressure of oxygen and the rate of blood flow are normal.

- **Signs and symptoms**

The signs and symptoms of carbon monoxide poisoning depend of the concentration and exposure time.

The most common early symptoms are irritated eyes, headache, nausea and vomiting, dizziness, lethargy and a feeling of weakness. Neurologic signs include confusion, disorientation, visual disturbance, syncope and seizures. The heart is particularly sensitive to the effects of CO; an acute exposure may give rise to cardiovascular effects which includes reduced myocardial function, hypotension, vasodilatation, cardiac arrhythmias, shock, circulatory failure and cardiac arrest (Wakefield, 2010).

- **COHb concentration - Stewart equation (Purser, 2002):**

$$\%COHb = (3.317 \times 10^{-5})(ppm\,CO)^{1.036}(RMV)(t)$$

Equation 4 – Stewart equation for COHb concentration for short exposures to CO high concentrations

- $\boldsymbol{FI_{CO}}$ **Fractional Incapacitation Dose for CO (Purser, 2002):**

$$FI_{CO} = \frac{K([CO]^{1.036})(t)}{D}$$

Equation 5 –Fractional incapacitation dose for CO (for each minute) for a 70 kg human engaged in light activity over periods of up one hour

Where:

- $F_{I_{CO}}$ is the fraction of incapacitation dose;
- $K = 8{,}2925 \times 10^{-4}$ for 25 l/min RMV (light activity);
- $[CO]$ is the CO concentration (ppm);
- t is the exposure time (min);
- D is COHB concentration at incapacitation (30 percent for light activity).

Note 1: The FICO expression is unreliable for small adults or children.

Note 2: The FICO model assumes that inhaled CO is immediately converted to COHb. In reality there may be a delay.

Note 3: The FICO model cannot be used reliably in situations where the CO concentration is decreasing.

3.2.2 HCN – Hydrogen Cyanide

Hydrogen cyanide (HCN) is known as the second most important toxic gas, it is a colourless gas or bluish-white liquid with a bitter almond odour.

- **Generation of HCN**

Any organic material containing carbon and nitrogen will produce HCN during combustion under most conditions. The production of HCN from the combustion of materials containing nitrogen is dependent upon both temperature and O_2 availability in the fire environment.

- **Toxicity of HCN**

HCN, approximately 25 times more toxic than carbon monoxide, is considered a potent and rapidly acting chemical asphyxiant (Gann and Bryner, 2008). Unlike CO, which remains primarily in the blood, the cyanide ion is readily distributed throughout the body water and is thus in contact with the cells of tissues and organs. HCN acts as a cellular asphyxiant, by binding to mitochondrial cytochrome oxidase, and so preventing the utilization of oxygen in cellular metabolism. This inhibition rapidly leads to loss of cellular functions (cytotoxic hypoxia) and then to cell death. Unlike carbon monoxide, a short exposure to a high concentration of hydrogen cyanide is much more hazardous than a longer exposure to a lower concentration.

- **Signs and Symptoms**

Early signs and symptoms of exposure to low concentrations of cyanide include rapid breathing, dizziness, weakness, nausea/vomiting, eye irritation, pink or red skin colour, rapid heart rate and perspiration. Later signs of exposure to moderate-high concentrations include loss of consciousness, respiratory arrest, cardiac arrest, coma and respiratory failure leading to death. Survivors of serious cyanide poisoning may develop heart and brain damage.

- ***FI_{HCN}*, Fractional incapacitation dose for HCN (Purser, 2002):**

$$FI_{HCN} = \frac{e^{\frac{[CN]}{43}}}{220}$$

Equation 6 - Fractional incapacitation dose for HCN

Where, [CN] represents the concentration (ppm) of cyanide corrected for the presence of others nitriles besides HCN and for the protective effect of NO_2.

Note: The FICN expression is unreliable outside the range 80-180 ppm HCN.

3.2.3 CO_2 – Carbon Dioxide

Carbon dioxide is a colourless gas. At low concentrations is odourless and at higher concentrations has a sharp, acidic odour.

- **Generation of CO_2**

CO_2 generation occurs in all fires which involves organic materials. In fact, "*in well-ventilated flaming fires, nearly all the carbon lost from the combustibles is converted to carbon dioxide (CO_2). Even in post flashover fires, the fraction of carbon convert into CO_2 is fairly high*" (Gann and Bryner, 2008). In a fire scene, the production of CO_2 is largely dependent upon the availability of oxygen. In fact, as the level of oxygen present in a fire environment diminishes, there is a shift from production of CO_2 to CO (Wakefield, 2010).

- **Toxicity of CO_2**

Carbon dioxide is quite low in its own toxicological potency and is not, by itself, normally considered to be significant as a toxicant in fire atmospheres (Hartzell, 1996). However, moderate concentrations (usually up to 5% in volume air) are responsible for the stimulation of both the rate and depth of breathing, as result of this respiratory stimulation there is an increase of others toxicants and irritant gas inhalation (equation 6) (Purser, 2002). When a CO_2 concentration is above 5% volume of air, this gas becomes an asphyxiant itself (equation 7) (Purser, 2002).

- **Signs and symptoms**

CO_2 has a continuum of effects that range from physiologic to toxic, anesthetic and lethal (Rice, 2004). Symptoms includes headache, dizziness, restlessness, paresthesia, dyspnoea (breathing difficulty), sweating, malaise (vague feeling of discomfort), increased heart rate, cardiac output, blood pressure, coma, asphyxia, convulsions, frostbite (liquid, dry ice) (CDC website).

- ***VCO_2*, A model for the enhanced uptake of other asphyxiant gases (Purser, 2002):**

$$VCO_2 = e^{\frac{[CO_2]}{5}}$$

Equation 7 - Enhanced uptake of other asphyxiant gases due to CO_2

Where:

- VCO_2 is a multiplication factor for the enhanced uptake of other asphyxiants gases;
- $[CO_2]$ is the CO_2 concentration (ppm).

- ***FI_{CO2}*, Fractional incapacitation dose for CO_2 (Purser, 2002):**

$$FI_{CO_2} = \frac{1}{e^{(6.1623 - 0.5189 \times \%CO_2)}}$$

Equation 8 - Fractional incapacitation dose for CO_2

3.2.4 Oxygen depletion – low O_2

Since oxygen is consumed in the combustion process and consequently its level is depleted, therefore a reduction of oxygen should also be considered as a toxic component of smoke.

- **Generation of low O_2**

In a combustion scenario, as oxygen is consumed by the fire, the level of oxygen is depleted, particularly if the fire is in a closed environment.

- **Toxicity of low O_2**

Since oxygen is consumed by the fire, less oxygen is available for humans. This decrease of oxygen leads to low blood oxygen, also known as hypoxemia. As blood oxygen dips down, the cells cease to perform as usual, upsetting the function of organs and tissues, leading to a retardation of the oxidising processes in the brain, and consequently to disturbances of the central nervous system.

- **Signs and Symptoms**

Early signs and symptoms of a low oxygen atmosphere include pulse and respiration rate increase (as the body attempts to compensate for the reduced oxygen levels), lack of muscle coordination, insensitivity to pain, emotional changes and rapid fatigue. More severe depletion can lead to nausea, vomiting, loss of consciousness, convulsions, respiratory collapse and death within just a few minutes.

- ***FI_{O2}*, Fractional incapacitation dose for low O_2 (Purser, 2002):**

$$FI_{O_2} = \frac{1}{e^{(8.13 - 0.54 \times (20.9 - \%O_2))}}$$

Equation 9 – Fractional incapacitation dose for low O_2

Where, (20.9-%O_2) represents the percent oxygen vitiation (%O_2 Vit).

3.2.5 Fractional incapacitation dose for asphyxiation and asphyxiant gases:

Based on all what was stated above, Purser (2002) has developed the fractional dose equation for the asphyxiant effects (hypoxia):

$$FI_{Asphyxiants} = \lfloor (FI_{CO} + FI_{HCN} + FLD_{irr}) \times V_{CO_2} + FI_{O_2} \rfloor or\ FI_{CO_2}$$

Equation 10 – Fractional incapacitation Dose for the asphyxiant effects

Note 1: FLD_{irr} (described on section 3.3 - Pulmonary irritation affecting the lungs) is the fraction of an irritant dose contributing to hypoxia (this term represents a correction for the effects on lung function).

Note 2: FLD_{irr} term may be omitted if the effects of asphyxiant gases are only under consideration.

However, Purser has also developed a fractional dose for the effects of asphyxiant gases only:

$$FI_{Asphyxiants} = \left[\left(FI_{CO} + FI_{HCN}\right) \times V_{CO_2} + FI_{O_2}\right] or\ FI_{CO_2}$$

Equation 11 – Fractional dose for the effects of asphyxiant gases only

3.3 Irritant Fire Products

Irritant gases are present in most fire atmospheres and they are the combustion result of the most commonly used materials, ranging from natural sources such as wood to synthetic plastics and polymers (Wakefield, 2010). In fact, both smouldering and flaming combustion have the ability to produce irritant gases; however its generation rate in a fire environment depends upon the combustion mode relatively to the associated temperature and ventilation of each combustion mode.

According to their chemical composition, irritant gases can be divided into two main classes: inorganic acid gases [e.g. halogen acids (HCl, HF and HBr), sulphur oxides, nitrogen and phosphorous] and organic irritants [e.g. unsaturated aldehydes (especially acrolein), isocyanates (from polyurethanes) and formaldehyde] (Wakefield, 2010). Unlike the incapacitation effects of asphyxiants, which are clear-cut and well understood, the effects of the irritant gases are much more difficult to determine (Purser, 2002), since the severity of the irritant effects depends upon the chemical involved, its concentration, the exposure duration and its solubility.

Despite all these obstacles, normally irritant fire products can lead to incapacitation during and after the exposure in two distinct ways:

- **Sensory irritation, which includes irritation of the eyes and the upper respiratory tract:**

During exposure, eye irritation is considered the immediate effect of irritant gases presence. According to Hartzell (1996), this irritation effect depends primarily on irritant concentration and does not have any severity increase during the exposure time. The eye irritation can cause painful effects: nerve endings in the cornea are stimulated causing pain, reflex blinking and tearing. In more serious cases, eye irritation may also lead to subsequent eye damage. Although sensory irritation may be painful, it is unlike to be directly lethal during the exposure; however because the eye irritation leads victims to shut their eyes for partially alleviating those effects, they may also impair the victims escape from a fire.

During the exposure to the airborne irritants, significant amounts of inhaled irritates can also enter into the upper respiratory tract causing burning sensations in the nose, mouth and throat, along with the secretion of mucus (Hartzell, 1996). As with the eye irritation, these effects are primarily related to the concentration of the irritant and do not normally increase in severity as the exposure time is lengthened.

According to Purser (2002), since these painful effects of the sensory irritation of the eyes and respiratory tracks are only related to the concentration of each irritant, they can be estimate using the Fractional Irritant Concentration (FIC):

$$FIC = FIC_{HCl} + FIC_{HBr} + FIC_{HF} + FIC_{SO_2} + FIC_{NO_2} + FIC_{CH_2CHO} + FIC_{HCHO} + \sum FIC_x$$

Equation 12 - Fractional Irritant Concentration

- **Pulmonary irritation affecting the lungs:**

Whilst significant amounts of irritants gases are inhaled and quickly taken into the lungs, pulmonary irritation may be exhibited (Hartzell, 1996). Coughing, bronchoconstriction, and increased pulmonary flow resistance are common symptoms of the pulmonary irritation. Unlike sensory irritation, pulmonary irritation's effects depend upon the irritant's concentration and the exposure's duration. So, in order to estimate these effects, Purser suggested the *Fractional lethal dose* concept (FLD):

$$FLD = FLD_{HCl} + FLD_{HBr} + FLD_{HF} + FLD_{SO_2} + FLD_{NO_2} + FLD_{CH_2CHO} + FLD_{HCHO} + \sum FLD_x$$

Equation 13- Fractional lethal Dose

Note 1: When FIC or FLD reaches unity, a tenability endpoint (escape impairment) is predicted.

Note 2: It is necessary to refer that normally, most of fire irritants produce signs and symptoms characteristic of both sensory and pulmonary irritation.

3.4 Estimation of the fire smoke toxicity in Evi

In order to estimate fire smoke effects, Evi has adopted the concept of Fractional Effective Dose (FED) presented by Purser (2002). This evacuation model calculates the FED values for each agent individually at a reference height of 1.5 m above floor level; and uses it to control the walking speed and consequently to determine the point at which an agent becomes fatally injured.

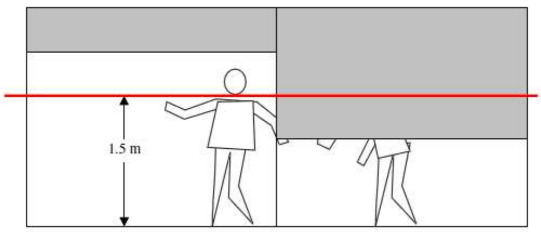

Figure 9 – Reference level for FED calculation

FED values are calculated within the Evi model through the Fractional Effective Dose of Incapacitation, FED_{IN}:

$$FED = \left(FED_{CO} \times V_{CO_2}\right) + FED_{O_2}$$

Equation 14 - Fractional Effective Dose of Incapacitation (*Evi*)

- FED_{CO} , Fractional Effective Dose for *CO* is calculated as follows:

$$FED_{CO} = \sum_{t_1}^{t_2} \frac{k \times [CO]^{1.036}}{D} \Delta t$$

Equation 15 - Fractional Effective Dose for *CO (Evi)*

Where *[CO]* is the average concentration of *CO* in ppm over the time increment Δt in minutes; *k* and *D* are constants depending on the activity of the person (their values for different levels of activities are given in Table 8).

Activity	K	D
At Rest	2.81945×10^{-4}	40
Light Work	8.29250×10^{-4}	30
Heavy Work	1.65850×10^{-3}	20

Table 8 – Values of constants K and D for different activity level

- Hyperventilation effect is calculated through the multiplication of the value of FED_{CO} at each time increment by a frequency factor VCO_2, given by the following equation:

$$V_{CO_2} = \frac{e^{(0.1903 \times \%CO_2 + 2.0004)}}{7.1}$$

Equation 16 - Frequency factor VCO_2 (*Evi*)

Where % CO_2 is the percentage of CO_2 in the evaluated compartment.

- FED_{O2} , Fractional Effective Dose for O_2 is calculated as follows:

$$FED_{O_2} = \sum_{t_1}^{t_2} \frac{\Delta t}{e^{[8.13 - 0.54 \times (20.9 - \%O_2)]}}$$

Equation 17 - Fractional Effective Dose for O_2 (*Evi*)

Where $(20.9 \times \% O_2)$ is the percent O_2 vitiation over the time increment Δt.

3.5 Estimation of the fire smoke toxicity in maritimeEXODUS

In order to determine the physiological impact of the fire smoke upon occupants, maritimeEXODUS uses also the Fractional Effective Dose concept of Purser. This concept is incorporated within its toxicity sub-model and calculates, for each agent, the dose received ratio over time to the effective dose that causes incapacitation or death at two different heights: the upper (e.g. 1.7m) and lower height (e.g. about 1.0 m above the floor).

The FED model within maritimeEXODUS considers the combined effect of HCN, CO, CO_2 and low O_2 in the following way,

$$FIN = (FICO + FICN + FLD) \times VCO_2 + FIO$$

Equation 18 – FIN (*maritimeEXODUS*)

In each of the following equations, *t* is the exposure time (minutes).

- *FICO* , Fractional Incapacitating Dose for CO (measured in ppm):

$$FICO = 3.317 \times 10^{-5} \times CO^{1.036} \times RMV \times \frac{t}{PID}$$

Equation 19 - Fractional Incapacitating Dose for CO (*maritimeEXODUS*)

Where RMV is the minute volume (litres/minute) and PID is the Personal Incapacitation Dose (%).

- *FICN* , Fractional Incapacitating Dose for HCN (measured in ppm):

$$FICN = e^{\left(\frac{HCN}{43}\right)} \times \frac{t}{220}$$

Equation 20 - Fractional Incapacitating Dose for HCN (*maritimeEXODUS*)

- *FIO*, Fractional Incapacitating Dose for Low O_2 (measured in %):

$$FIO = \frac{t}{e^{(8.13 - 0.54 \times (20.9 - \%O_2))}}$$

Equation 21 - Fractional Incapacitating Dose for Low O_2 (*maritimeEXODUS*)

- *$FICO_2$*, Fractional Incapacitating Dose for CO_2 (measured in %):

$$FICO_2 = \frac{t}{e^{(6.1623 - 0.5189 \times \% CO_2)}}$$

Equation 22 - Fractional Incapacitating Dose for CO_2 (*maritime*EXODUS)

- *VCO_2* is a multiplicative factor which measures the increased uptake of *CO* and *HCN* due to CO_2 - induced hyperventilation:

$$VCO_2 = e^{\left(\frac{CO_2}{5.0}\right)}$$

Equation 23 - *VCO_2* parameter (*maritime*EXODUS)

3.6 Heat

According to Grant (1990), heat released during a fire represents an important fire hazard. Heat governs the fire intensify and in a human safety point view, it is a crucial parameter which affects the occupant survivability. For example, it was reported that in a large fire building in 1996, some of the occupants decided not to use the escape corridor claiming that it was very hot, so they had stayed in the adjacent rooms for several hours until they used the windows for evacuation (Wong and Hui, 2006). Although all the psychological stress that may affect the occupants, there are also physical effects which can be also very harmful to human life.

In fact, heat produced from a fire represents significant physical effects on humans in three basic ways:

- **Heat stroke (hyperthermia)**:

When an occupant is exposed in a prolonged mode (approximately 15 minutes or more) to heated environments at temperatures too low to cause burns there is a possible danger of incapacitation due to hyperthermia. The exposure to these conditions leads the core temperature of an individual to increase to unhealthy levels, which may result in unconsciousness or even death (Kuligowski, 2009).

One of the most common forms of hyperthermia is heat stroke which is also considered one of the most dangerous heat effects. Some of the heat stroke symptoms are confusion, combativeness, bizarre behaviour, faintness, staggering, strong and rapid pulse, and possible delirium or coma.

- **Skin pain followed by body surface burns:**

When an individual is exposed to air temperatures above 121ºC (or radiant fluxes above 2.5 kW/m^2), this can result into pain to the exposed skin followed by body surfaces burns and hyperthermia if exposure is prolonged (Purser, 2009). The body surface burns occur when the skin temperature increases to a point where there are skin damages (Kuligowski, 2009).

- **Respiratory tract burns:**

The respiratory tract burns is a heat effect responsible for the thermal damage or burn to the respiratory tract. This effect occur when an individual inhaled sufficiently hot gases, and consequently affects its respiratory system like burns to the larynx (which may result in an edema) or even damage to the lungs.

Note: The heat effects on people depend on the level of heat (temperature or heat flux) and also on the exposure time.

3.6.1 Fractional incapacitation dose for heat

In order to estimate heat effects, some investigations were carried out. One of the most known and complete is present in the "Toxicity Assessment of Combustion Products" document of Purser (2002). In this research, Purser has considered three basic heat exposure scenarios for occupants during a fire:

- **Exposure to conductive heat** (the temperature of the hot object in °C):

The effects of the conductive heat on humans are related to hot object temperature and its thermal inertia. These effects resume to the interaction between hot objects and body tissue at the victim skin surface, resulting in pain and sometimes cellular damage.

- **Exposure to convective heat** (hot gases in °C):

The convective heat from hot gases is one of the most important sources of heat that humans have to face during their escape from a fire. Convective heat effects occur when the individual's surface comes in contact with hot gases which may lead humans to incapacitation, mainly due to skin pain and burns, fatal burns and fatal hyperthermia.

For exposures of up to one hour to convected heat from air containing less than 10 percent by volume of water vapour, Purser (2002) suggest the following equation to predict the time (minutes) to incapacitation:

$$t_{conv} = 5 \times 10^{7} \times T^{-3.4}$$

Equation 24 – Time (minutes) to incapacitation due to convected heat

- **Exposure to radiant heat** direct from fire or hot upper smoke layer:

Radiative heat is the energy radiated by solids, liquids and gases in the form of electromagnetic waves as a result of their temperature. This radiant energy can travel outward in all directions from the emitting source (fire or heat source) and then be absorbed by any surface that it encounters, which includes the human beings (Countryman, 1976). Exposure to this type of heat can cause local heating of particular areas of skin.

Above 200ºC, Purser (2002) suggested the following equation to predict the time (seconds) to incapacitation due to radiant heat:

$$t_{rad} = \frac{80}{q^{1.33}}$$

Equation 25 – Time (seconds) to incapacitation due to radiant heat

Where, q is the radiant flux (kW/m^{-2}).

According to Purser (2002), just like the toxic gases, a similar fractional incapacitation model for heat may be acquired during a fire and can be estimated by summing the radiant and convected fractions as the following equation shows:

$$FED = \sum_{t_1}^{t_2} \left(\frac{1}{t_{conv}} + \frac{1}{t_{rad}} \right) \Delta t$$

Equation 26 – Fractional Effective Dose for heat

3.7 Estimation of the heat toxicity in Evi

In order to determine the physiological impact of the fire heat upon occupants, Evi defends that only two criteria need to be considered:

- The threshold of burning skin;
- The exposure where hyperthermia is sufficient to cause mental deterioration and, therefore, threaten survival.

Evi uses a methodology based on additive FED similar to that used with toxic gases, which provides the total FED of heat acquired during an exposure which can be calculated according to the following equation:

$$FED = \sum_{t_1}^{t_2} \left(\frac{1}{t_{conv}} + \frac{1}{t_{rad}} \right) \Delta t$$

Equation 27 – Fractional Effective Dose for heat (*Evi*)

Where,

- t_{rad} (in minutes) is the skin's burning time due to radiant heat according to:

$$t_{rad} = 1.333 \times \dot{q}_{rad}^{\left(-\frac{4}{3}\right)}$$

Equation 28 - skin's burning time due to radiant heat (*Evi*)

Where, $\dot{q}$ (in kW/m^2) is the radiant heat flux

- t_{conv} (in minutes) is the time to incapacitation under conditions of exposure to convective heat from air containing less than 10% by volume of water vapour, according to:

$$t_{conv} = k_1 \times T^{k}$$

Equation 29 - time to incapacitation under conditions of exposure to convective heat (*Evi*)

Where T is the temperature in °C; k_1 and k_2 are model parameters here taken as 4.1×10^8 and - 3.61respectively for fully clothed persons.

3.8 Estimation of the heat toxicity in maritimeEXODUS

In order to estimate heat hazards' effect, maritimeEXODUS considers two contributions: convective heat (i.e. elevated temperature) and radiative flux. Another aspect is EXODUS model considers also the heat hazard data located at two heights, head and near floor height.

- Convected heat

$$FIH_c = t \times 2.0 \times 10^{-8} \times T^{3.4}$$

Equation 30 – FIH for convected heat (*maritimeEXODUS*)

Where *T* is the temperature (ºC)

- Radiative heat

$$FIH_r = \frac{q^{1.33}}{Dr} \times t \times 60.0$$

Equation 31 – FIH for radiative heat (*maritimeEXODUS*)

Where *t* is the time (minutes), *q* is the radiative flux (kW/m^2) and *Dr* is the radiative denominator. *Dr* is the dose of radiation required to cause the desired effect and has units of [s(kW/m^2)$^{4/3}$].

In maritimeEXODUS, the FED model considers the combined effect of the above agents in the following way,

$$FIH = FIH_c + FIH_r$$

Equation 32 – FIH for the combined effect of radiative and convected heat (*maritimeEXODUS*)

When *FIH* is equal or exceeds 1.0, the affected passenger is assumed to be incapacitated.

Note: the way the above equations are stated here may appear fundamentally different from those of Purser (see section 3.6.1). However, they are not. For instance,

$$FIH_c = t \times 2.0 \times 10^{-8} \times T^{3.4} = \frac{1}{5 \times 10^{7} \times T^{-3.4}} = \frac{1}{\text{equation 24}}$$

And,

$$FIH_r = \frac{q^{1.33}}{Dr} \times t \times 60.0 = \frac{1}{80 / q^{1.33}} = \frac{1}{equation \quad 25}$$

3.9 Evi vs. maritimeEXODUS

As an important part of the societal consequence assessment, this section compares toxicity models between Evi and maritimeEXODUS.

- **Smoke effects:**

	Evi	maritimeEXODUS
Asphyxiant effects	✓	✓
Irritant effects	✗	✓

Table 9 – Smoke effects simulated in Evi and maritimeEXODUS

- **Gases effects:**

	Evi	maritime EXODUS
CO	✓	✓
CO_2	✗	✓
Enhanced uptake of other asphyxiant gases	✓	✓
Low O_2	✓	✓
HCN	✗	✓
Irritant gases	✗	✓

Table 10 – Smoke effects simulated in Evi and maritimeEXODUS (detailed information)

Evi				maritime EXODUS		
	Influenced by	Influences			Influenced by	Influences
FED_{CO}	CO concentration, activity of the person	FED_{IN}		*FICO*	CO concentration, activity of the person	*FIN* and incapacity status
--	--	--		$FICO_2$	CO_2 concentration	incapacity status
VCO_2	CO_2 concentration	FED_{IN}		VCO_2	CO_2 concentration	*FIN*
FED_{O2}	O_2 concentration	FED_{IN}		*FIO*	O_2 concentration	*FIN* and incapacity status
--	--	--		*FICN*	HCN concentration	*FIN* and incapacity status
--	--	--		*FLD*	--	--

Table 11 – FED/FI parameters: Evi and maritimeEXODUS

The equations used by both tools are presented in Appendix 1.

- **Heat effects:**

	Evi	**maritimeEXODUS**
Convective heat	✓	✓
Radiative heat	✓	✓

Table 12 – Heat consequences simulated in Evi and maritimeEXODUS

- **Other aspects:**

	Evi	maritimeEXODUS
***FED* calculation height [meters]**	▪ 1.5	▪ 1.0 and ▪ 1.7

Table 13 – FED calculation heights in Evi and maritimeEXODUS

- **FED output options:**

	Evi	maritimeEXODUS
Level of likely injury of the survivors	✓	✓
Injuries	✓ Number of injuries is produced by Evi as people with FEDs less than 1	✓ Exodus cannot explicitly represent injuries, however they can be implicitly represented via the mobility and agility attributes
Fatalities	✓	✓
Time of each fatality	✓	✓
Fatalities location	✓	✓
CO dose for each individual	✓	✓
Enhanced uptake of other asphyxiant gases due to CO_2 uptake	✓	✓
CO_2 dose for each individual	✗	✓
Low O_2 dose for each individual	✓	✓

Table 14 – FED output options in Evi and maritimeEXODUS

4 Human behaviour in a ship evacuation

Over the past years, human behaviour in fires has become an important area of research into the Fire Safety Engineering community. In fact, human behaviour study in evacuation has provided crucial information to legislation and regulations, helping developing rules to, among other objectives, decrease fire death rate. However, it is difficult to predict individual's behaviour in a particular fire scenario.

Capturing human behaviours computationally is one of the most complicated and difficult tasks in the evacuation simulation field (Lee *et al.*, 2003). Human behaviours' complex nature is difficult to understand and formalize, and current human behaviour models can present some limitations in simulating human behaviour (Pan, 2006).

Moreover, there are some additional aspects to be considered when simulating evacuations on a ship, for instance, ship motions.

In order to compare Evi and maritimeEXODUS, this section will provide some important aspects about evacuation under a fire scenario, and verify both models compliance.

4.1 Effects of ship motions on evacuation

IMO regulations do not require that ship motions effect should be taken into account in human walking speed, for evacuation purpose. And therefore, in most software applications, passengers' time required to travel to assembly stations is estimated based on normal speed walking, which is human walking speed in buildings (IMO, 2007).

In fact, effects of ship motions on walking speed for sinusoidal pitch and roll motion patterns were investigated by TNO Human Factors. Altogether the data showed a walking speed decrease for dynamic motion conditions (Boer and Skjong, 2001) and consequently an increase of evacuation time.

Since evacuation time undoubtedly depends on ship motions, it is important for ship evacuation analysis to incorporate this in the escape time estimation.

		Evi	maritimeEXODUS
Impact of ship motions	Upon agent speed	✓	✓
	Upon agent behaviour	✗	✗

Table 15 – Ship motions in Evi and maritimeEXODUS

Note 1: Evi can take into account time domain simulation data for 6 degrees-of-freedom motion. Particular emphasis is placed in heave, pitch and roll motions, which can heavily impede the evacuation process. It should be noted that the spatial movement of an agent, or a human being, does not depend on the motion of the vehicle itself but on the change of the acceleration vector as a function of time. Considering that that the acceleration is directly linked to mass distribution of a ship (for passenger ships this approximates the loading condition), it is reasonable to expect the different passenger ships (in terms of type and size) have different motion response in waves, which in turn affects the agents movement. All in all, despite the capability to model and assess the evacuation process of a passenger ship in waves, this feature is not fully implemented yet due to lack of benchmarking data for various cases of acceleration levels.

Note 2: maritimeEXODUS can model ship motion in a quasi static fashion by changing a particular heel or trim angle with a particular time period. A user can therefore simulate a sinusoidal motion with respect to time. However, the model does not take into account the rate of change of angle and the location of the passenger relative to the axis of trim or heel.

4.2 Crowd density

During evacuation, some passengers may show some of the following behaviour patterns (Helbing *et al.*, 2000):

- People move or try to move faster than normal,
- Some competitive behaviour may be adopted by the occupants, such as start pushing,
- Escape can became slower due to fallen or injured people, which act as "obstacles",

So, it is important to consider crowd density during an evacuation situation. Previous investigations showed travel speed has a direct relationship with crowd density, for example:

- There are differences on the walking speed on the different places of a crowd: speed at the head of the crowd is faster than the speed at the end of the group (Koss *et al.*, 1997);
- AME CRC's experiments showed that there was a 50% speed decreased when two groups from opposite direction met, (Koss *et al.*, 1997);
- According to Murayama *et al.* (2000), crowd speed decreased as the width of corridors decreased.

		Evi	maritimeEXODUS
Impact of crowd density upon agent speed		✓	✓
Agents interact directly with building geometries and egress components	**Example: agents can avoid obstacles**	✓	✓
Customize egress route according to congestion levels		✗	✗
Pushing	**Competitive behaviour**	✗	✗
Trampling	**Competitive behaviour**	✗	✗
Overtaking		✓	✓
Stampede		✗	✗

Table 16 – Crowd density in Evi and maritimeEXODUS

4.3 Others behavioural options

There are some input options for agent profile; each agent may have, or not, the following parameters:

		Evi	maritimeEXODUS
Distinction between passenger and crew member		✓	✓
Agent	gender	✓	✓
	age	✓	✓
	height	✗	✓

		Evi	maritimeEXODUS
Agent speed	Fast flat walk speed	✓ (is not a default parameter in Evi but could be specified)	✓
	Flat walk speed	✓	✓
	Leap speed	✗	✓
	Crawl speed	✗	✓
	Upstairs speed	✓	✓
	Downstairs speed	✓	✓
Agent response time	Time occupant takes between the first alarm sounding and reacting	✓	✓
Agent mobility	Allows the introduction of physical disabilities	✓	✓
Agent agility	Reflection on prowess, i.e. capacity to overpass an obstacle	✗	✓
Agent drive	Parameter used to conflict resolutions, i.e. each agent has its own value and during a conflict the biggest value wins the conflict	✗ (Conflict resolution is not based on values assigned to agents)	✓
Agent patience	Amount of time agent is prepared to wait	✗	✓
Specific muster station	Allows the user to specify the muster station to each agent	✓	✓
Passenger familiarity	Reflects the knowledge degree of ship layout (example: knowledge of specific exit points)	✓ (Agents have a global knowledge of the ship layout)	✓
Agent specify tasks		✓	✓
Gene	Family connections	✗	✓

Table 17 – Agent profile options in Evi and maritimeEXODUS

Secondly, there are some particular behaviours which may also be incorporated under evacuation models:

		Evi	maritimeEXODUS
Mental tension	Related to agent knowledge of scenario severity	✗	✗
Perceived fire by agents	Example: agent can identify a fire and have a different behaviour because of it	✗	✓
Fire impact upon agent speed		✓	✓
Fire impact upon agent behaviour	Example: agent adjust its route according to conditions	✗	✓
Fire products' impact on agent's health		✓	✓
Follow assign routes different from shortest one		✓	✓
Use wall to assist evacuation		✗ (Use of wall to assist evacuation is an option for flooding scenarios only. Not for Fire)	✓
Lost		✓	✗
Communication	between agents	✓	✓
Conflict resolution		✓	✓
Return to cabin		✓	✓
Life jacket retrieval and donning		✓	✓

Table 18 – Behaviour options in Evi and maritimeEXODUS

Finally, there are specific task that can be associated to crew members:

	Evi	**maritimeEXODUS**
Passengers control	✓	✓
Damage control (example: fire fighting)	✗	✗
Oversee mustering	✓	✓
Enable LSA	✗	✓
Search in cabins / regions for passenger	✓	✓
Imparting escape router information to passengers	✓	✓ ([This implicitly modelled via the ability to define muster station routes. However, crew cannot explicitly impart information to passengers])

Table 19 – Crew task options in Evi and maritimeEXODUS

5 Conclusions

- Both models, Evi and maritimeEXODUS, simulate asphyxiant gases' effects;
- Only maritimeEXODUS simulates irritant gases' effects, using Fractional Incapacitation Concentration (FIC) and Fractional Lethal Dose (FLD);
- Unlike the maritimeEXODUS, Evi does not take into account the fractional effective dose (FED) of CO_2;
- In Evi software, individual effective doses of asphyxiants interact together and influence an evacuee health status. The highest FED (either toxicity or heat) will influence the travel speed and as FED reaches unity the expected travel speed will decrease sharply toward total incapacitation.
- In maritimeEXODUS, different gases can influence different parameters, for instance fractional incapacitation dose for CO influences FIN and occupant's incapacity status, whereas fractional incapacitation dose for CO_2 only affects the incapacity status;
- Radiative and convective heat effects are simulated in both evacuation models;
- Evi calculates each fractional dose at 1.5 meters. Whereas, maritimeEXODUS uses two heights to calculate each fractional dose: 1.0 meter to simulate the crawl behaviour and the 1.7 meters to represent the standing head height;
- In order to simulate ship motions impact upon agent speed, Evi import motions data from Proteus software;
- Both models have the same options for crowd density aspects, for instance crowd density impact upon agent speed, and overtaking;
- When it comes to agent profile inputs there are some differences. MaritimeEXODUS, unlike Evi, allows specifying agent height, agility, drive, patience, leap and crawl speed and also gene (family connections).
- Regarding psychological behaviours considered, once again, there are some dissimilarities:
    - Evi, unlike maritimeEXODUS, enables the agent to be lost;
    - maritimeEXODUS, unlike Evi, allows fire to be perceived by agents, simulates fire impact upon agent behaviour, and also has the possibility for agents to use wall to assist evacuation;
- When it comes to specific crew member tasks, there is only one difference, maritimeEXODUS, unlike Evi, enables LSA;
- Both Evi and maritimeEXODUS software meet the IMO regulations (*IMO MSC Circular 1033, June 2002*).

6 References

Boer, L. C., Skjong, R. (2001), "Emergency Evacuation: How Better Interior Design Can Improve Passenger Flow". *Cruise Ferry 2001*, London, 8-10 May 2001.

Blomqvist, Per (2005), "Emissions from Fires - Consequences for Human Safety and the Environment", *Doctoral Thesis*, Department of Fire Safety Engineering, Lund Institute of Technology.

(CDC website): http://www.cdc.gov/niosh/npg/npgd0103.html

Countryman, C. M. (1976), "Radiation". *Heat – Its Role in Wildland Fire*, part 4.

Evi – Modelling Crew Functionality and Objectives.

Evi – User Manual.

Gann, R. G., Brynner, N. P. (2008), "Combustion Products and Their Effects on Life Safety". *Fire Protection Handbook*, 20th Edition. Vol. 1, chapter 2, section 6, National Fire Protection Association, Quincy, MA, pp. 6/11-34.

Glen, I. F., Galea, E. R. (2001), "Ship Evacuation Simulation: Challenges and Solutions". Discussion. Society of Naval Architects and Marine Engineers, 109, pp 121-139.

Hartzell, G. E. (1996), "Overview of combustion toxicology". *Toxicology*, vol. 115 (1-3), pp. 7-23.

Helbing, D., Farkas, I., Vicsek, T. (2000), "Simulating dynamical features of escape panic". *Nature*, 407, pp. 487–490.

IMO (2007), MSC.1/ Circ.1238 "Guidelines for evacuation analysis for new and existing passenger ships".

Koss, L. L., Moore, A., Porteous, B. (1997), "Human mobility data for movement on ships". Proceedings of International Conference on Fire at Sea, pp. 1-11.

Kuligowski, E. (2009), "Compilation of Data on the Sublethal Effects of Fire Effluent". *National Institute of Standards and Technology Technical Note 1644*, pp. 47.

Lee, D., Kim, H., Park, J.-H., Park, B.-J. (2003), "The current status and future issues in human evacuation from ships". *Safety Science*, 41(10), pp. 861-876.

Murayama, M., Itagaki, T., Yoshida, K. (2000), "Study on evaluation of escape route by evacuation simulation". *Journal of the Society of Naval Architects of Japan*, 188, pp. 441–448.

Pan, Xiaoshan (2006), "Computational Modeling of human and social behaviors for emergency egress analysis". *Doctoral Thesis, Standford University.*

Purser, A. D. (2009), "Physiological effects of combustion products and fire hazard assessment". Europacable Seminar "Safety during fire", 6th May 2009, Brussels.

Purser, A. D. (2002), "Toxicity assessment of combustion products*", SFPE Handbook of Fire Protection Engineering*, Quincy (MA), USA.

Rice, S. A. (2004), "Human Health Risk Assessment of CO_2: Survivors of acute high-level exposure and populations sensitive to prolonged low-level exposure". Third Annual Conference on Carbon Sequestration, 3-6 May 2004, Alexandria, Virginia, USA.

Robinson, J. E. (2005), "The Toxicity of Combustion Gases". The 54th International Wire & Cable Symposium - IWCS/FOCUS, 13-16 November 2005, Providence, USA.

Sharp, G., Gwynne, S., Galea, E. R. (2003). "The effects of ship motion on the evacuation process", Maritime and Coastguard Agency Research project 490.

SOLAS, Consolidate Edition (2004). *IMO*.

Tavares, Rodrigo Machado (2009), "Evacuation Processes Versus Evacuation Models: "Quo Vadimus"?". *Fire Technology*, 45, pp. 419-430.

Vassalos, D., Kim, H., Christiansen, G., Majumder, J. (2001a), "A Mesoscopic Model for Passenger Evacuation in a Virtual Ship-Sea Environment and Perfomance-Based Evaluation". Pedestrian and Evacuation Dynamics.

Vassalos, D., Guarin, L., Bole, M., Majumber, J., Vassalos, G. C., Kim, H. S. (2004), "Effectiveness of Passenger Evacuation Performance For Design, Operation & Training using First-Principles Simulation Tools". *Escape, Evacuation & Recovery*, Lloyds Lists Events.

Wakefield, J. C. (2010), "A Toxicological Review of the Products of Combustion". Health Protection Agency – Chemical Hazards and Poisons Division.

Wong, L. T., Hui, P.S. (2006), "Experimental verification of a thermal radiation model for human skin heat exposure". Building *Services Engineering Research and Technology*, vol. 27, 1, pp. 55-61.

7 Appendix 1

		Evi	maritimeEXODUS
Asphyxiant gases	CO	$FED_{CO} = \sum_{t_1}^{t_2} \frac{k \times [CO]^{1.036}}{D} \Delta t$	$FICO = 3.317 \times 10^{-5} \times CO^{1.036} \times RMV \times \frac{t}{PID}$
	HCN	---	$FICN = e^{\left(\frac{HCN}{43}\right)} \times \frac{t}{220}$
	CO_2	---	$FICO_2 = \frac{t}{e^{(6.1623 - 0.5189 \times \% CO_2)}}$
	VCO_2	$V_{CO_2} = \frac{e^{(0.1903 \times \% CO_2 + 2.0004)}}{7.1}$	$VCO_2 = e^{\left(\frac{CO_2}{5.0}\right)}$
	Low O_2	$FED_{O_2} = \sum_{t_1}^{t_2} \frac{\Delta t}{e^{[8.13 - 0.54 \times (20.9 - \% O_2)]}}$	$FIO = \frac{t}{e^{(8.13 - 0.54 \times (20.9 - \% O_2))}}$
Irritant gases		---	FLD
FED equation for smoke effects		$FED_{IN} = (FED_{CO} \times V_{CO_2}) + FED_{O_2}$	$FIN = (FICO + FICN + FLD) \times VCO_2 + FIO$

Table 20 – FED/FIN equations associated to smoke effects: Evi vs.maritimeEXODUS

Note: In order to allow an evident and straightforward comparison between the both softwares, it should take into account that $FED = \sum FI$.

		Evi
Heat Effects	time to incapacitation (minutes) under exposure to Convective Heat	$t_{conv} = k_1 \times T^{k_2}$
	time to skin burning (minutes) due to Radiative Heat	$t_{rad} = 1.333 \times \dot{q}_{rad}^{\left(-\frac{4}{3}\right)}$
FED equation for heat effects		$FED_{Heat} = \sum_{t_1}^{t_2} \left(\frac{1}{t_{conv}} + \frac{1}{t_{rad}} \right) \Delta t$

Table 21 – FED equations associated to heat effects in Evi

		maritimeEXODUS
Heat	Cumulative exposure to Convective Heat	$FIH_c = t \times 2.0 \times 10^{-8} \times T^{3.4}$
	Cumulative exposure to Radiative Heat	$FIH_r = \frac{q^{1.33}}{D_r} \times t \times 60.0$
FED equation for heat effects		$FIH = FIH_r + FIH_c$

Table 22 – FIH equations associated to heat effects in maritimeEXODUS

8 Appendix 2

"The Passenger Evacuation Simulation Model – Evi" document – by SSRC

This report provides a description of the evacuation simulation model *Evi* in general and, in particular, for the purpose of deploying the model in Task 2.3 (Societal Consequence Model) of FIREPROOF project. The main concept of the model, its features and capabilities are presented followed by the effects of fire effluents and ship heeling on evacuees.

1 Introduction

Evi (Evacuability Index) is an evacuation simulation model specifically developed for maritime applications. The model is implemented in a computer program that can be customised to any vessel environment. The vessel information required pertains to semantics, topology and geometric data. The latter is varying from very simple 3D virtual environment (allowing quick calculations at high level planning) up to detailed replication of the actual ship environment. It is a multi-agent mesoscopic model, i.e. it combines macroscopic and microscopic modelling to provide intelligent multi-level planning capability. These features are coupled to uncertainty modelling in the parameters that can affect evacuation time and the ability to review the evacuation process (in video mode) of a given scenario, thus providing a wide range of modelling capabilities for realistic representation of complex evacuation situations on a moving ship platform. The model has already been deployed in numerous projects of passenger evacuation of cruise liners and ROPAX ships.

Eve is the *Evacuation Editor* for *Evi*. The general arrangement of the ship can be imported into *Eve* in DXF format and all the geometrical information, like space categories, connections, gates, stairways, etc., can be assigned. The model is imported in *Evi* in XML format. *Eve* and *Evi* use SI units, so the drawing has to be scaled appropriately before imported in the system.

The following sections will elaborate on the concept used in the evacuation model, the approaches followed, the main issues associated with evacuation, and the calculation of fire and heeling effects on evacuees.

2 Evacuability

The ability to evacuate a ship environment within a given time interval (i.e. evacuability), can be defined as function of a set of initial conditions and evacuation dynamics as follows:

$$E = f\{env, d, r(t), s(n_i); t\}$$

The initial conditions and evacuation dynamics (figure 10) should be defined and remain fixed during the execution of the simulation:

env stands for the ship environment model, pertaining to geometry, topology and domain semantics. For any comparisons to be meaningful a time invariant environment for evacuation simulations is modelled. An environment changing with time (e.g., blocking doors) could not easily allow for quantifiable assessment of these effects, as it would be very difficult to repeat any such action in precisely the same state of the simulated system. However, the ability to change the environment could offer a strong basis for crew training and for decision support in crisis management. Moreover, fire/smoke spreading and progressive flooding, the principal hazards giving reason for evacuation, result in a time varying environment. Hence, for any comparisons concerning global and local effects to be meaningful, any environment changes ought to be affected in a deterministic way.

d represents the initial conditions of the evacuation problem, pertaining to spatial and temporal demographics of the people onboard. People in the environment are randomly distributed with the possibility of fixing some initial values, e.g., placing handicapped people on the embarkation decks and/or near an exit. As such, the initial distribution of people's demographics is sampled in order to identify its effect on evacuability. The latter could be avoided if the passenger and crew distribution is known with sufficient accuracy in a given time and it is used to define a specific scenario for operational or design purposes.

r(t) is the response time (awareness) that is reflecting the total time spent in pre-evacuation movement activities starting from the initial sound of the alarm. This includes aspects such as cue perception provision, interpretation of instructions, reaction time of each individual, and performance of all other miscellaneous pre-evacuation activities. In addition, in-situ response time or any change in the state of a moving agent through intervention of crew is taken into consideration. Response time is a random variable and its effects on evacuability are studied by sampling from various statistical distributions.

The evacuation dynamics term relates specifically to the walking speed of passengers and crew and constitutes the main motion variable of evacuation dynamics.

s(t) corresponds to walking speed of individual flow of units (agents or persons). The fact that each person onboard is addressed as an individual flow unit and that every procedural (evacuation plan) / functional (crew assistance) / behavioural (microscopic behaviour) parameter could be accounted for as a multiplicative factor ascertaining walking speed, provides a unique and relatively easy way for simulating evacuation, essentially being able to deal with the effect of all of these parameters by simply following a given evacuation plan, accounting for crew assistance in some agreed quantifiable way and then sample walking speed for each individual flow unit from a corresponding distribution dependent on the environment and demographics. Using the relevant Mobility Impairment Index (MII) the walking speed in each case can be calculated. Development of a realistic evacuation simulation implies that a great deal of effort is necessary for accurate quantification of MII for all the microscopic behaviour as well as for specific crew assistance.

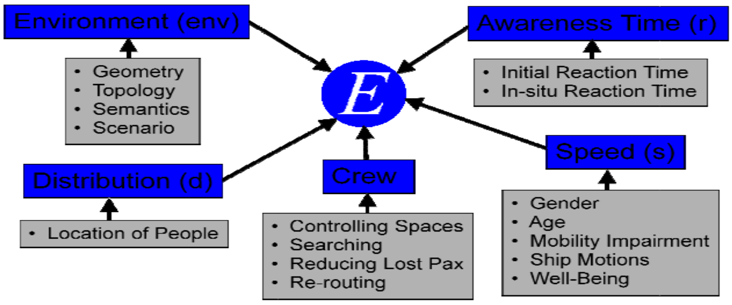

Figure 10 – The concept of evacuability

3 Mathematical modelling

3.1 Multi-agent modelling

The lowest common denominator of many definitions of *agent* is an encapsulation of code and data which has its own thread of control and is capable of executing independently the appropriate piece of code depending on its *own state* (the encapsulated data), the *observables* (the environment) and the *stimuli* (messages from other parts of the system or interactions provided). The agent's action model is essentially a "sense-decide-act" loop. The *sense* and *decide* steps may be coalesced, as the sensing is nothing more than the interface of the agent with the data structures representing the environment. The decision process requires access to the perceived information, thus perception is not a complex process but rather a simple access interface between the environment and the agents.

Notably, the actions of agents may also change the environment, giving rise to what is called *interactive fiction*. Multi-agent is a further generalisation of process-based modelling methods, where the environment is very well defined and the agents may communicate in a fairly versatile manner. In natural systems, all component parts "live" in some sort of topological space, very much like predators and prey that live together on a two dimensional forest floor, data packages traversing a network graph, evacuees move around on a 2-D deck or offshore installation layout, etc.

An *environment* is defined to be an artificial representation of this space. Autonomous agents can perform the activities defined by a computer program in this environment. This strong sense of environment does not exist in a process-based simulation. Processes are only aware of themselves and the resources they wish to acquire. During implementation the environment will be represented as a collection of data structures in the computer. Communication in multi-agent simulation describes all interaction between real life entities, which makes multi-agent simulation an extremely powerful tool and, at the same time, one which is difficult to verify in the context of known mathematical theory. The essence of using agents requires a rigorous definition and full implementation of the environment and its interfaces with the agents as well as an inter-agent communication protocol.

3.2 The environment model

Modelling of the environment is one of the most important aspects of multi-agent simulation. As a whole, this task consists of three aspects: geometry, topology and domain semantics. The perception model for the agents is able to use the information in these three abstractions at different levels of the decision processes. A multi-deck layout may be modelled as a *manifold* of topological dimension 2. A ship layout can be a pedagogical example of a topological space, where uniform coordinate charts are assumed for large finite neighbourhoods. Such two dimensional Euclidean coordinate charts will hold for large regions, typically a corridor. Therefore, the overall model may consist of many interconnected regions with local coordinate systems, where the structure of a linear space may be assumed.

The ship area manifold is segmented into convex subsets whose mutual intersection can be subsets of 1-D topological manifolds for which a Euclidean structure holds. Furthermore, this segmentation is done in such a way that three regions may intersect only at points (i.e. 0-D topological sets). These subsets are called *regions* and the 1-D sub-manifolds (curves) along which two of them intersect is termed *gates*. Two regions are *directly connected* if they have a common gate. Similarly, gates are defined to be directly connected if they lie on the same region. This connectivity, for all computation and analysis purposes, can be represented by a *graph*. In ship layout terms, regions are defined as cabins, corridors, public areas (or subsets of these), each with its own co-ordinate system and connectivity, defined by gates.

Figure 11 and figure 12 illustrate schematically these ideas. The path of the agents leading to the embarkation station is determined by searching the connectivity graph. A *depth first* exhaustive search over the gate graph is used for choosing the optimal path that will be used for high level planning activities. Currently, the length of the path is taken as the criterion of optimality for network flow.

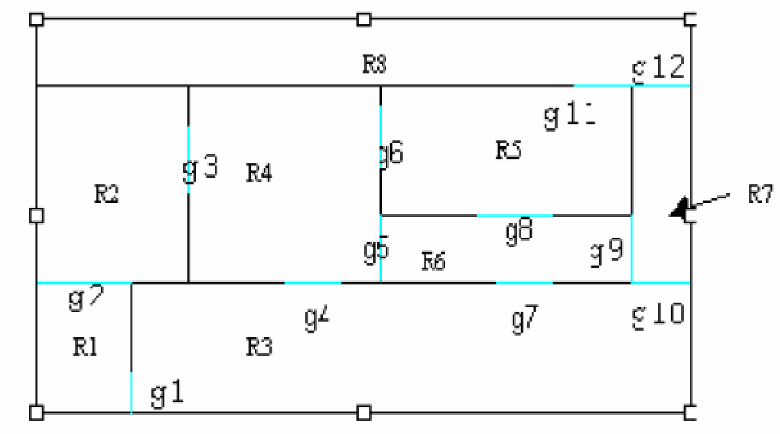

Figure 11 – An example layout of regions and gates

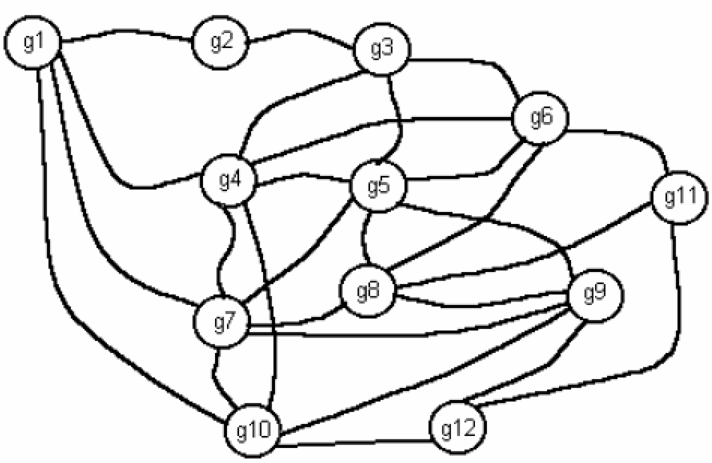

Figure 12 – Gates graph corresponding to Figure 11

The availability of 2½-D and 3-D models allows real time visualisation, in which the complete geometric details of the ship and human agents will combine in a realistic simulation. As an alternative, the code can also be executed separately, allowing a much faster evaluation of a scenario, thus reserving visualization as a post-processing alternative.

Finally, a minimal description of the ship arrangement will enable designers to modify the layout easily (e.g. to swiftly add a new corridor), hence obtaining evacuation performance faster and making part of the early design process. The contrary can also be achieved: by blocking areas, regions or whole fire zones the effect of these changes can be examined and therefore the sensitivity of each different part of the vessel on evacuation performance. This will make *what if* questions easier to answer. The main strength of the modelling adopted derives from the inherent capability to utilise high and low level planning interchangeably in a way that human behaviour is modelled realistically, whilst ensuring high computational efficiency.

3.2.1 The environment model

The *Evi* environment model is a large data structure of linked entities. Level entities can be seen as layers, which contain spaces and doors (containers), representing decks, stairway landings or other horizontal levels in the ship. Spaces, which can be either represented by simple rectangles or convex polygons, model open areas where passengers and crew (agents) can freely walk about. Doors connect a pair of spaces together allowing more complex ship arrangements to be defined. Note that the term door is used to describe any connection between two spaces and not just physical doors. Spaces are extended in the case of Stairs allowing two Levels to be connected together.

The environment model database is defined using the Evacuation Editor. Using this tool, the general arrangement drawings (DXF) can be imported into the software and the entities of the environment can be defined accordingly.

> Levels (decks) are defined by one parameter specifying the height above a horizontal reference point, usually corresponding to the baseline of the ship. As stair connections are defined in a unidirectional manner, levels should be defined from the bottom of the vessel upwards. In cases where it is necessary to quickly develop an arrangement, the lowest deck can be located at 0.0 m and subsequent decks at 2.50 m intervals.

> Spaces are closed convex loops containing areas in which agents can freely move and can be defined as rectangular or convex polygons. Rectangular spaces are defined by a centre (x, y), a width and a height dimension, although the editor makes available the left, top, right and bottom dimensions as editable parameters. Convex polygons are defined by a set of points and as such no geometric parameters are directly available for editing. Geometrically, agents are defined by a point and a fixed radius of 0.20 m. Consequently, to impose containment (prevent agents crossing space boundaries) a virtual boundary is defined 0.20 m within the boundaries, which the centre of the agent cannot cross. Hence, spaces where this internal boundary cannot be generated, because the space is too small, are considered invalid and the editor will display warnings during definition. Due to the simpler nature of rectangles, the calculation of containment in rectangles is slightly faster than for polygons.

> Doors represent the connections between spaces and are defined by a reference point and the door width. The direction of the door is found by analysis the location of the point with respect to the boundary segments of the two connected spaces. In order for an agent to cross from one space to another the containment of both spaces must be violated to allow the agent to travel through the boundary segments. Doors act as bridges, overriding the boundaries of spaces, by providing new containment information allowing agents to travel between the two spaces. As with spaces, doors that have a nominal width of less than 0.40 m are invalid because they prevent agents

from travelling through them. This restriction will be increased in the connection of polygons with large external angles at the corners adjacent to the door.

3.2.2 Environment attributes

In addition to geometry parameters, spaces and doors have several parameters that control initial conditions and semantic information that agents may query when traversing through. The parameters and explanation of each are given below:

CabinCapacity specifies the maximum capacity of a cabin when analysing a scenario that requires passengers to return to their cabins from other places of the ship. The parameter is used following specific commands: CheckPaxCabinPlaces, CheckCrewCabinPlaces, AssignPaxCabinPlaces and AssignCrewCabinPlaces.

FireZone specifies the fire zone of a space. This information is used in the analysis of agent information with respect to location in the vessel. The command ListAgentLocations lists the location of passenger and crew agents with respect to a deck and a fire zone. The command ListZoneEvacuationTimes lists the time it takes for each fire zone to empty. Fire zone information is also use in the selection of commands like SelectSpacesInZone, SelectDoorsInZone, SelectAreaSpaces and SelectAreaDoors.

InitialPax specifies the initial number of passenger agents within a space and is used by AddDefaultPax when adding the initial number passenger agents to a scenario.

Initial Crew specifies the initial number of crew agents within a space and is used by AddDefaultCrew when adding the initial number crew agents to a scenario.

MusterStation specifies the assembly station to which the agents contained in this room should travel to if they have not been assigned this information previously.

PrimaryRoute: In a complex local arrangement, certain areas will be assigned as the main evacuation routes. In this case, the path planning calculation is forced to focus on these areas rather than alternative routes. In the path planning calculation itself, the distances to traverse spaces that have been assigned as primary routes are reduced by 90%.

SpaceType specifies the designation of the space. The options are: Cabin, Corridor, CrewCabin, Public, Stairs, CrewPrivate, CrewService and Open Deck. Generally, space designation has no direct functionality in the simulation although some objective functions may avoid travelling into spaces specified as cabins as these spaces are not normally accessible.

Doors Blocked specifies whether a door is initially blocked when the ship database file is loaded for simulation.

DoorType specifies the designation of the door. The options are: Door, Union, Opening, Fire Door and Watertight Door. The door designation has no direct functionality in the simulation itself except from the way that verbal agent messages are transferred between spaces. However, in Eve, doors specified as Union maintain the largest size possible and automatically update as connected spaces are resized.

PrimaryRouteBreak: At the beginning of a simulation, if a door is tagged as a PrimaryRouteBreak is virtually closed in order to force agents to use more preferable routes. However, if agents find their route blocked, these doors will become available as valid routes.

3.2.3 Assembly station

In almost all cases, the majority of agents within an evacuation scenario will ultimately head for designated assembly stations. In *Evi*, assembly stations (or muster stations) represent a group of spaces that can be referred to by a single reference throughout. This reference can then be used when devising a scenario in Eve or with the command line. Assembly station references can be used when assigning signage to spaces using the "MusterStation" attribute or when assigning agents objectives.

Path-planning data for assembly stations is managed differently than routes to other locations. As assembly stations are well-defined locations, once generated, the path-planning data is retained for the duration of the simulation. This is in contrast to data for other routes where the data is generated on demand and discarded once no longer required. Consequently, higher simulation efficiency can be achieved by defining a zone of spaces as an assembly station if a large number of agents will use this location as an intermediate point of a longer route.

Once agents have arrived within an assembly station, which is the final destination or their currently defined route, their behaviour alters to prevent blocking of entry points. Moreover, while in an assembly station, agents continually monitor the global density within their current space and will move to a less dense space within the assembly station if the density increases above that defined by the argument "MusterStationDensityMoveTrigger" (default value: 1.50 agents per square meter).

3.3 Path planning and graph search

With increasing complexity of the minimal geometry of the ship to thousands of doors and regions, it is very important to have an efficient path-planning process. The path-planning algorithm adopted is illustrated in figure 13. If all doors neighbouring the final door that leads to the embarkation station were searched and the distance information to each door were stored, doors of cabins could be straightforwardly reached within a few cases of the search process. Then only the distance information from each door to the embarkation station needs to be left with the door's id. When an agent is located in a region, the distance information from each door of the region can be obtained, thus allowing the agent to follow to the shortest path leading to the destination area. Having the pre-planning of the paths to be followed completed before the actual simulation starts, re-planning during evacuation is still possible if, for example, there is a dense crowd 'blocking' a door or a visual blackout in the presence of fire or smoke.

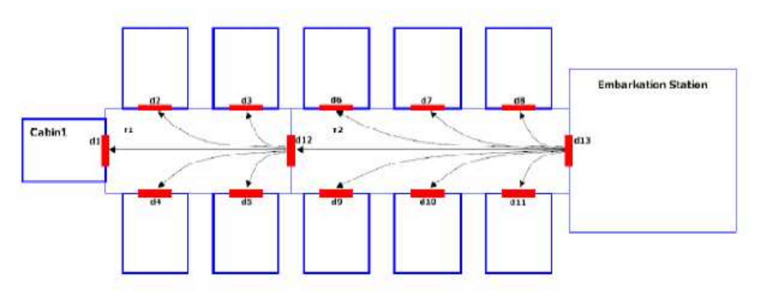

Figure 13 – Simple illustration of the path planning algorithm

Pursuit of a static target acts like the steering of an agent towards a specified position in the space. This behaviour adjusts the agent so that its velocity is radially aligned towards the target. The "desired velocity" is a vector in the direction from the agent to the target representing global "flow speed", adjusted on the basis of local density.

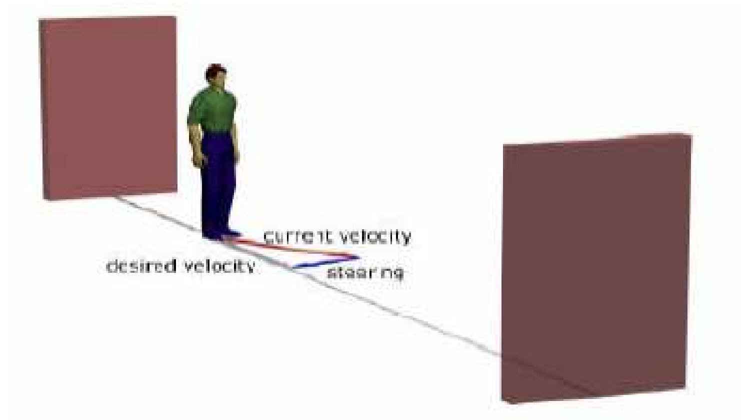

Figure 14 – Pursuit of a straight target

The steering vector is the difference between this desired velocity and the agent's current velocity, as shown in figure 14. Derivation of the evacuation direction requires a calculation from the current point to the closest point on the target with a simple closed form algebraic calculation. In the absence of any obstacle and other evacuees, every agent will "flow" along the evacuation direction field (passing through the gates unobstructed). Avoidance heuristics are used to prevent collision with the neighbouring agents and obstacles along the evacuation path.

4 Modelling the human behaviour

4.1 Framework adopted

The evolution and outcome of an evacuation scenario is determined by a large number of population and behavioural parameters. The former aspect is addressed by the profile of each individual passenger (age, gender, etc.), the group of passengers (total number, proportion of persons with impaired mobility, etc.), the passenger and crew distribution (spatial and temporal) in various crisis situations and it is modelled easily as there is statistical data available from most ship operators. On the other hand, Evi treats passengers as agents moving in a "command" and "decision" structure suitable for a given scenario and in accordance with a set of attributes which are modelled as an array of *genes*: the tendency of a mother to search for her child before abandoning the ship, the leadership a father provides to his family in a crisis situation, parents followed by their children, the grouping of the members of the same family, etc. Genes may be active or inert depending on circumstances, time and domain semantics, e.g. if the current leader of a group becomes incapacitated, a new leader (someone with the right gene) would take this role.

Individual or group behaviour and requisite control is application-specific, demands different levels of sophistication and involves a range of control options: predefined behaviour ("programmed"), rule-based behaviour ("autonomous"), interactive control ("guided"), and adaptive control ("intelligent").

4.2 Synchronisation

One of the most important aspects of the microscopic behaviour algorithms is the synchronisation between agents as this has a great effect on the overall quality of the simulations. However, considering that each agent is represented by a finite piece of code (encapsulation of code and data) the simulation of an evacuation scenario would require substantial parallel processing of the information input to each agent but such capability is not readily available in most personal computers. The update process in *Evi* is separated into two steps. In the first step, the Perception–Decision Phase, all agents calculate / update their vector but do not move, and therefore, they perceive the update in parallel, i.e. they all update using one environment state. In the second case, the agents carry out their calculated / updated actions.

4.3 Perception phase

The perception algorithm checks the space (in the form of discreet directions) around the agent for boundaries and other agents. Twenty-one directions are checked, starting from directly ahead then 10º to one side followed by 10º to the other side, until reaching 100º. As the checked directions become progressively wider, the calculation stops if a direction is found where the agent can progress without reaching any walls or interfering with other agents. Each direction is checked by looking for intersections with space boundaries (containment) or other agents (collision avoidance) between the agent's current location and the end of update vector defined for the direction being checked. For angles in the forward quadrant (± 45º) the magnitude of the update vector corresponds to the distance that can be travelled over the time step. Above 45º, the distance of travel is linearly reduced by 1/3 at 100º to simulate the loss of speed due to change in direction.

The modelling of lane formation is also introduced in the perception algorithm. Based on the location of the surrounding agents or whether surrounding agents have already chosen a lane, the search direction is either restricted to the left or right side. Under normal operation, the perception algorithm will check agents on the basis of avoiding the personal space of other agents. However, when a squeezing operation is being checked, the physical radius of the agents is used.

4.4 Decision phase

The decision algorithm uses a rational rule-based process to select the action to take for the current time step. The decision process makes use of information on the previous time step combined with information acquired from the Perception algorithm. The Perception algorithm may be called twice for cases of high congestion when "Squeezing" is considered as alternative course of action. Before entering the decision process, the algorithm first gathers state information from the current environment that may affect the perception process. This includes update of the desired travel direction, consideration of the current waypoint and selection of the current maximum speed taking into account environmental and well-being parameters (i.e. effect of ship motions, smoke and toxicity). Once this information becomes available, it is projected onto the 2-D horizontal plane for compatibility with the Perception Algorithm. Considering that at each time step each agent is concerned with calculating a new position the number of possible actions is small. However, there are a few scenarios that must be considered in order to select the best action to proceed. Five decision states are possible, each with an associated movement update vector:

> Update: The agent should update as normal moving as far along the update vector as possible.
>
> Wait: The agent does not move.
>
> SwapAgentPosition: The agent in collaboration with another oncoming agent has decided to swap positions to resolve a deadlock.
>
> Squeezing: The agent is located in a congested space but perception indicates that if the personal space is disregarded, progress can be made.
>
> Stepback: Another agent who is squeezing through has violated the agent's personal space. The direction of update is reversed to allow the squeezing agent through.

The decision process, takes account of the previous actions, considers whether the agents personal space is being violated or whether it can get through by taking more aggressive action.

4.5 Action phase

Although the Perception – Decision Phase takes great care in identifying the most appropriate update to take, the likelihood for two agents to occupy the same region of space remains high. Therefore, it is necessary that each agent checks how far it can move before executing its selected action. Again, due to the nature of software programming, this will be a sequential activity and it is necessary to take a special approach to the action update to avoid loss of synchronisation. Despite the flexibility of the Perception – Decision Phase, if agent A is updated before B, agent A cannot travel all of the distance it had planned as agent B can. If the order of update is reversed, both agents can travel the same distance. To ensure that agents update properly, order is introduced into the system whereby each agent requests those travelling in front and in the same direction to update first, before updating itself.

Once the agent has moved, it then performs a number of housekeeping tasks:

(i) It verifies the containment by checking whether it has moved into the next or previous containment region, either a space or a door.

(ii) It then checks to see whether it has reached its current waypoint, if so it updates it to the next one.

(iii) Finally, any information that should be kept for post-processing is recorded.

4.6 Waiting behaviour

Agents do not travel through the environment constantly: prior to reacting to the assigned awareness time, upon reaching an assembly station they will need to wait until all other agents have completed their tasks, etc. In these situations, waiting agents should not block those travelling around them as this could prevent aware agents from leaving areas like public spaces or from entering an assembly station. To address this issue, agents who are waiting can move as a reaction to other agents around. Using the concept of personal space, waiting agents will shift away from walking agents if they are in the way or the personal space has been violated. The distance that a waiting agent can travel is small in a single time step, i.e. maximum 1.2 times the agent's physical radius.

The algorithm of surrounding agents review those moving and those waiting separately. For moving agents the average location and direction for the group is calculated and a change of direction perpendicular to average direction of travel is selected. If surrounding waiting agents come too close to move out of the way of other agents themselves, the average location of agents violating personal space is calculated and a direction is selected that will direct the shift in the opposite direction from this point.

The need for waiting agents to move out of the way of moving agents is most important for assembly stations and the algorithm is very effective in these respects. Agents entering the assembly station will be allocated a place to stand and as they walk through, waiting agents are pushed aside not only forming a lane but also clearing the entry of the space. Following agents moving to similar locations within the space will use the lanes as a result of the collision avoidance algorithm.

4.7 Objectives

Objectives are the means of controlling an agent's tasks. A variety tasks can be assigned to agents, such as to evacuate to assembly stations or to be lost. Objectives can be assigned individually or to group, with each agent beginning with a default objective, to evacuate to an assembly station (using available information, signage or crew instructions). Crew agents have a wider range of functional objectives allowing modelling of realistic evacuation scenarios.

Messaging provides a medium for agents to communicate between each other. Through this mechanism, crew agents can directly affect the behaviour of passenger agents and ultimately the overall evacuation time. A passenger agent is given information from crewmembers, which will allow it to get to an assembly station. A passenger could meet another agent that is sending passengers via an alternative route. Messages are also sent between passengers, informing each other of the presence of blocked doors and the system provided the basis for a public address system.

4.7.1 Customising agent tasks

In developing a realistic model of an evacuation scenario onboard a passenger vessel it is necessary to model other behaviours in addition to the simple evacuation of passengers to assembly stations. To these end a way of customising an agent's task is required. Considering that potentially there an unlimited number of tasks that an agent could be asked to perform a separation of the task model from the agent model is implemented. This structure allows the task to drive the agent to its objectives, i.e. its behaviour, its destination and whether to wait once arrived. In the case of objectives controlling crew behaviour, complex routes can be generated which direct the agent to look into many spaces, walk up to and control the speed and reaction time of surrounding passenger agents, even change passenger agent's objectives. This high level of additional control is implemented using a message system that is discussed next.

4.7.2 Messages

Messages provide the primary mechanism for agents to communicate with each other and, to a lesser extent, to passenger agents. By broadcasting messages, crew can change the attributes of passenger agents. Two forms of messages are supported:

(i) Local verbal messages are broadcast at the location of the sending agent and travel for only a short distance, which is determined by global arguments that define a range distribution for passenger (PassengerMessageRange) and crew (CrewMessageRange) separately.

(ii) System wide messages are broadcast at the centre of all spaces and have an unlimited range of travel. This kind of message is used to represent broadcasts across the public address system or evacuation control radio traffic to crewmembers.

Verbal messages can travel between spaces using the doors as a routing system. However, as the message travels through the door the distance the message has travels is modified to ensure that it does not exceed the broadcast range. Different door types affect the way the message is relayed depending on the general size of the door. All doors of relatively small size create a diffusion effect, whereas door types that would generally be large, i.e., union, do not create a diffusion effect. Blocked doors do not allow messages to go though.

4.7.3 The Default Objective

In order to perform properly, all agents require an objective. Rather than assigning an objective to each agent, they are capable of finding an (default) objective using a basic set of rules. As the primary aim of the simulation is to model the evacuation process, agents without a directly assigned objective will use attributes in the environment in order to find their way to an assembly station. Agents will read the MusterStation attribute of spaces in order to define an objective that will direct them to the designated assembly station for that space. If they cannot find any signage, they select the Lost objective, until they find or are provided assembly station information through signage or meeting of a crewmember. Crewmembers always know the ship arrangement and will not become lost through the default objective although they can be assigned as lost.

When assigned Objectives are completed and no further information has been given to guide an agent to an assembly station, the agent will revert to the default objective. This does not apply in the case of an Objective that causes the agent to wait for an unspecified period of time.

4.7.4 General Objectives

The general objective functionality is to force an agent to travel to a location and do something. Three kinds of objectives are provided and they are applicable to passenger and crew agents alike. These objectives use the single route path-planner to generate routing information to a destination.

> The <u>Goto</u> objective makes an agent travel to an allocation region. Once the agent arrives, it will execute the next objective or revert to the default objective.
>
> The <u>Wait</u> objective makes an agent to wait for a specified duration of time (seconds) before continuing. If the time to wait is omitted, the agent will wait indefinitely. Once the agent finished waiting, the agent will execute the next objective or revert to the default objective.
>
> The <u>Goto&Wait</u> objective makes an agent travel to a location and wait for a specified duration of time (seconds). If the time to wait is omitted, the agent will wait there indefinitely. Once the agent is finished waiting, the agent will execute the next objective or revert to the default objective.
>
> The <u>Clear</u> objective, removes all current objective assignments from agents.

4.7.5 Evacuation objectives

The evacuation objectives are those that are most likely to be used when modelling an evacuation scenario. These objectives can be used by both passenger and crew agents although, in the case of the Lost objective, it is unlikely that crew would be intentionally modelled as lost. The objectives are as follows.

> The <u>Evacuate</u> objective (the Default objective) is used to assign an assembly station to an agent and control the route it takes to get there. The objective requests the route information from the assembly station path-plan (it is generated if it is not already available). If an Evacuate Objective is not provided with an assembly station, it will search for environmental attributes or crewmembers that can provide it with routing

information. During this process the agent behaves as though it is lost, by selecting doors to travel through at random.

The Lost Objective is applied to passenger agents when they are modelled as lost as part of the initial conditions of the scenario. Lost agents will build a route by selecting an exit door at random from those available in the current space. This behaviour continues until route information is found from the environment or a crewmember. Lost agents are not as coherent at identifying signage information as those with the Default objective. This behaviour is controlled by the global argument ProbabilityOfLostAgentSeeingSignageInSpace, which controls the probability of the detection of signage information in a space for every time step.

4.7.6 Crew objectives

The final group of objectives are used to control crew behaviour during an assisted evacuation scenario. The effect of crew was illustrated in the topic on Evacuability as one of the primary means to affect evacuation during the process. Three main kinds of objectives are provided for controlling passenger behaviour, for guiding passengers on stairways and for searching spaces. A fourth form of objective is provided for re-routing agents through an alternative route when the first route becomes congested. All crew objectives complete when the PassengersEvacuated message is send across the environment and crew return to their assembly station. Finally, any lost passenger agents meeting crew agents are directed to an assembly station.

The Control objective is used to model crew procedural activities such as Stairway Guiding. The objective has the effect that passengers increase speed due to increased confidence (within the message range of the crew agent) and any lost agents are directed to an assembly station. The magnitude of the speed increase is controlled by the global argument "CrewPaxSpeedIncrease" and represents a decimal multiplier.

The Search objective is used to model crew travelling around the environment making passenger agents aware of the evacuation. This behaviour reduces passenger's awareness time by (i) either reducing the existing assigned passenger awareness time to the minimum or (ii) assigning a new awareness distribution based on the point in time the passenger was affected by the crew. This characteristic is controlled by the global argument "RousedPassengerAwarnessness". In addition, any lost agents are directed to an assembly station.

The Search2 objective is used to model crew searching the corridors and cabin spaces of a ship arrangement. The Search2 models exactly the same crew behaviour (and is controlled by the same parameters) as the Search Objective except that it will automatically work out a route around the specified spaces and seek out agents that have not been made aware.

The InspectClear objective is similar to the Search2 objective except that the crew agent will wait until all passenger agents have left the space before proceeding to the next in the specified search.

The Route objective can be assigned to crew agents in order to reduce congestion around a specific area by directing passenger agents to alternative routes. The crew agent only imposes this behaviour once flow has become congested.

4.8 Speed of advance

The speed of agents varies according to range of parameters pertaining to ship/sea environment, the scenario in question and the passenger distribution and profile as described by an even larger number of parameters (like passenger age, size, gender, physical location and position on vessel, signage, crew guiding, ship motion, etc.). In fact, speed of advance is the compounded outcome of all that is going on onboard a ship during evacuation. As per the IMO Interim Guidelines, the speed of an agent is determined by the density of the crowd in the region. In general, crowd density is non-uniform and it strongly depends on the size of the area considered in the density calculation. If the crowd is concentrated near a gate in a big region the remaining part of which is empty, on dividing the number of occupants by the total area of the region may give a small value of density, which clearly fails to capture the situation.

To overcome this drawback the concept of *perceived density* has been adopted, in which the local density in a region in front of the agent is computed and the IMO speed values assigned in accordance with this local density value. This makes the scheme conformant with IMO without sacrificing realism. The crowd density corresponding to an evacuee in an escape route describes the number of persons divided by the available escape route area pertinent to the space where the evacuee is located. As the model geometry is replicating the actual vessel, the density calculations are very accurate. The available escape route area is determined by the actual overlapping area between the regions (e.g. corridors, stairways, etc.), and a density rectangle (2.14 m × 2.14 m was identified as the best choice) that moves with the agent, as shown in figure 15. Additionally, when long queues are formed, the effect on speed of advance is calculated on the basis of the queue length. Dependence of speed on other parameters is modelled by using a set of factors, which are functions of the parameters as explained next. These factors are adequately parameterised for calibration with experimental behavioural data, when it becomes available.

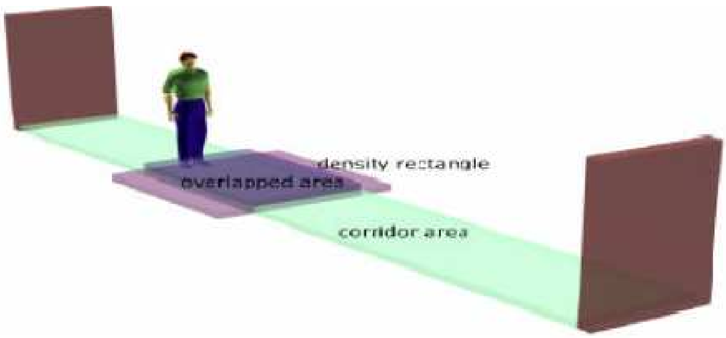

Figure 15 – The concept of local density

4.9 Superposition of behaviour

Superposition of behaviour refers to the way an action (or some parameter) is computed when some conditions hold *simultaneously*, assuming that a method is known of how to compute the same action under each of those conditions *individually*. The speed of advance of individual agents is the most relevant example of this and it is affected by various operating conditions (the individual's attributes, surrounding situation, etc.). As these conditions change with time, speed reduction factors corresponding to different situations are obtained. The more common way of superposing quantities like reduction factors is to multiply them and obtain a resultant factor, which may be thought of as MII, ranging from zero to one and characterising the speed of every agent. Even in the case of actions that are associated with conditions probabilistically, it may be shown that the method of multiplying the speed reduction factors is conformant with the conditional probability based superposition, even if the speed were modelled as a normally distributed random variable.

4.10 Effect of ship motion

With time, humans can adapt to small regular motions and small acceleration variation. However, when the latter become unpredictable and sudden, maintaining balance and forward motion become difficult. Few studies have been undertaken on the effect of inclination on the speed of people's movement but none has been particularly comprehensive and all have used young and physically fit subjects.

Another way of approaching this subject is to relate the speed reduction to the roll angle. To this end, a maximum roll angle of 35º assumed, at which the speed reduction becomes 100%. The reduction in other angles follows the relationship described next. The effect of ship's dynamic and static heeling angles is included in the advancing speed of agents by the following analytically derived function:

$$f(\theta) = \begin{cases} \dfrac{e^{\left(1-\frac{\theta}{\theta_{max}}\right)} - 1}{e - 1} & 0 < \theta < \theta_{max} \\ 0 & \theta > \theta_{max} \end{cases}$$

where θ is the heel (roll) angle of the ship in degrees with θ_{max} set at 35º.

Figure 16 below represents the speed reduction factor in function of the heel angle. The x-axis represents the heel angle from 0º to a maximum of 35º, while y-axis represents the resulting multiplication factor, which reduces the speed of advance. When modelling the dependence of speed on roll motion it would not be appropriate to define is as function of the instantaneous roll angle, as the speed will return to normal even when the roll angle becomes zero momentarily. This indicates that the speed reduction should be expressed as a function of the history of roll motion. Such dependence should account for a reasonably distant past in a way that a more recent part of the history would affect the speed more than a less recent one. Keeping this in mind, a scheme has been proposed in which every agent feels the effect of the roll angle values experienced in the immediate past (this ensures that a too distant past does not have any effect) and reduce the speed according to a weighted average of these with a decreasing function of temporal distance of the corresponding time step as weight (this ensures greater weight of more recent values).

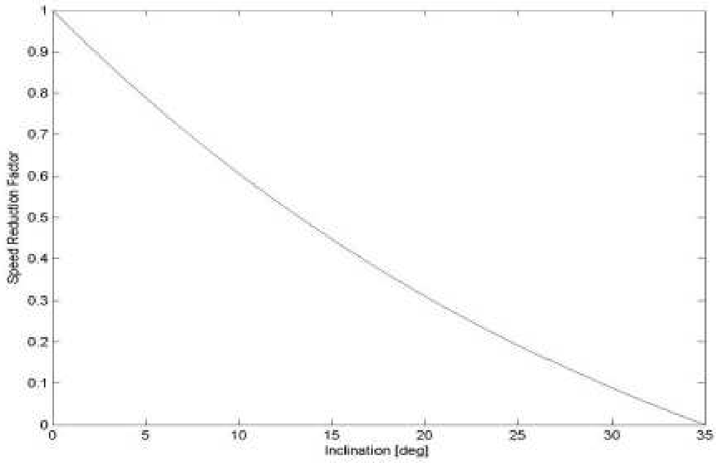

Figure 16 – Walking speed reduction factor as a function of ship heeling angle

4.11 Modelling uncertainty

4.11.1 Human behaviour parameters

The psychological and physiological attributes of human beings are non-deterministic fuzzy quantities. Even in successfully contrived experiments one can hardly reproduce human actions/reactions even if all of the conditions remain the same. This inherent unpredictability of human behaviour, especially under unusual and stressful circumstances, rules out the possibility of a deterministic mathematical structure (or program) to model evacuation correctly. For this reason, human behaviour has to be modelled with some built in uncertainty. To this end, every parameter (continuous or discrete) is modelled as a constrained random variable with a predefined distribution. Continuous variables (attributes) are modelled as normally distributed random variables with pre-assigned mean and variance (the Box-Müller transform allows a continuous distribution to be implemented in the simulation). Variables that are discrete in a deterministic context are treated as fuzzy variables and the Roulette Wheel technique is used for de-fuzzification. This is to eliminate the occurrence of unrealistic behaviour, for example, every female agent having exactly 15% lower speed of advance than a male agent or everybody of the same age reacting exactly at the same time to an alarm call.

4.11.2 Monte Carlo method

The inherent uncertainty in human behaviour gives rise to a certain amount of variation in the simulation results for different instances of execution. Thus, the individual results obtained in each simulation will not be suitable for evaluation or sensitivity analysis and some statistical aggregate quantities evaluated over several simulation runs have to be defined with the property of approaching a limit as the number of ensembles grows indefinitely. Considering this, the term *Evacuability (t, env, dist)* discussed earlier in this document, is abstractly defined to be the probability of an environment being completely evacuated of human occupants no later than a time *t* elapsed after the initial sound of the alarm, in a given state of the environment *env* (i.e. the layout , the conditions, and the egress system if applicable) and a given state of initial distribution *dist* of people in the environment (including the distribution of behavioural attributes).

Hence, if data were available on evacuation time from a number of simulation runs (given that the environment and the distribution remain the same) as a multi-set $\{t_1, t_2, t_3, t_4, \ldots, t_n\}$ then by the law of large numbers Evacuability may be determined with an accuracy directly dependent on the number of runs. With this formalism a mathematically sound regulatory rule can be expressed as:

Evacuability (60 min., entire ship (worst anticipated conditions), worst passenger distribution) > 0.99.

This is a more suitable way of addressing regulatory issues since the inherent uncertainty in the system is acknowledged and allows for any desired degree of stringency.

5 Fire Effects Assessment

Fire effects are crucial in the evacuation procedure as fire and its products can severely impair the evacuees and even cause total incapacitation or fatalities. Therefore, the assessment of these effects on the agents is vital from the human safety point of view. Generally speaking, when evaluating the consequences of fire effluent to human life, the crucial criterion for life safety is that the time available for escape should be greater than the time required. The time available for escape is the interval between the time of ignition and the time after which conditions become untenable such that occupants can no longer take effective action to accomplish their own escape. Untenable conditions during fires may result from:

- Inhalation of asphyxiant gases, which may cause loss of consciousness and ultimately death due to hypoxic effects, particularly on the central nervous and cardiovascular systems
- Exposure to radiant and convective heat
- Visual obscuration due to smoke

The above represent the fire hazards and can be imported and distributed in time and space into the evacuation environment (*Evi*) as explicit semantic information for the agents. These include concentrations of CO, CO_2, and O_2, as well as temperature, radiant heat flux and optical density directly affecting the awareness and walking speed of the evacuee, at each time step.

In order to estimate the effect of the fire hazards, an approach presented by (Purser, 2002) was adopted. The approach is based on the concept of Fractional Effective Dose (FED) for toxicity and heat, and Fractional Effective Concentration (FEC) for visibility. FED and FEC are values indicating the human vulnerability to the cumulative effects of exposure to heat and toxic gases as well as the level of visibility in a space. Their values are calculated for each agent individually at a reference height of 1.5 m above floor level and are used to control walking speed and awareness, and determine the point at which an agent becomes fatally injured (see figure 17 and figure 18). The specific models used are elaborated next.

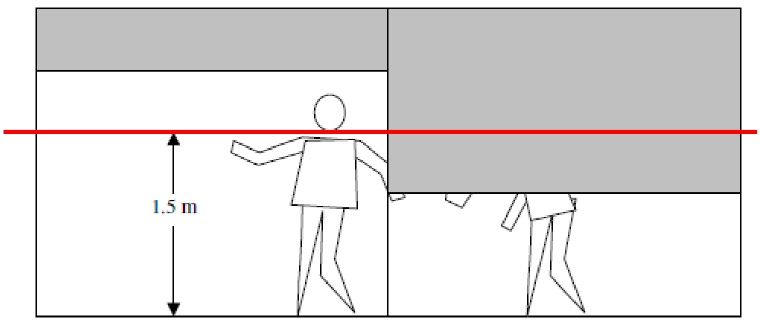

Figure 17 – Reference level for calculation of FED and FEC

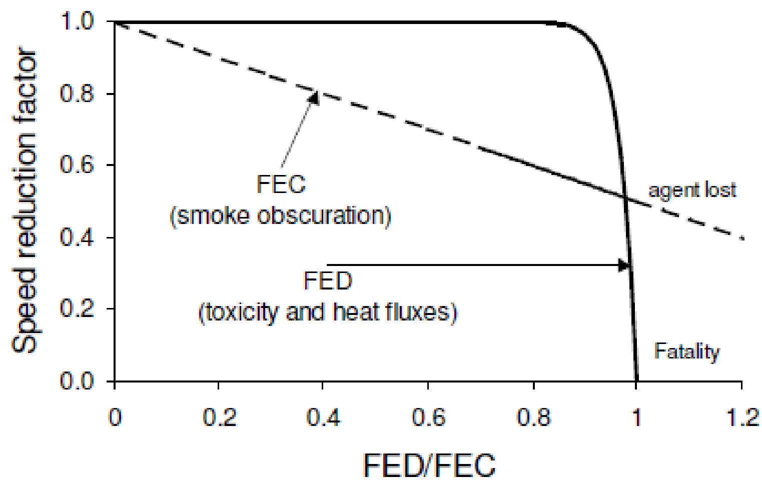

Figure 18 – Speed reduction factor due to hazards, based on conservative engineering judgement and pending of further of experimental data.

5.1 Toxicity

The Fractional Effective Dose of incapacitation, FED_{IN}, due to toxicity is depending on the interactive asphyxiants considered in the model (carbon monoxide CO, carbon dioxide CO_2, and depletion of oxygen O_2) and it is given as follows:

$$FED_{IN} = \left(FED_{CO} \times V_{CO_2}\right) + FED_{O_2}$$

Carbon Monoxide (CO) is produced in both smouldering and flaming combustion and is largely dependent on oxygen supply. Ventilation controlled fires favour the formation of CO. The toxic effects of CO are those of anemic hypoxia, i.e. the condition in which there is an inadequate supply of oxygen to body tissue and by a lowered oxygen-carrying capacity of blood even when the arterial pressure of oxygen and the rate of blood flow are normal.

The Fractional Effective Dose for CO (FED_{CO}) is calculated as follows:

$$FED_{CO} = \sum_{t_1}^{t_2} \frac{k \times [CO]^{1.036}}{D} \Delta t$$

where *[CO]*:; is the average concentration of CO in ppm over the time increment Δt in minutes; *K* and *D* are constants depending on the activity of the person (their values for different levels of activities are given in Table 23).

Activity	K	D
At Rest	2.81945×10^{-4}	40
Light Work	8.29250×10^{-4}	30
Heavy Work	1.65850×10^{-3}	20

Table 23 – Values of constants K and D for different activity level

Carbon dioxide (CO_2), like carbon monoxide, is universally present in fires. Although CO_2 is not toxic at concentrations of up to 5%, it stimulates breathing. This hyperventilation, apart from being stressful, can increase the rate at which other toxic fire products (such as CO) are inhaled. The increased uptake resulting from CO_2-induced hyperventilation will significantly reduce time to incapacitation and death. To take this effect into consideration, the value of FED_{CO} at each time increment, shall be multiplied by a frequency factor V_{CO2} to allow for the increased rate of asphyxiant uptake due to hyperventilation, given by the following expression:

$$V_{CO_2} = \frac{e^{(0.1903 \times \%CO_2 + 2.0004)}}{7.1}$$

where $\%CO_2$ is the percentage of CO_2 in the evaluated compartment.

Oxygen (O_2) depletion is also a result of fire and it is capable of causing human hypoxia and hence incapacitation. The effects of low oxygen are dependent on both the concentration and the exposure time. For oxygen concentrations between 20.9% and 14.4% per volume, no significant effects are observed apart from slight loss of exercise tolerance. Slight effects on memory, mental task performance and reduced exercise tolerance are expected at concentration in the range of 14.4% to 11.8% of O_2 in air. At 11.8% to 9.6%, severe incapacitation and loss of consciousness can occur, while between 9.6% and 7.8% also loss of consciousness and death are expected. The FED_{O2} is calculated as follows:

$$FED_{O_2} = \sum_{t_1}^{t_2} \frac{\Delta t}{e^{(8.13 - 0.54 \times (20.9 - \%O_2))}}$$

where $(20.9 \times \%O_2)$ is the percent O_2 vitiation over the time increment Δt.

5.2 Convective and radiative heat

The body of an exposed occupant may be regarded as acquiring a "dose" of heat over a period of time. There are three basic ways in which exposure to heat may lead to life threats:

- Hyperthermia
- Body surface burns
- Respiratory tract burns

For use in the modelling of life threat due to heat exposure in fires, it is necessary to consider only two criteria:

- The threshold of burning the skin
- The exposure where hyperthermia is sufficient to cause mental deterioration and, therefore, threaten survival

A short exposure to a high radiant heat flux or temperature is generally less tolerable than a longer exposure to a lower temperature or heat flux. A methodology based on additive FED similar to that used with toxic gases may be applied and, provided that the temperature in the fire is stable or increasing, the total FED of heat acquired during an exposure can be calculated according to the following expression:

$$FED_{Heat} = \sum_{t_1}^{t_2} \left(\frac{1}{t_{conv}} + \frac{1}{t_{rad}} \right) \Delta t$$

where, t_{rad} (in min) is the time to burning of skin due to radiant heat. The tenability limit for exposure of skin to radiant heat is approximately 2.5 kW/m^2. Below this incident level exposure can be tolerated for 30 minutes or longer without significantly affecting the time available for escape. Above this threshold, the time to skin burning due to radiant heat decreases rapidly according to the following equation (Figure 19):

$$t_{rad} = 1.333 \times \dot{q}_{rad}^{\left(-\frac{4}{3}\right)}$$

where, $\dot{q}_{rad}$ (in kW/m^2) is the radiant heat flux.

Calculation of the time to incapacitation t_{conv} (in min) under conditions of exposure to convective heat from air containing less than 10% by volume of water vapour can be made using the following equation:

$$t_{conv} = k_1 \times T^{k_2}$$

Where T is the temperature in °C; k_1 and k_2 are model parameters here taken as 4.1x10^8 and - 3.61 respectively for fully clothed persons.

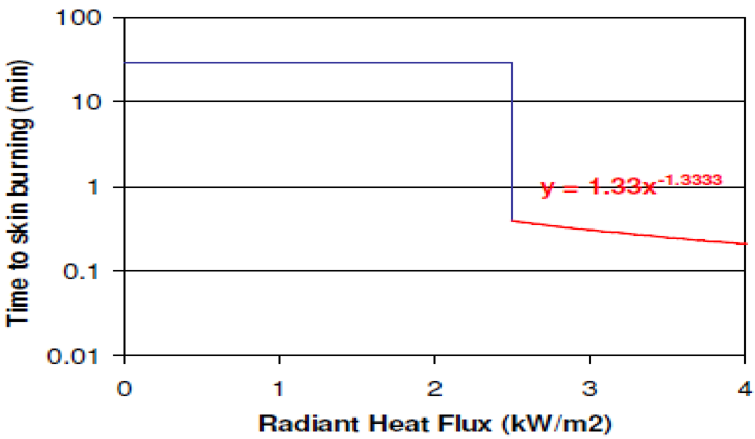

Figure 19 – Assumed relationship between time to skin burning and radiant heat flux: up to 2.5 kW/m² the tolerability is 30 minutes or longer without incapacitation

5.3 Visibility

In addition to the gaseous part of smoke there is the visible part of smoke. This visible part is constituted of the fine liquid and/or solid particulates dispersed in the air and known as aerosols. Since aerosol and visible lights have approximately similar wavelengths, light is scattered and vision is obscured through smoke. Therefore, smoke block visibility of the exit routes and effectively deteriorate the escape of occupants. The development of smoke that can hinder evacuation is known to be very rapid. Smoke obscuration is usually known as the first hazard to occur after a fire incident; it is observed in an early stage before heat or toxicity attains untenable conditions. The fast development of visible smoke can give a quick warning of fire; however, it impairs evacuation either partially or totally and poses threat on human lives. Smoke effects on the movement speed and way-finding ability of evacuees depend on the concentration of the smoke and its irritancy to eyes. The ability of smoke to obscure visibility is governed by the smoke's light extinction coefficient (k_{ext}) which is directly dependent on smoke concentration in the air.

Experimental data for behaviour of humans whose visibility are impaired by smoke are limited. One of the first fundamental studies on this subject was conducted by Jin in Japan (Jin). The studies included investigation of the walking speed of evacuees in a smoke filled corridor. A range of low mass concentrations of smoke was used, where the maximum light extinction coefficient did not exceed a value of 1.15 (1/m). Recent experimental studies were performed by Frantzich to investigate walking speed and behaviour in a smoke filled tunnel (Frantzich & Nilsson, 2004). The light extinction coefficient in the experiments varied between 2 and 7 (1/m). The walking speed of each evacuee was calculated by dividing the total distance walked (traced by cameras) by the total time in the tunnel. As the range of light extinction coefficient used in each experiment is different, no direct comparison between the two sets of data is feasible. However, the two ranges of extinction coefficients are found continuous where Jin's experiments do not exceed an extinction coefficient value of (1.15/m) and Frantzich considers smoke concentrations with k_{ext} between (2/m) and (7/m). The results of both experiments relating the walking speed to the extinction coefficient are presented in Figure 20.

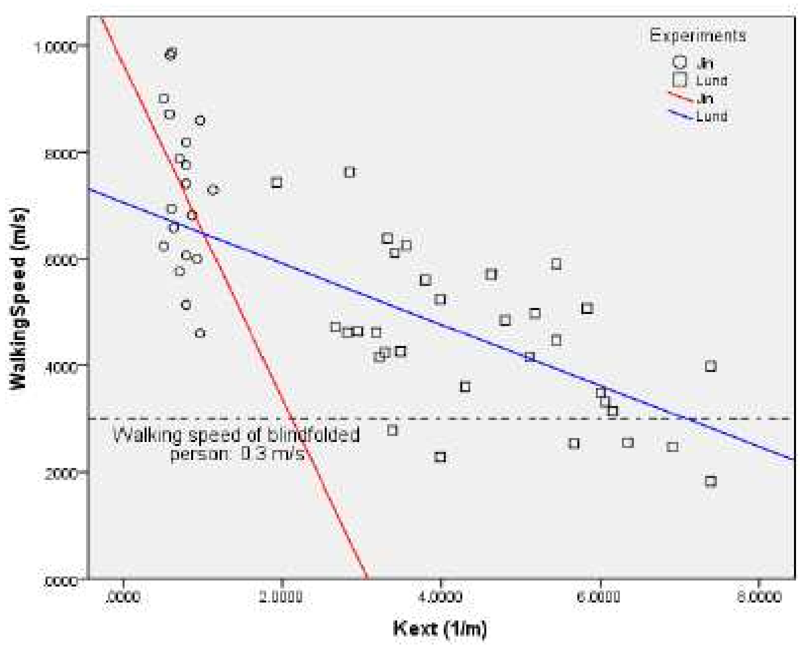

Figure 20 – Jin and Frantzich experimental data relating the extinction coefficient to walking speed (Azzi & Vassalos, 2009)

A linear regression analysis for each data set provided a linear relation between the walking speed (m/s) and the light extinction coefficient, k_{ext} (1/m).

$$\text{Walking speed} = \beta \times k_{ext} + \alpha$$

The values of the regression coefficients and their standard errors are given in Table 24 below.

	$\beta(m^2/s)$	$\alpha(m/s)$	Std. error $\beta(m^2/s)$	Std. error $\alpha(m/s)$
Frantzich	- 0.057	0.706	0.015	0.069
Jin	- 0.314	0.965	0.198	0.152

Table 24 – Regression analysis values for the experimental data relating walking speed and extinction coefficient (Azzi & Vassalos, 2009)

The relation used to relate walking speed to extinction coefficient is a combination of Jin and Frantzich lines. The two lines in the graph intersect at the point (k_{ext}, *Walking speed*) ≅ (1, 0.65). The relation derived from Jin's data is used for $k_{ext} \leq 1/m$ while Frantzich's relation is used for $k_{ext} > 1/m$. The minimum average walking speed of a person was taken as the speed of a blindfolded person or people walking in total darkness using their hands to find their way; this speed was set as 0.3 m/s (Bukowski, 2003).

6 Batch Running

The batch running process is designed to be as automatic as possible depending on the problem size and complexity. Data analysis from simulation runs are written to the results list using various built-in commands. The following solutions are available for batch running simulation scenarios.

The Batch Manager features the user interface when setting up a simulation. The user is provided with a text editor to specify the scenario and the number of runs. The results are saved in separate files and they are accessed from the results text editor.

The Multicase Batch Runner requires less user interaction compared to the batch manager, but it is capable of running a larger number of different scenarios. For each scenario, the model file, the scenario script and the number of runs are specified separately.

The EviNet system allows concurrent execution of simulations across a network of computers, thus reducing the processing time of the overall simulation. It is based on the Multicase Batch Runner where cases are specified using model files, a scenario script and the number of runs. These files are then sent to remote versions of Evi running on computers in the network for processing. After the run is finished, the contents of the result list and the simulation time are sent back to the main manager software, which collates all the information and produces a scenario report.

Command line interface: there are also three batch run commands which do not use any graphical functions and continue to display the simulation. These are the BatchStart, the BatchCancel and the BatchRestart.

7 Conclusions

This report provides a description of the Evacuability Index (*Evi*) evacuation simulation model. The main concept of evacuability and the approaches used to model the main issues associated with evacuation in general and the ones specific to shipboard evacuation are presented and explained. Details of the methods used to calculate the effects of fire effluents on evacuees are all presented and explained in their three categories, toxicity, heat and visibility.

References

(Azzi & Vassalos, 2009), "DESIGN FOR SHIPBOARD FIRE HAZARDS ASSESSMENT." In, 10th International Marine Design Conference (IMDC), Trondheim, pp. 476-488.

(Bukowski, 2003), "Fire Hazard Analysis." In, Fire Protection Handbook. NFPA, Quincy Massachusetts.

(Frantzich & Nilsson, 2004), "Evacuation Experiments in a Smoke Filled Tunnel." Lund University, Sweden.

(Guarin et al., 2007), "Design for fire safety", Guarin, L., Logan, J., Puisa, R., Jasionowski, A. and Vassalos, D., Proceedings of the International Conference on Design for Safety, San Francisco, USA, 2007

(Guarin et al., 2004), "Fire and flooding risk assessment in ship design for ease of evacuation", Guarin, L., Majumder, J., Vladimir, S., Vassalos, D. and Vassalos G., Proceedings of the International Conference on Design for Safety, Osaka, Japan, 2004

(HSE, 2001a), "Marine Risk Assessment", Offshore Technology Report 2001/063, prepared by DNV for HSE UK, 2001

(HSE, 2001b), "Reducing Risks – Protecting People", HSE UK, 2001 (ISBN: 0 7176 2151 0)

(Mather & Strang, 1997), "Regulatory Requirements – Do These Adequately Reflect Actual Fire Experience?", Mather, P. and Strang, T., International Conference Fire at Sea, London, November 1997

(Purser, 2002), "Toxicity assessment of combustion products", Purser, D., SFPE Handbook of Fire Protection Engineering, Quincy (MA), USA, 2002

(Safety@Sea, 2009), "Program Overview – Evi", Safety at Sea Ltd, internal report, Glasgow, UK, 2009

(SSRC, 2007), "Quantitative Risk Analysis (QRA)", FP6 Project SAFEDOR (IP-516278), Deliverable 2.5.2, 2007

(SSRC, 2006), "Human life safety – Qualitative Design Review (QDR)", FP6 Project SAFEDOR (IP-516278), Deliverable 2.5.1, 2006

(Vassalos et al., 2004), "Effectiveness of passenger evacuation performance for design, operation and training using first principles simulation tools", Vassalos, D., Guarin, L., Bole, M., Majumder, J., Vassalos, G. and Kim, H.S., Lloyds Register, London, 2004

(Vassalos et al., 2001), "A mesoscopic model for passenger evacuation in a virtual ship-sea environment and performance-based evacuation", Vassalos, D., Kim, H., Vassalos, G. and Majumder, J., Proceedings of the Pedestrian and Evacuation Dynamics, Duisburg, Germany, 2001.

9 Appendix 3

"maritimeEXODUS Technical Documentation for effect of toxic species and smoke on physiology and movement" document – Compiled by Fire Safety Engineering Group - University of Greenwich

This document is intended to give an outline of the manner in which heat, smoke and gases (i.e. both irritant and non-irritant) affect individuals within the maritimeEXODUS model. Aspects of the model not affected by either heat, smoke or toxic gases are therefore not within the scope of this document, and hence are not directly explained.

1 Introduction to maritimeEXODUS

In this chapter the theoretical basis of the EXODUS software is described [1-15, 25-27, 28-30, 32-36].

1.1 EXODUS Overview

EXODUS [1-15, 25-27, 28-30, 32-36] is a suite of software tools designed to simulate the evacuation and movement of large numbers of individuals within complex structures. The EXODUS family of evacuation models currently consists of airEXODUS, buildingEXODUS and maritimeEXODUS.

The EXODUS software takes into consideration *people-people*, *people-fire* and *people-structure* interactions. The model tracks the trajectory of each individual as they make their way out of the enclosure, or are overcome by fire hazards such as heat, smoke and toxic gases. The EXODUS software has been written in C++ using Object Orientated techniques and rule-base concepts to control the simulation. Thus, the behaviour and movement of each individual is determined by a set of heuristics or rules. For additional flexibility these rules have been categorised into five interacting sub-models, the PASSENGER, MOVEMENT, BEHAVIOUR, TOXICITY and HAZARD sub-models (see Figure 2.1). These sub-models operate on a region of space defined by the GEOMETRY of the enclosure. Each of these components will be briefly described in turn.

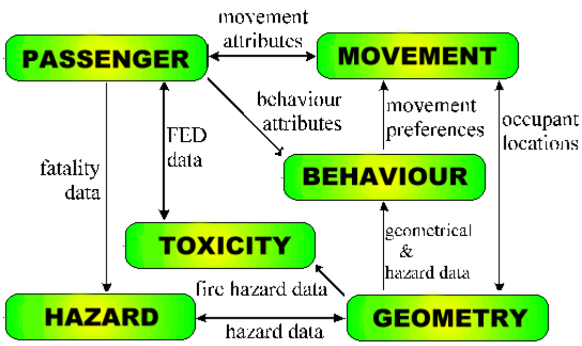

Figure 21 – EXODUS sub-model interaction

The GEOMETRY of the enclosure can be defined in several ways. It can be (i) read from a geometry library, (ii) constructed interactively using the tools provided or (iii) read from a CAD drawing using the DXF format. Internally the entire space of the geometry is covered in a mesh of nodes that are typically spaced at 0.5m intervals. The nodes are then linked by a system of arcs. Each node represents a region of space typically occupied by a single passenger.

The MOVEMENT SUB-MODEL controls the physical movement of individual passengers from their current position to the most suitable neighbouring location, or supervises the waiting period if one does not exist. The movement may involve such behaviour as overtaking, side-stepping, or other evasive actions.

The BEHAVIOUR SUB-MODEL determines an individual's response to the current prevailing situation on the basis of his/her personal attributes, and passes its decision on to the movement sub-model. The behaviour sub-model functions on two levels: global and local. The local behaviour determines an individual's response to his/her local situation while the global behaviour represents the overall strategy employed by the individual. This may include such behaviour as, evacuate via the nearest serviceable LSA or evacuate via most familiar LSA.

The PASSENGER SUB-MODEL describes an individual as a collection of defining attributes and variables such as gender, age, fast walking speed, walking speed, response time, agility, presence of a life jacket, etc. Some of the attributes are fixed throughout the simulation while others are dynamic, changing as a result of inputs from the other sub-models.

The HAZARD SUB-MODEL controls the atmospheric and physical environment. It distributes pre-determined fire hazards such as heat, smoke and toxic products throughout the atmosphere and controls the opening and closing of exits and the availability of LSAs.

The TOXICITY SUB-MODEL determines the effects on an individual exposed to toxic products distributed by the hazard sub-model. These effects are communicated to the behaviour sub-model which, in turn, feeds through to the movement of the individual.

1.1.1 Node attributes

Associated with each node is a set of attributes that are used to define the nodes terrain type, environmental state and location. The attributes associated with a node are important as they may exert an influence over the person traversing the node. Nodes have a set of core attributes - common to all nodes - and a set of specialist attributes, associated with their special roles Table 25 lists the set of core attributes associated with each node. Specialist attributes are described in later sections.

Nodes that have common distinguishing features may be assigned to a node terrain type. For example, nodes which correspond to *Stairs* have different features to those nodes associated with *Free-Space*. *Stair* nodes are thus in a different terrain type to *Free-Space* nodes. There are 14 types in EXODUS. These are STAIRS, LANDING, SEATS, LIFE SAVING APPLIANCES (LSAs), TRANSFER (LSA) NODES, WATERTIGHT DOORS, INTERNAL EXITS, FREE-SPACE, 60 DEGREE STAIR/LADDER, CENSUS REGIONS, BOUNDARY, ATTRACTOR, DISCHARGE and REDIRECTION. The nature of the terrain type will influence the behaviour and maximum travel speed of the passenger passing over the node. Information concerning the terrain type is thus passed onto the BEHAVIOUR sub-model and the PASSENGER sub-model.

Associated with each node is a set of attributes defining the environmental state of the node. These are, concentration of HCN (ppm), CO (ppm), CO_2 (%), oxygen depletion (%), smoke (l/m), temperature (ºC), HCL (ppm), HBr (ppm), HF (ppm), SO_2 (ppm), NO_2 (ppm), CH_2CHO (*Acrolein*) (ppm), HCHO (*Formaldehyde*) (ppm) and Radiative Flux (kW/m^2). With the exception of Radiative Flux, for each of these variables, two values are stored, representing the value at head height (e.g. can be arbitrarily set to 1.7m) and near deck level (e.g. can be arbitrarily set to 0.5m).

Attribute	Unit
Title	-
Type	-
Potential	-
Node Dir	°
Collapsed	-
Min UFR	occ/m/s
Max UFR	occ/m/s
Width	m
Temperature*	°C
O_2*	%
Smoke*	1/m
CO*	ppm
CO_2*	%
HCN*	ppm
Radiative Flux	kW/m^2
HCL*	ppm
HBr*	ppm
HF*	ppm
SO_2*	ppm
NO_2*	ppm
CH_2CHO* (*Acrolein*)	ppm
HCHO* (*Formaldehyde*)	ppm

Table 25 – List of node attributes used in EXODUS

* indicates attributes that have two values, an *upper* and *lower* value, that indicate the value at two heights

NOTE: The Smoke attribute is measured in units of extinction coefficient (K).

The spatial and temporal variation of the environment is defined in the *SCENARIO MODE*. A passenger located on a node will experience the environmental state present at that node for as long as he/she remains at that location and for as long as that state persists. Environmental information is passed onto the TOXICITY SUB-MODEL, which determines the physiological response to the hazards for each individual, and the BEHAVIOUR SUB-MODEL, which modifies his/her physical behaviour. The environmental state of a node is controlled by the HAZARD SUB-MODEL.

1.1.1.1 Physical Attributes

These attributes are used to assist in distinguishing one individual from another and in providing a rationale for assigning various attributes.

(1) *Height* attribute
Attribute : *Height.*
Range : 1.0 – 2.0 m.
Default : 1.8 m.
Influenced by : Age and Gender.
Influences : *FIN, FIH.*
Used in level : 2
Note : Used to represent the height of each person. This attribute can be used when fire hazards are defined, particularly when a hazard description is imported from the CFAST model.

(2) *Mobility* attribute

The *Mobility* attribute is a multiplicative factor used in conjunction with the *Travel Speed* and *Agility* attributes. It has two functions: initially, it is intended to allow the introduction of physical disability into the passenger description. A passenger not suffering from any disability will have an initial *Mobility* of 1.0, while a passenger with a minor disability, such as an arm in plaster, will have a slightly reduced *Mobility* value of for example 0.9. A major disability, such as blindness or a broken leg, will result in a considerable reduction to say 0.2.

The second function of the *Mobility* attribute is to reduce the passengers' *Travel Speed* and *Agility* in response to their growing exposure to the narcotic agents and smoke concentration. The *Mobility* may vary from its initial value (no detrimental effects), to zero (individual has expired). The *Mobility* decreases as FIN - determined by the TOXICITY sub-model - increases and/or the smoke concentration increases.

NOTE: As not much is known for certain concerning the linkage between FIN and Mobility, users have the option of activating or deactivating this link. If the link is deactivated, individuals exposed to narcotic gases will remain fully mobile until incapacitation is predicted.

In a similar manner to the narcotic gases, the irritant gases also directly affect the *Mobility* of the individual, as well as their well-being. It should be emphasised that only the instantaneous (FIC) impact of the irritant products influence the *Mobility* of an individual. As the combined FIC value increases, so the *Mobility* of the individual decreases, reducing the *Travel Speed* of the individual (it should be borne in mind that within maritimeEXODUS the *Mobility* attribute of an individual is a coefficient of their travel speed).

Smoke has the effect of obscuring vision and irritating the eyes thus impairing the ability of an individual to escape. Several studies [16,17] have suggested that a victim's movement rate decreases as the smoke concentration increases. This effect is thought to be concentration related and does not increase with prolonged exposure. Within EXODUS, the smoke density is linked to the *Mobility* attribute.

NOTE: In addition to affecting a passenger's Travel Speed, the Smoke density may also exert an influence on the passenger's navigation efficiency.

The impact of smoke upon the individual's Mobility is related to the representation of irritants within the simulation. If the irritant gases are not explicitly represented in the fire hazard, the Jin, "irritant" data-set is used to describe the complete impact of the smoke and irritant gases on the movement rates of exposed individuals. This does not require the specification of irritant gas concentrations. The applied relationship is intended to approximate the reduction in the individuals travel speed due to the impact of irritant smoke (including the obscuration effect of smoke). However, it does not directly impact the well-being of the exposed individuals.

For smoke concentrations above a critical smoke concentration passenger escape abilities are severely limited and the model assumes a maximum *Travel Speed* equivalent to the *Crawl Rate* rather than establishing the *Travel Speed* according to the passenger *Mobility*. Within the model the *Crawl Rate* of an individual is defined as a fraction of their *Fast Walk* Speed.

Exposure to irritant gases (like exposure to smoke) also results in reduction to individuals *Mobility*. If irritant gas concentrations are specified then a more comprehensive model is utilised in relation to the impact of smoke obscuration upon the mobility of the individual. This examines the concentration of several irritants and determines the impact upon the individual accordingly. Initially the Jin data relating to experiments involving "non-irritant" gases are used. This is assumed to represent the impact of the visual obscuration of the smoke alone, without representing any of the irritant effects of the smoke present. This produces a slight decrease in travel speed resulting from the obscuration affects of the smoke at sufficiently high levels.

The function defining the reduction in *Mobility* represents the impact of the environment, specifically in relation to reduced visibility. The effects of the irritants and narcotics (in terms of the reduction in the occupants travel speed) are then combined with this effect. The most severe impact upon the individual's mobility and health is then adopted.

(3) *Respiratory Minute Volume (RMV)* Attribute

The volume of air breathed per minute (or minute volume) is a measure of the volume of air taken into the lungs (litres/min). It is used by the TOXICITY SUB-MODEL (see Section 1.1.4) to calculate the *FICO* (Carbon Monoxide dose). The *RMV* is typically dependent on *Gender*, *Weight*, *Age* and type of activity the individual is involved in. For example, a 70kg male involved in light work has an *RMV* of about 25 l/min, while at rest, it falls to 8.5 l/min and while involved in heavy work it increases to 50 l/min [18]. In the current implementation of EXODUS the *RMV* shows only a dependence on *Gender* and activity.

Attribute : *RMV*.
Range : 0.0 - 50 l/min.
Default : For males, rest =8.5 l/min, light work=25 l/min, heavy work=50 l/min
Influenced by : Activity, *Gender*.
Influences : FICO, *Mobility*, Performance and behaviour.
Used in level : 2
Note : Used in calculation of carbon monoxide up-take and in prediction of incapacitation. Influences mobility calculation.

1.1.1.2 Hazard Effect Attributes

(1) *Personal Incapacitation Dose (PID)* attribute.

The *Personal Incapacitation Dose* (*PID*) is a measure of the carboxyhaemoglobin (COHb) concentration necessary to cause incapacitation. It is used by the TOXICITY SUB-MODEL (see Section 1.1.4) to calculate the FICO. The incapacitation dose is known to be dependent on age, gender, body size, state of health and level of activity [18, 20-24, 31]. In the present implementation of EXODUS, only a fixed value is used due to the lack of reliable data.

Attribute : *PID*
Range : 0 – 100 %.

Default : 30
Influenced by : None.
Influences : FICO.
Used in level : 2
Note : The *Personal Incapacitation Dose* is a measure of the carboxyhaemoglobin (COHb) concentration necessary to cause incapacitation.

NOTE: Levels of blood COHb in non-fire CO related fatalities can vary from 20% to over 90% with the majority of fatalities occurring in the range 50 to 90% [31].

(2) *FIH* attribute.

The *FIH* attribute measures the passenger's cumulative exposure to radiative and convective heat. It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When *FIH* is equal to 1.0, the passenger is incapacitated due to heat exposure. As the *FIH* increases the *Mobility* attribute decreases. The default value for *FIH* is zero.

Attribute : *FIH.*
Range : 0 - 1.
Default : 0
Influenced by : *FIHc, FIHr.*
Influences : incapacity status.
Used in level : 2

Note : The *FIH* attribute measures the passenger's combined cumulative exposure to convective and radiative heat.

(3) *FIHc*

The *FIHc* measures the passenger's cumulative exposure to convective heat. It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When *FIHc* is equal to 1.0, the passenger is incapacitated due to convective heat exposure. The default value for *FIHc* is 0.0. The *FIHc* attribute is one of the components that affect the *FIH* attribute.

Attribute : *FIHc.*
Range : 0 - 1.
Default : 0
Influenced by : Temperature.
Influences : FIH.
Used in level : 2

Note : The *FIHC* attribute measures the passenger's cumulative exposure to convective heat.

(4) *FIHr*

The *FIHr* measures the passenger's cumulative exposure to radiative heat. It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When *FIHr* is *equal* to 1.0, the passenger is incapacitated due to radiative heat exposure. The default value for *FIHr* is 0.0. The *FIHr* attribute is one of the components that affect the *FIH* attribute.

Attribute : *FIHr*.
Range : 0 - 1.
Default : 0
Influenced by : Radiative Flux, Radiative Denominator.
Influences : *FIH*.
Used in level : 2.
Note : The *FIH* attribute measures the passenger's cumulative exposure to radiative heat.

(5) *Dr*

Dr (the Radiative Denominator) is the dose of radiation required to cause the desired effect and has units of $[s(kW/m^2)^{4/3}]$. It is a user defined attribute used in the TOXICITY SUB-MODEL (see Section 1.1.4). Within EXODUS two values for *Dr* are provided, these represent the critical value for "pain threshold" *Dr* = 80 and the critical value for "incapacitation", *Dr* = 1000. A means is also provided for the user to specify any desired value. The default value for *Dr* is 80.

Attribute : *Dr*.
Range : unlimited.
Default : 80
Influenced by : None.
Influences : FIHr.
Used in level : 2
Note : The Dr value is a measure of the dose of radiation necessary to cause the desired effect.

(6) *FICO* attribute.

The *FICO* attribute measures the passenger's cumulative exposure to carbon monoxide (*CO*). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When *FICO* is equal to 1.0, the passenger is incapacitated due to *CO* poisoning. The default value for *FICO* is 0.0.

Attribute : *FICO*.
Range : 0 - 1.
Default : 0
Influenced by : CO concentration, RMV.
Influences : FIN, incapacity status.
Used in level : 2

Note : The FICO attribute measures the passenger's cumulative exposure to CO.

(7) *FICN* attribute.

The *FICN* attribute measures the passenger's cumulative exposure to hydrogen cyanide (*HCN*). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When *FICN* is equal to 1.0, the passenger is incapacitated due to *HCN* poisoning. The default value for *FICN* is 0.0.

Attribute : *FICN*.
Range : 0 - 1.
Default : 0
Influenced by : HCN concentration.
Influences : *FIN*, incapacity status.
Used in level : 2

Note : The *FICN* attribute measures the passenger's cumulative exposure to *HCN*.

(8) *FIO* attribute.

The *FIO* attribute measures the passenger's cumulative exposure to low oxygen (O_2). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When *FIO* is equal to 1.0, the passenger is incapacitated due to lack of oxygen. The default value for *FIO* is 0.0.

Attribute : *FIO*.
Range : 0 - 1.
Default : 0
Influenced by : O_2 concentration.
Influences : FIN, incapacity status.
Used in level : 2
Note : The FIO attribute measures the passenger's cumulative exposure to low oxygen.

(9) VCO_2 attribute.

The VCO_2 attribute is an estimate of the hyperventilation effect caused by the passenger's exposure to carbon dioxide gas (CO_2). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). As VCO_2 increases the ventilation rate increases and so the intake of the toxic gases increases. The default value for VCO_2 is 0.0.

Attribute : *VCO2*.
Range : 0 - 20.
Default : 0
Influenced by : CO2 concentration.
Influences : FIN.

Used in level : 2
Note : VCO_2 estimates the hyperventilation effect caused by exposure to CO_2.

(10) *$FICO_2$* attribute.

The *$FICO_2$* attribute measures the passenger's cumulative exposure to carbon dioxide gas (*CO_2*). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When *$FICO_2$* is equal to 1.0, the passenger is incapacitated due to carbon dioxide. The default value for *$FICO_2$* is 0.0.

Attribute : *$FICO_2$*.
Range : 0 - 1.
Default : 0
Influenced by : CO_2 concentration.
Influences : VCO_2.
Used in level : 2
Note : The $FICO_2$ attribute measures the passenger's cumulative exposure to carbon dioxide.

(11) *FIN* attribute.

The *FIN* attribute measures the passenger's combined cumulative exposure to low *O_2*, *HCN, CO* and *CO_2*. It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When *FIN* is equal to 1.0, the passenger is incapacitated due to the combined effect of these gases. As the FIN increases the mobility decreases. The default value for *FIN* is 0.0.

Attribute : *FIN*.
Range : 0 - 1.
Default : 0
Influenced by : FICO, FICN, FIO, FLD, VCO_2.
Influences : Mobility, incapacity status.
Used in level : 2
Note : FIN measures the combined cumulative exposure to low O_2, HCN, CO and CO_2

(b) Irritant Gases

The instantaneous impact of the irritant gases is described by the attributes with the prefix FIC.

(1) *FIC attribute*

The *FIC* attribute measures the occupant's instantaneous exposure to all of the irritant gases. It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see

Section 1.1.4). When *FIC* is equal to 1.0, the occupant is incapacitated. The default value for *FIC* is 0.0.

Attribute : *FIC*
Range : 0 - 1.
Default : 0
Influenced by : the concentration of HCL, HBr, HF, SO_2, NO_2, CH_2CHO (Acrolein) and HCHO (Formaldehyde).
Influences : -
Used in level : 2
Note : The FIC attribute measures the occupant's combined exposure to the irritant gases.

(2) FIC_{HCL} attribute

The FIC_{HCL} attribute measures the occupant's instantaneous exposure to HCL (Hydrogen Chloride). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FIC_{HCL} is equal to 1.0, the occupant is incapacitated due to HCL. The default value for FIC_{HCL} is 0.0.

Attribute : FIC_{HCL}
Range : 0 - 1.
Default : 0
Influenced by : HCL concentration.
Influences : FIC.
Used in level : 2
Note : The FIC_{HCL} attribute measures the occupant's exposure to HCL.

(3) FIC_{HBr} attribute

The FIC_{HBr} attribute measures the occupant's instantaneous exposure to HBr (Hydrogen Bromide). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FIC_{HBr} is equal to 1.0, the occupant is incapacitated due to HBr. The default value for FIC_{HBr} is 0.0.

Attribute : FIC_{HBr}
Range : 0 - 1.
Default : 0
Influenced by : HBr concentration.
Influences : FIC.
Used in level : 2
Note : The FIC_{HBr} attribute measures the occupant's exposure to HBr.

(4) FIC_{HF} attribute

The FIC_{HF} attribute measures the occupant's instantaneous exposure to HF (Hydrogen Fluoride). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see

Section 1.1.4). When FIC_{HF} is equal to 1.0, the occupant is incapacitated due to HF. The default value for FIC_{HF} is 0.0.

Attribute : FIC_{HF}
Range : 0 - 1.
Default : 0
Influenced by : HF concentration.
Influences : FIC.
Used in level : 2
Note : The FIC_{HF} attribute measures the occupant's exposure to HF.

(5) FIC_{SO2} attribute

The FIC_{SO2} attribute measures the occupant's instantaneous exposure to SO_2 (Sulphur Dioxide).It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FIC_{SO2} is equal to 1.0, the occupant is incapacitated due to SO_2. The default value for FIC_{SO2} is 0.0.

Attribute : FIC_{SO2}
Range : 0 - 1.
Default : 0
Influenced by : SO_2 concentration.
Influences : FIC.
Used in level : 2
Note : The FIC_{SO2} attribute measures the occupant's exposure to SO_2.

(6) FIC_{NO2} attribute

The FIC_{NO2} attribute measures the occupant's instantaneous exposure to NO_2 (Nitrogen Dioxide).It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FIC_{NO2} is equal to 1.0, the occupant is incapacitated due to NO_2. The default value for FIC_{NO2} is 0.0.

Attribute : FIC_{NO2}
Range : 0 - 1.
Default : 0
Influenced by : NO_2 concentration.
Influences : FIC.
Used in level : 2
Note : The FIC_{NO2} attribute measures the occupant's exposure to NO_2.

(7) FIC_{CH2CHO} attribute

The FIC_{CH2CHO} attribute measures the occupant's instantaneous exposure to CH_2CHO (*Acrolein*). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FIC_{CH2CHO} is equal to 1.0, the occupant is incapacitated due to CH_2CHO (*Acrolein*). The default value for FIC_{CH2CHO} is 0.0.

Attribute : FIC_{CH2CHO}
Range : 0 - 1.
Default : 0
Influenced by : CH_2CHO (Acrolein) concentration.
Influences : FIC.
Used in level : 2
Note : The FIC_{CH2CHO} attribute measures the occupant's exposure to CH_2CHO (Acrolein).

(8) FIC_{HCHO} attribute

The FIC_{HCHO} attribute measures the occupant's instantaneous exposure to HCHO (*Formaldehyde)*. It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FIC_{HCHO} is equal to 1.0, the occupant is incapacitated due to HCHO (*Formaldehyde)*. The default value for FIC_{HCHO} is 0.0.

Attribute : FIC_{HCHO}
Range : 0 - 1.
Default : 0
Influenced by : HCHO (Formaldehyde) concentration.
Influences : FIC.
Used in level : 2
Note : The FIC_{HCHO} attribute measures the occupant's exposure to HCHO (Formaldehyde).

The impact of an exposure to irritant gases over a period of time is described by the attributes with the prefix FLD.

(9) *FLD* attribute

The *FLD* attribute measures the occupant's cumulative exposure to the irritant gases. It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When *FLD* is equal to 1.0, the occupant is incapacitated due to the irritant gases. The default value for *FLD* is 0.0.

Attribute : *FLD*
Range : 0 - 1.
Default : 0
Influenced by : The dose of HCL, HBr, HF, SO_2, NO_2, CH_2CHO (Acrolein), HCHO (Formaldehyde).
Influences : -.
Used in level : 2
Note : The FLD attribute measures the occupant's cumulative exposure to the irritant gases.

(10) FLD_{HCL} attribute

The FLD_{HCL} attribute measures the occupant's cumulative exposure to HCL (Hydrogen Chloride). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FLD_{HCL} is equal to 1.0, the occupant is incapacitated due to HCL. The default value for FLD_{HCL} is 0.0.

Attribute : *FLDHCL*
Range : 0 - 1.
Default : 0
Influenced by : HCL dose.
Influences : FLD.
Used in level : 2
Note : The FLDHCL attribute measures the occupant's cumulative exposure to HCL.

(11) FLD_{HBr} attribute

The FLD_{HBr} attribute measures the occupant's cumulative exposure to HBr (Hydrogen Bromide). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FLD_{HBr} is equal to 1.0, the occupant is incapacitated due to HBr. The default value for FLD_{HBr} is 0.0.

Attribute : FLD_{HBr}
Range : 0 - 1.
Default : 0
Influenced by : HBr dose.
Influences : FLD.
Used in level : 2
Note : The $\mathrm{FLD}_{\mathrm{HBr}}$ attribute measures the occupant's cumulative exposure to HBr.

(12) FLD_{HF} attribute

The FLD_{HF} attribute measures the occupant's cumulative exposure to HF (Hydrogen Fluoride). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FLD_{HF} is equal to 1.0, the occupant is incapacitated due to HF. The default value for FLD_{HF} is 0.0.

Attribute : FLD_{HF}
Range : 0 - 1.
Default : 0
Influenced by : HF dose.
Influences : FLD.
Used in level : 2
Note : The $\mathrm{FLD}_{\mathrm{HF}}$ attribute measures the occupant's cumulative exposure to HF.

(13) FLD_{SO2} attribute

The FLD_{SO2} attribute measures the occupant's cumulative exposure to SO_2 (Sulphur Dioxide). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FLD_{SO2} is equal to 1.0, the occupant is incapacitated due to SO_2. The default value for FLD_{SO2} is 0.0.

Attribute : FLD_{SO2}
Range : 0 - 1.
Default : 0
Influenced by : SO_2 dose.
Influences : FLD.
Used in level : 2
Note : The FLD_{SO2} attribute measures the occupant's cumulative exposure to SO_2.

(14) FLD_{NO2} attribute

The FLD_{NO2} attribute measures the occupant's cumulative exposure to NO_2 (Nitrogen Dioxide). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FLD_{NO2} is equal to 1.0, the occupant is incapacitated due to NO_2. The default value for FLD_{NO2} is 0.0.

Attribute : FLD_{NO2}
Range : 0 - 1.
Default : 0
Influenced by : NO_2 dose.
Influences : FLD.
Used in level : 2
Note : The FLD_{NO2} attribute measures the occupant's cumulative exposure to NO_2.

(15) FLD_{CH2CHO} attribute

The FLD_{CH2CHO} attribute measures the occupant's cumulative exposure to CH_2CHO (*Acrolein*). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FLD_{CH2CHO} is equal to 1.0, the occupant is incapacitated due to CH_2CHO (*Acrolein*). The default value for FLD_{CH2CHO} is 0.0.

Attribute : FLD_{CH2CHO}
Range : 0 - 1.
Default : 0
Influenced by : CH_2CHO (Acrolein) dose.
Influences : FLD.
Used in level : 2
Note : The FLD_{CH2CHO} attribute measures the occupant's cumulative exposure to CH_2CHO (Acrolein).

(16) FLD_{HCHO} attribute

The FLD_{HCHO} attribute measures the occupant's cumulative exposure to HCHO (*Formaldehyde*). It is a dynamic attribute calculated by the TOXICITY SUB-MODEL (see Section 1.1.4). When FLD_{HCHO} is equal to 1.0, the occupant is incapacitated due to HCHO (*Formaldehyde*). The default value for FLD_{HCHO} is 0.0.

Attribute : FLD_{HCHO}
Range : 0 - 1.
Default : 0
Influenced by : HCHO (Formaldehyde) dose.
Influences : FLD.
Used in level : 2
Note : The FLD_{HCHO} attribute measures the occupant's cumulative exposure to HCHO (Formaldehyde).

1.1.2 Movement Sub-model

The MOVEMENT sub-model is only active during *SIMULATION* mode. It is primarily concerned with the physical movement of the passengers through the different terrain types. It consists of a number of rules, the main function of which is to determine the appropriate travel speed for the current terrain type. For example, *Leap Speed* is selected for passengers who have decided to climb over a row of seats, while *Fast Walk Speed* is selected for a passenger who is travelling through open space. In addition, the MOVEMENT sub-model ensures that the passenger has the capability of performing the requested action, for example it checks if the passenger *Agility* is sufficient to allow travel over nodes with particular *Obstacle* values.

While the movement sub-model is responsible for moving the passenger, it is the BEHAVIOUR sub-model that selects the direction of travel. If a suitable move is not available to the passenger, the MOVEMENT sub-model will supervise a *Wait* period. During the *Wait* period the passenger remains stationary until a suitable move becomes available.

Movement rules are fired on even ticks of the Simulation Clock, while selection rules (from the BEHAVIOUR sub-model) are fired on odd ticks. The wait rules are fired continuously, as the passenger always has the option to wait. Movement decisions and actions will only take place if the Simulation Clock shows a time that is at least as large as the *PET*.

When a move decision has been made, EXODUS waits until the next tick of the Simulation Clock, and then moves the passenger to the location. Using the passenger's *Travel Speed* and distance travelled, EXODUS calculates the travel time and advances his/her *PET* by the appropriate amount. The passenger then sits on the selected node until the Simulation Clock catches up with the *PET*, at which time another movement decision may be taken. If the passenger is forced to wait at the current location the *PET* is updated with each tick of the Simulation Clock.

In the current version of EXODUS there is no provision for passenger's to push past each other while in queues. In these circumstances, the person can wait for his/her turn to move, or if their *Patience* has expired, take a detour round the obstruction.

1.1.3 Hazard Sub-model

The HAZARD SUB-MODEL is accessed by the user during *SCENARIO* mode and it is utilised by EXODUS during *SIMULATION* mode. The HAZARD sub-model controls the development of the atmospheric and physical environment. The atmospheric aspects comprise the distribution of fire hazards *CO_2, CO, HCN, O_2* depletion, *Heat* (radiative and conductive) and *Smoke*, as well as the irritant gases HCl, HBr, HF, SO_2, NO_2, CH_2CHO (*Acrolein*) and HCHO (*Formaldehyde*). The physical aspects include setting of opening and closing times for LSAs.

The primary function of the HAZARD sub-model is to distribute the fire hazards. EXODUS does not possess a component such as a zone or field fire model [19] to predict the generation and spread of fire hazards. There are however several means by which fire hazard data may be included. These are manual data entry, arbitrary calculation, library data, direct import of history files (.HI) from the CFAST (version 4.0.1 to 5.1.1) zone model, direct import of data files (.DAT) from the SMARTFIRE V4.0 fire field model, and the importation of data files converted to the SMARTFIRE data file format from CFAST version 6 data output files (.OUT).

Within EXODUS fire hazards operate at two heights: the upper and lower height. The definition of the upper and lower height is dependent on the approach used to specify the hazards. When using the user-defined option, evacuees are continually exposed to hazards at the upper height while they assume the standing position. The hazards defining the upper height conditions should represent those hazards existing at a nominal head height e.g. 1.7m. When evacuees are forced to crawl, they are then exposed to the hazard values at the lower height and so lower height hazard values should represent those hazards existing near the floor e.g. about 1.0 m above the floor. However, when CFAST generated hazards are used, the height of the upper hazard layer is also determined, thus the height of the upper layer changes with time as do the hazard values. In this case evacuees do not typically come into contact with the upper layer until it has descended to a distance equal to their height.

When using the SMARTFIRE defined hazards, the rationale used is similar to that used when making use of user-defined data. When people are standing they are continually exposed to the environmental conditions that exist at the upper height. When evacuees are forced to crawl, they are then exposed to the hazard values at the lower height and so lower height hazard values should represent those hazards existing near the floor. The position and depth of both the upper and lower regions are defined by the user within SMARTFIRE prior to running the simulation. Hence it is up to the user to ensure that the upper and lower regions are representative of the regions to which standing and crawling people would be exposed. The exception to this is the exposure to radiative flux, which is provided as constant in both the upper and lower regions. It is suggested that the hazards defining the upper height conditions should represent those hazards existing at a nominal head height e.g. 1.7m while those for crawling individuals should represent a height of about 1.0 m above the floor.

The methods of data entry are now described.

(1) Direct import of History files from the CFAST (version 4.0.1 to 5.1.1) zone model.

History files (.HI) generated by the CFAST (version 4.0.1 to version 5.1.1) zone model [37, 38] can be imported directly into maritimeEXODUS. Once CFAST has been run, the CFAST generated history file contains a record of the simulation results. This file can then be imported into maritimeEXODUS as a fire hazard, which then requires association with an area within the geometry. The imported data can consist of the fire products that maritimeEXODUS makes use of in its hazard calculations (i.e. *Smoke Concentration, Temperature, Radiative Flux, HCN, HCL, CO,* CO_2 *and* O_2 concentrations). The units that CFAST uses for these variables are similar to those used by maritimeEXODUS except for the *Smoke Concentration* - where CFAST makes use of the optical density rather than extinction coefficient - Temperature - where CFAST uses Kelvin and maritimeEXODUS uses Centigrade and radiative heat flux where maritimeEXODUS uses kWatts/m2 and CFAST uses Watts/m2. Once maritimeEXODUS reads the CFAST data, these units are automatically converted to the appropriate units and therefore require no further user attention. The ship geometry can consist of any multi-compartment structure that both CFAST and maritimeEXODUS can accommodate.

(2) Direct import of data files from the SMARTFIRE V4.0 fire field model.

maritimeEXODUS will accept data from the CFD based fire simulation model SMARTFIRE. This enables evacuation analysis to benefit from the greater modelling accuracy that CFD fire field modelling offers fire simulation. In order to simplify the data importing process, from the user's point of view, the EXODUS-SMARTFIRE link has been implemented so as to be as consistent as possible with the existing CFAST data importing mechanism, described in the previous section. The data link is achieved using a zone-filter that processes some of the data produced by SMARTFIRE and allows the required "zoned" data to be loaded into EXODUS and used as EXODUS evacuation “hazards”.

maritimeEXODUS will only read data from SMARTFIRE V4.0 or later. SMARTFIRE V4.0 [47-53] is an open architecture CFD environment, written in C++, comprising four major components: the CFD numerical engine, various Graphical User Interfaces, an automated meshing tool and the Intelligent Control System. The SMARTFIRE system has been described in previous publications [47-53], and so only a brief outline is presented here. SMARTFIRE includes a six-flux radiation model, a multiple ray radiation model, provision for heat transfer through walls, a volumetric heat release model or gaseous combustion model (using the eddy dissipation model) to represent fires, smoke modelling and turbulence (using a two equation K-Epsilon closure with buoyancy modifications). SMARTFIRE uses three-dimensional unstructured meshes, enabling complex irregular geometries to be meshed. The code uses the SIMPLE algorithm and can solve turbulent or laminar flow problems under transient or steady state conditions.

SMARTFIRE V4.0 produces a data file (named "casename".dat), which is formatted in such a way that it can be directly imported into maritimeEXODUS. The format is consistent with the CFAST output format. In the present implementation of the

EXODUS-SMARTFIRE interface, the data imported from SMARTFIRE consists of the following fire hazards: *Smoke Concentration*, *Temperature* and *Radiative Flux*.

NOTE: The native units that SMARTFIRE uses for the fire hazards Smoke Concentration, Temperature and *Radiative Flux are different to those required by EXODUS. SMARTFIRE makes use of optical density for Smoke Concentration while EXODUS requires extinction coefficient, for the temperature, SMARTFIRE uses Kelvin while EXODUS uses Centigrade and for radiative heat flux, SMARTFIRE uses Watts/m2, whereas EXODUS makes use of KWatts/m2. The filter within the EXODUS software automatically converts the SMARTFIRE data into the appropriate units and so no user intervention is required to convert these units.*

While EXODUS works on a nodal system similar to SMARTFIRE, for evacuation analysis it is not generally necessary to have unique and individual hazard identification at each nodal location. The EXODUS simulation therefore uses a zonal system for the specification of hazard information. Furthermore, within EXODUS, hazard information is only required at two characteristic heights known as "upper height" and "lower height". Therefore, before the hazard data from SMARTFIRE can be used by EXODUS it must be averaged over the same spatial zones as defined within the EXODUS simulation and at the required vertical locations.

NOTE: Conversion of the SMARTFIRE nodal data into zonal data is performed within the SMARTFIRE software. Within SMARTFIRE, the user may use a default averaging approach or may specify their preferred averaging algorithm. It is recommended that the user selects the default averaging algorithms as there is a distinct possibility that manual configuration will create averaged values with incompatible units to those required by EXODUS.

Within SMARTFIRE the radiative flux is determined for a standing individual – which is represented as an elongated cuboid – and is summed over all the components of radiation intersecting the surface area of the standing individual. Therefore irrespective of the posture adopted by the individual they will always be exposed to the standing value for the thermal radiation.

NOTE: SMARTFIRE provides upper and lower region values for the Temperature and the Smoke concentration levels. However, SMARTFIRE provides EXODUS with a single radiative flux value, which is assumed to be constant for both the upper and lower layers.

A volume averaging technique is used to harmonize the three-dimensional control-volume discretisation used within SMARTFIRE with the meshing and zoning system used within EXODUS. This technique effectively groups together potentially large numbers of cells and averages the data within them to produce representative values for the hazards over the specified zone.

The zoned data is generated at each time-step within the SMARTFIRE simulation. An ambient set of initial data is produced at a time of 0 seconds – before the simulation commences. The size of the time-step within SMARTFIRE is user defined and will be dependent – to a large extent – upon the nature of the simulation, the geometry, the meshing and the numerical stability of the scenario being examined. The amount of data generated by SMARTFIRE and transferred to EXODUS can be further reduced by increasing the size of the SMARTFIRE time-steps (only possible if the simulation has sufficient stability) or by requesting that SMARTFIRE perform output data saves less frequently.

In addition, the SMARTFIRE time step size can be adjusted automatically by SMARTFIRE due to predicted or detected difficulties at a particular stage of the simulation. In order for EXODUS to be able to interpret the possibly inconsistent temporal data, the EXODUS zoned data reader is able to linearly interpolate the imported data, between available data times, if a required matching simulation time is unavailable.

Once these parameters have been specified and the SMARTFIRE simulation has been completed, SMARTFIRE will have generated an output file containing the appropriate hazard information specified at the appropriate locations that can be read by EXODUS. If the zonal definition has been correctly specified within SMARTFIRE, this file will be compatible with the EXODUS hazard zone specification. ***It is the user's responsibility to ensure that the zones defined in the SMARTFIRE model and those used in the maritimeEXODUS simulation coincide.*** If this is not the case then anomalous results may occur. Care should be taken to account for any extended regions that might be created when the CFD scenario is meshed as these may alter the coordinates of the geometry and hence can change the user's geometric understanding of the scenario.

NOTE: The user must generate a fire scenario that is compatible with both maritimeEXODUS *and SMARTFIRE. This means that the data created for the zones in SMARTFIRE should be appropriate (i.e. should represent the same geometrical space) for the zones that it is intended to represent within* maritimeEXODUS. *This alignment is not automated and will therefore be the user's responsibility to ensure that the fire being modelled within SMARTFIRE is appropriate for the structure in which it will be located within* maritimeEXODUS.

(3) Direct import of data files converted to the SMARTFIRE data file format from CFAST version 6 data output files.

At present maritimeEXODUS only has the ability to directly load hazard data contained within binary History files (.HI) generated using CFAST version 4.0.1 to 5.1.1. **Consequently, any History files generated using CFAST versions greater than 5.1.1 can therefore NOT be used within maritimeEXODUS.** For CFAST versions greater than 5.1.1, maritimeEXODUS instead utilises the data contained within the ASCII output files (.OUT) produced automatically by CFAST upon completion of any given simulation. These output files typically contain information about all aspects of any given CFAST simulation (including those aspects not relevant to maritimeEXODUS) in a text based format designed to be read by people, as opposed to computers. To overcome the un-optimised format and excess simulation information that these output files (.OUT) contain, a conversion utility called CFAST2SMF was produced to convert their relevant hazard data into corresponding optimised data files in the existing SMARTFIRE file format. As with conventional binary History files, converted data files will contain each of the CFAST fire products relevant to maritimeEXODUS (i.e. *Smoke Concentration, Temperature, Radiative Flux, HCN, HCL, CO, CO2 and O2* concentrations). The units of those fire products will also be automatically converted (where necessary) from the units used within CFAST to the units appropriate to SMARTFIRE data files (see Section 2). Once converted into a SMARTFIRE data file, the hazard data originally generated using CFAST can then be loaded into maritimeEXODUS in the same manner as conventional SMARTFIRE generated data (see Section 2).

Thus, using one of the six techniques defined above, each node in the geometry is assigned hazard data. Hazard data is defined for two heights, *Head Height* and near *Floor Height*.

1.1.4 Toxicity Sub-model

The TOXICITY sub-model is accessed by the user during *SCENARIO* mode and it is utilised by EXODUS during *SIMULATION* mode. To determine the effect of the fire hazards on passengers, EXODUS uses a Fractional Effective Dose (FED) toxicity model [2, 18, 20-24, 31, 39]. FED models assume that the effects of certain fire hazards are related to the dose received rather than the exposure concentration. The model calculates, for these agents, the ratio of the dose received over time to the effective dose that causes incapacitation or death, and sums these ratios during the exposure. When the total reaches unity, the toxic effect is predicted to occur. These effects are communicated to the BEHAVIOUR SUB-MODEL which, in turn, feeds through to the movement of the individual. As the FED approaches unity the passenger's *Mobility*, *Agility*, and travel speeds can be reduced making it more difficult for the affected passenger to escape.

The core toxicity model implemented within EXODUS is the FED model of Purser [18, 20-22, 39]. This model considers the toxic and physical hazards associated with elevated temperature, *HCN, CO,* CO_2 and low O_2 and estimates the time to incapacitation.

In each of the following expressions, *t* is the exposure time (minutes). The Fractional Incapacitating Dose (FID) for each of the agents is calculated as follows:

(i) *CO* (measured in ppm):

$$FICO = 3.317 \times 10^{-5} \times CO^{1.036} \times RMV \times \frac{t}{PID} \qquad (31)$$

where *RMV* is the minute volume (litres/minute) and PID is the *Personal Incapacitation Dose* (%) (see Sections 1.1.1.1 and 1.1.1.2).

NOTE: The FICO expression (equation 31) is unreliable for small adults or children.

NOTE: The FICO model assumes that inhaled CO is immediately converted to COHb. In reality there may be a delay.

NOTE: The FICO model cannot be used reliably in situations where the CO concentration is decreasing.

(ii) *HCN* (measured in ppm):

$$FICN = e^{\left(\frac{HCN}{43}\right) \times \frac{t}{220}} \qquad (32)$$

NOTE: The FICN expression (equation 32) is unreliable outside the range 80-180 ppm HCN (see Section 1.1.1.2).

(iii) Low O_2 (measured in %):

$$FIO = \frac{t}{e^{(8.13 - 0.54 \times (20.9 - O_2))}} \tag{33}$$

(iv) CO_2 (measured in %):

$$FICO_2 = \frac{t}{e^{(6.1623 - 0.5189 \times CO_2)}} \tag{34}$$

Another effect that CO_2 has is to increase an exposed person's *RMV* and thus increase their rate of uptake of other toxic gases.

The FED model considers the combined effect of these agents in the following way,

$$(FICO + FICN + FLD) \times VCO_2 + FIO \tag{35}$$

where,

$$VCO_2 = e^{\left(\frac{CO_2}{5.0}\right)} \tag{36}$$

is a multiplicative factor which measures the increased uptake of *CO* and *HCN* due to CO_2-induced hyperventilation (see Section 1.1.1.2). It should be noted that the *Fractional Lethal Dose* term (FLD) is described in Section 1.1.1.2.

The final hazard considered is due to heat. There are two contributions to this relationship, convective heat (i.e. elevated temperature) and radiative flux,

(v) Convected Heat:

$$FIH_c = t \times 2.0 \times 10^{-8} \times T^{3.4} \tag{37}$$

where T is the temperature (°C) (see Section 1.1.1.2).

(vi) Radiative Heat:

$$FIH_r = \frac{q^{1.33}}{D_r} \times t \times 60.0 \tag{38}$$

where q is the radiative flux (kW/m^2) (see Section 1.1.1.2) and *Dr* is the radiative denominator. *Dr* is the dose of radiation required to cause the desired effect and has units of [s(kW/m^2)$^{4/3}$].

To select the appropriate value of *Dr* used in a simulation it is necessary to consider the purpose of the *FIHr* equation within EXODUS. The primary intention of the *FIHr* equation is to indicate when the passenger is likely to be unable to continue to evacuate efficiently due to exposure to thermal radiation.

The FED model considers the combined effect of these agents in the following way,

$$FIH = FIH_c + FIH_r \quad (39)$$

When *FIN* or $FICO_2$ or *FIH* equal or exceed 1.0, the affected passenger is assumed to be incapacitated. The EXODUS model considers fire hazard data located at two heights, head and near floor height.

In Pursers model the FIH_C acquired each minute (equation 37) is based on data using subjects with exposed skin,

$$FIH_c = t \times 2.4 \times 10^{-09} \times (T^o C))^{3.61} \quad (40)$$

(vii) *Irritant Gases*

A significant component of the fire effluent produced by the fires is the irritant gases. The irritant model implemented within maritimeEXODUS is based on the model originally developed by Purser from a variety of experimental data-sets [20, 42-46] to a particular irritant gas as well as the accumulated dose that is acquired during the evacuation process. The Purser data has been pooled with the data produced by Jin [16] to form an approximation of the impact of an exposure to irritant substance during an evacuation.

The Purser irritant model represents the impact of the following irritant gases: HCl, HBr, HF, SO_2, NO_2, CH_2CHO (*Acrolein*) and HCHO (*Formaldehyde*). The evolution and propagation of these irritant gases is represented within maritimeEXODUS in an identical manner to the other fire hazards (i.e. their development can be manually described, or may be automatically imported from the CFAST zone model).

The final parameters, which can be accessed through the TOXICITY sub-model, are called the *Triggering Temperature* and *Triggering Smoke Concentration*. These parameters apply to the entire population. They represent the critical temperature and smoke concentrations at which a passenger's response time attribute is overridden. When the temperature or smoke concentration at the location equals or exceeds these values the person at that location will begin to evacuate regardless of their response time.

1.1.5 Environmental interaction

Here we consider the impact of the atmospheric conditions resulting from fire and the impact of vessel orientation.

NOTE: The behaviour interaction associated with conditions of smoke, heat and toxic gas is only available with level 2 of maritimeEXODUS.

(i) Smoke and Temperature trigger.

Under non-fire conditions passengers will not begin to actively take part in the evacuation until their *Response Time* has elapsed. However, if the person is made aware of the danger of the fire through his/her perception of the local temperature or smoke concentration, he/she will begin to evacuate before his/her *Response Time* has elapsed. This behaviour can either be controlled through the setting of the *Triggering Temperature* and *Triggering Smoke Concentration* attributes in the TOXICITY sub-model in the SCENARIO mode, or by the setting of the *Response Time* overrides of a zone in the HAZARD mode.

(ii) Smoke interaction.

It is known that a person's *Walk Rate* decreases with increasing smoke concentration [16,17]. EXODUS links the smoke concentration with the *Mobility* attribute. As the smoke concentration increases the *Mobility* decreases and this in turn decreases the persons travel speed.

(iii) Inefficient movement within smoke

Under experimental conditions Jin found that when encountering smoke, in addition to a reduction in travel speed the evacuee movement became increasingly inefficient, with evacuee's „staggering" along a smoke-filled corridor [16,17]. This was due to the visual obscuration caused by the dense, irritant environmental conditions. An additional behaviour noticed by Jin was that in smoke conditions, passengers tended to use the walls to assist them in navigation [16,17]. Both these behaviours have been included in EXODUS [33].

The staggering behaviour is controlled through the setting of the *Smoke Stagger* option on the *BEHAVIOUR OPTIONS* dialogue box. This function operates independently of the physical impediment provided by smoke. It should be possible for the user to enable these functions simultaneously or independently according to the user's needs.

This function only affects passenger behaviour if the passenger is not situated on stairs, amongst seats or is not adjacent to an LSA (i.e. the passenger is not located on a node that is connected to an LSA). Under these conditions it is assumed that the passenger's ability to navigate is not further impaired. As described later, the algorithm also has no impact upon the passenger movement if the conditions have forced the passenger to crawl, which supersedes any other form of behaviour.

The likelihood of the passenger moving through smoke is extracted from the work of Bryan [41] and Wood [40].

(iv) Toxicity interaction.

EXODUS links the *FIN* and *FIC* attributes to the *Mobility* attribute. As the *FIN* and the *FIC* increases, the *Mobility* decreases and this in turn decreases the persons *Travel Speed*.

References

1. M Owen, E R Galea and P J Lawrence, The EXODUS evacuation model applied to building evacuation scenarios, Journal of Fire Protection Engineering, Vol.8(2), pp.65-86, 1996.

2. E R Galea, M Owen and P J Lawrence, Computer Modelling of Human behaviour in aircraft fire accidents, Toxicology, vol 155, 1-3, pp 63-78, 1996.

3. M Owen, E R Galea and P J Lawrence, The EXODUS evacuation model applied to building evacuation scenarios, Fire Engineers Journal, pp 26-30, vol 56 No. 183, July 1996.

4. S Prew, Computerised evacuation modelling, Cabin Safety Update, pp 1-4 Vol.2 No. 3, 1996.

5. E Galea, P Lawrence, L Filippidis, Extending the Capabilities of the buildingEXODUS Evacuation Model to Cater for Hospital Evacuations, Proceedings of the Third International Conference on Fire Research and Engineering, 4-8 October 1999, Chicago, USA, pp 39-50, 1999.

6. E R Galea, The Role of Evacuation and Fire Modelling in the Development of Safer Aircraft, Proceedings International Conference on Cabin Safety Research, pp 145-160, Atlantic City, Nov. 1995, Report: DOT/FAA/AR-95/120 pub: Office of Aviation Research, Washington, 1995.

7. E R Galea, M Owen, and P J Lawrence, Emergency Egress from Large Buildings under Fire Conditions Simulated Using the EXODUS Evacuation Model, Proceedings of the 7th International Fire Science and Engineering Conference: Interflam'96, pp 711-720, St John's College, Cambridge, England, March 1996, compiled by C Franks and S Grayson, Published by Interscience communications Ltd, ISBN 0 9516320 9 4, London, UK, 1996.

8. M Owen, E R Galea and P Lawrence, The EXODUS evacuation model applied to building evacuation scenarios, Proc International conference, Fire Safety By Design, ISBN 0 9527398 3 6, Vol.3, pp.81-90, Compiled by G W Butler, 1995.

9. E R Galea and M.Owen, Predicting the Evacuation Performance of Mass Transport Vehicles, 'Fire Safety on Ships', Developments into the 21st Century. ISBN 0-907206-57-3, IMarE Conference, Vol 106,2, 239 – 247, Lond 1994.

10. E R Galea and J M P Galparsoro, A Computer Based Simulation Model for the Prediction of Evacuation from Mass Transport Vehicles, Fire Safety Journal Vol 22 pp 341 - 366, 1994.

11. E R Galea, A Computer Based Simulation of the Evacuation of Passengers under Hazardous and Non-Hazardous Conditions from Wide and Narrow Body Aircraft, Invited Paper, Proc. 11th Annual Int. Aircraft Cabin Safety Symp., Southern California Safety Institute, Calif. USA, pp 259 – 280, 1994.

12. E R Galea, J M P Galparsoro and J Pearce, EXODUS: A simulation Model for the Evacuation of Large Populations from Mass Transport Vehicles and Buildings under Hazardous Conditions. CIB W14, Int. Symp. and Workshop Engineering Fire Safety in the Process of Design. Univ. of Ulster, Part 3 pp 11-25, 1993.

13. E R Galea, How University Professor's Prototype Egress Model Helps Evacuation Design, Fire, p.23, July 1993.

14. E R Galea, J M Perez Galparsoro and J Pearce, A Brief Description of the EXODUS Evacuation Model, Proceed, 18th Int Conf on Fire Safety. San Francisco, USA, Vol.18, pp.149-162, 1993.

15. E R Galea and J M Perez Galparsoro, EXODUS: An Evacuation Model for Mass Transport Vehicles. UK CAA Paper 93 006 ISBN 0 86039 543X, 1993.

16. Jin, T. Visibility through fire smoke, J of Fire and Flammability, 9, 135-155, 1978.

17. Jin, T. and Yamada, T Experimental Study of Human behaviour in smoke filled corridors. In: T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. Seeger, P. Pagni and C. Grant (Eds.) Fire Safety Science Proceedings of the Second International Symposium, Hemisphere Publishing Company, New York, 561-570, 1989.

18. D.A.Purser, Modelling time to incapacitation and death from toxic and physical hazards in aircraft fires. AGARD No 467, pp 41-1 - 41-12, 1989.

19. Galea E R, On the field modelling approach to the simulation of enclosure fires, Journal of Fire Protection Engineering, vol 1 (1), pp 11-22, 1989.

20. Purser, D.A., Toxicity Assessment of combustion products. In: C.L.Beyler (Ed) SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy M.A., 1-200 - 1-245, 1988.

21. Purser, D.A., Interactions between behaviour patterns and physiological impairment in escape from fire. In: C.A.Franks (Ed.) Interflam'93, Interscience communications Ltd, London, 579 – 593, 1993.

22. Purser, D.A., Toxicity Assessment of combustion products. In: J.L.Linville (Ed) SFPE Handbook of Fire Protection Engineering 2nd Edition, National Fire Protection Association, Quincy M.A., 2-85 - 2-146, 1995.

23. Speitel, L.C., Analytical Method for water vapour collection and analysis in aircraft cabin fires. DOT/FAA/CT - TN93/33, US Department of Transportation, 1993.

24. Speitel, L.C., Toxicity Assessment of Combustion Gases and Development of a Survival Model, DOT/FAA/AR-95/5, US Department of Transportation, 1995.

25. Gwynne, S., Galea, E. R., Owen, M., Lawrence, P. J., and Filippidis, L., Validation of the buildingEXODUS Evacuation Model. CMS Press Paper 98/IM/29, ISBN 1899991298, 1998.

26. Gwynne, S., Galea, E. R., Owen, M., Lawrence, P. J., and Filippidis, L., A Systematic Comparison of Model Predictions Produced by the buildingEXODUS Evacuation

Model and the Tsukuba Dataset. Journal of Applied Fire Science, Volume 7 Number 3, pp 235 – 266, 1997/1998.

27. Owen, M., Galea E. R., Lawrence, P., and Filippidis, L., The Numerical Simulation of Aircraft evacuation and its application to aircraft design and certification, Aeronautical Journal, June/July pp 301- 312, 1998.

28. Weckman, H., Lehtimaki, S., and Mannikko, S. Evacuation of a theatre: Exercise Vs Calculations., Human Behaviour in Fire – Proceedings of the First Int Symp, Ed: J.Shields, ISBN 1 85923 103 9, pp 479 - 488, 1998.

29. Galea E.R., Gwynne S., and Lawrence, P., Using Computer Simulation to Predict the Evacuation Performance of Passenger Ships, Paper 00/IM/61, CMS Press, ISBN 189999162X, 2000 .

30. Gwynne,S., Galea, E.R., Owen, M., Lawrence, P.J. and Filippidis, L., A Comparison of Predictions from the buildingEXODUS Evacuation Model with Experimental Data, pp711-721, Human Behaviour in Fire: Proceedings of the 1st International Symposium, Ed: Shields,J., University of Ulster, ISBN 1859231039, TextFlow Ltd, 1998.

31. Hartzell, G. E., "Engineering analysis of hazards to life safety in fires: The fire effluent toxicity component." Human Behaviour in Fire – Proceedings of the First Int Symp, Ed: J.Shields, ISBN 1 85923 103 9, pp 621 - 629, 1998.

32. Gwynne,S. and Galea, E.R.,A Review of the Methodologies Used in the Computer Simulation of Evacuation from the Built Environment, Published by the Society of Fire Protection Engineers, 1998.

33. Gwynne,S., Galea, E.R., Owen, M., Lawrence, P.J. and Filippidis, L., Modelling Occupant Interaction with Fire Conditions using the buildingEXODUS Evacuation Model, CMS Press Paper 00/IM/54, ISBN 1899991557, 2000.

34. Gwynne, S., Galea, E., R., Lawrence, P.J. and Owen, M., An Investigation Of The Aspects Of Occupant Behaviour Required For Evacuation Modelling, Journal of Applied Fire Science, Vol 8(1), pp 19-59, 1998/1999.

35. Gwynne,S. Galea, E., R., Lawrence, P.J.,Owen, M. and Filippidis, L., Adaptive Decision-Making in buildingEXODUS, Journal of Applied Fire Science, 8 (4), pp265-289, 1999.

36. Gwynne,S., Galea, E.R., Owen, M., Lawrence, P.J. and Filippidis, L.,A Review of the Methodologies used in Evacuation Modelling, FIRE AND MATERIALS, 23,pp383-388, Wiley & Sons, 1999.

37. A Technical Reference For CFAST: An Engineering Tool For Estimating Fire And Smoke Transport, NIST Technical Note 1431, Building And Fire Research Laboratory, January 2000.

38. NIST Website: http://cfast.nist.gov/

39. Purser, D.,A., Inaugural Lecture Series, University of Greenwich, ISBN 1861661177, 1999.

40. Wood, P.G, Survey Of Behaviour In Fires, Edited D. Canter pp 83 - 95). Fires And Human Behaviour (2nd Edition), Ed. D. Canter, Fulton, pp205-234,1990.

41. Bryan, J., Behavioural Response To Fire And Smoke, The SFPE, Handbook Of Fire Protection Engineering(2nd Edition), Ed:Dilenno, P.J., Beyer, C.L.,Custer, R.L.P.,Walton, W.D.,Watts, J.M.W.,Drysdale, D., Hall, J.R., National Fire Protection Association,Quincy,Ma, pp (1-241)-(1-262), 1996.

42. Purser, D.A. "Modelling Time To Incapacitation And Death From Toxic And Physical Hazards In Aircraft Fires", Agard No 467, pp41-1 - 41-12, 1989.

43. Purser, D., "People And Fire", Inaugural Lecture Series, 17th February, University Of Greenwich, ISBN 1-86166-117-7, 1999.

44. Purser, D.A., "Toxicity Assessment Of Combustion Products", The Sfpe, Handbook Of Fire Protection Engineering (1st Edition), Ed: Beyer, C.L. National Fire Protection Association, Quincy, Ma, pp(1-200) - (1-245), 1988.

45. Purser, D.A., "Toxicity Assessment Of Combustion Products", The Sfpe, Handbook Of Fire Protection Engineering (2nd Edition), Ed:Dilenno, P.J., Beyer, C.L.,Custer, R.L.P.,Walton, W.D.,Watts, J.M.W.,Drysdale, D., Hall, J.R., National Fire Protection Association,Quincy,Ma, pp (2-85)-(2-146),1996.

46. Purser, D., "Human Tenability", Technical Basis for Performance-Based Fire Regulations, Engineering Foundation Conference, 7-11 January, San Diego, United States, 2001

47. Taylor S., Petridis M., Knight B., Ewer J., Galea E.R. and Patel M. K. "SMARTFIRE: An Integrated Computational Fluid Dynamics code and Expert System for Fire Field Modelling", Fire Safety Science – Proceedings of the Fifth International Symposium, pp 1285-1296, 1997.

48. Ewer J., Galea E.R., Patel M.K., Taylor S., Knight B. and Petridis M., "SMARTFIRE: An Intelligent CFD Based Fire Model, Fire protection Engineering", vol 10, no 1, pp 13-27, 1999.

49. Taylor S, Galea E, Patel M K, Petridis M, Knight B and Ewer J, "SMARTFIRE: An Intelligent Fire Field Model", Proceedings Interflam 96, Cambridge, UK, pp 671-680, 1996.

50. Wang, Z., Jia, F., Galea, E.R., Patel, M.K. and Ewer, J., Simulating one of the CIB W14 round robin test cases using the SMARTFIRE fire field models, Fire Safety J., vol. 36, 2001, pp. 661-677.

51. Ewer, J., Jia, F., Grandison, A., Galea, E.R., and Patel, M.K.,. SMARTFIRE V3.0 User Guide and Technical Manual, Fire Safety Engineering Group, University of Greenwich, UK, 2002."

52. "Smartfire Verification and Validation Report", Software Version 2.01, Report Version 1.01, Fire Safety Engineering Group, University of Greenwich, Revision Date 25/05/99.

53. Galea E.R., “On the field modelling approach to the simulation of enclosure fires”, Journal of Fire Protection Engineering, vol 1 (1), 1989, pp 11-22.