Safety at Speed - S@S

RISK/COST CONTAINMENT MODEL

DELIVERABLE NO. D4.3.0

Document ID Code: S104.30.09.054.001A
Date: 2003-10-13
Contract No. G3RD-CT-2001-00331

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DOCUMENT HISTORY:

Issue:	Date:	Initials:	Revised pages:	Short description of changes: File name:
001	2003-08-17	DK		First Issue (for internal review)
001A	2003-10-13	DK		Final Issue to the Coordinator and the EC (no comments made by reviewers)

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1. EXECUTIVE SUMMARY SUITABLE FOR PUBLICATION

The principal aim of Task 4.3 of the S@S Project is to synthesis a systematic method, which contrasts risks and associated costs pertaining to the containment of fire onboard high speed craft.

Following the work undertaken on the identification of the main means for containment of fire (Task 4.1) and on the analysis of parameters related to fire containment (Task 4.2), the work performed in this task has primarily focused on the implementation of a model suitable for application during the early design stages.

The risk model pertaining to HSC fire resistance is developed through the following main steps:

1) preparation of a simplified Event Tree taking into account active, passive and human factors elements;
2) quantification of probability of the Event Tree gates through Fault Trees. Data needed to perform this step have been retrieved from literature;
3) identification of scenarios (sub-sets of the simplified Event Tree) used for quantification of consequences.
4) quantification of the consequences by means of CFD analysis. The fire modeling has been applied to HSC public spaces in order to evaluate the variation of consequences as a function of the parameters identified in Task 4.2 (refer to D420). The consequences have been quantified on the basis of the conditions (Heat release rate Curve method) inside the compartment where the fire occurs;
5) risk evaluation.

The cost model is developed evaluating the costs variations of systems related to fire (in terms of through life costs and maintenance costs) with respect to the different configuration of the design parameters. The cost of each parameter has been evaluated in terms of material, labour and overhead costs in order to produce a model suitable for integration into WP5.

In the second part of this report, elements of a probabilistic risk/cost model for consequence analysis of large-scale flooding have been presented in this report. This risk/cost model forms an integral part of a risk-based design methodology, targeting holistic design solutions, by setting global design goals, through the integration of safety-related considerations in the design process.

As primary initiating events (hazards) for incidents with potential to lead to large scale flooding the following have been considered: collision; grounding; impact; failure of bow or stern door; mechanical failure of watertight barriers; and operational safety management systems failure / human error. Specifics of the work carried out include the following:

1) A full survivability assessment of the project's basis ship and variants has been carried out, with the view to provide risk data for the assessment of collision, grounding and impact incidents. It should be noted that the basis ship has very high stability characteristics, which combined with the lack of data on

distributions of extent of damages for high speed craft, renders the derivation of probabilities of capsize difficult, which in any case would be very low.

2) In the case of failure of bow or stern doors a fault tree has been proposed. This fault tree is populated with data deriving from experience of operation of passenger Ro-Ro vessels, due to lack of data from operation of high-speed craft and the proximity in the patterns of operation.
3) Failure of watertight barriers and human errors have been treated as factors contributing to the severity of the potential incidents above, using data from operation of passenger Ro-Ro vessels and human reliability analysis, respectively.
4) For the assessment and evaluation of the severity of the consequences the severity scale contained in the IMO's Formal Safety Assessment guidelines is proposed.
5) Finally, with reference to the cost element of the model, for the quantification of the effectiveness of risk control options relevant to containment of flooding following damage, trade-offs between design characteristics (for example, the available carrying capacity and the weight of the structure) have to be performed in order to calculate the marginal costs of the corresponding risk control options. Techno-economic cost models for this reason have been proposed.

S@S is the acronym for Safety at Speed, a project supported by the European Commission under the Growth Programme of the 5TH Framework Programme. The support is given under the scheme of RTD, Contract No. G3RD-CT-2001-00331.

PART 1
RISK/COST MODEL FOR FIRE RESISTANCE

2. INTRODUCTION

Task 4.3 aims to implement a 'fire resistance' risk-cost model in order to evaluate the safety level on board an HSC and the related costs associated to different design options. Within Task 4.3, D'Appolonia has developed a methodology for the analysis and the assessment of risk and cost relevant to the containment of damage and fire during HSC operations, suitable for application at the early stages of design.

During the design and construction of an HSC the main goal is twofold:

- to reduce the risk of fire outbreak;
- to reduce fire propagation if it does break out.

The purpose of the fire risk and cost model herein proposed is to provide a fire-safety analyst with a decisional tool aimed at directing his/her design choices in order to reduce the risk of fire outbreak and its propagation by minimising costs at the same time.

The design options involved in the risk model are represented by the different "status" of the parameters influencing the fire resistance of bulkhead and the reaction to the fire of furnishings.

Parameters related to fire safety have been identified and analysed during the work performed by D'Appolonia within Task 4.2 (refer to D4.2.0 [1]). The most relevant parameters are resumed in Table 1.

PARAMETERS	PARAMETERS DEFINITION	SCENARIO DEFINITION
Sprinklers	- Number - Position - RTI Index - Activation Temperature - Typology	Presence or Absence
Heat Detectors	- Number - Position - RTI Index - Activation Temperature - Typology	Presence or Absence
Fire Size	Quantity and thermal properties of combustible materials	Heat Release Rate Curve
Boundary Conditions	Material properties of walls	Type of Fire Resisting Divisions

Table 1: Main Parameters Related to Fire Event

Active and passive design systems differ, in type and characteristics, through the whole HSC; both risk and cost analyses have been performed only for a single HSC location, i.e., the public space.

The designer can apply both fire risk and cost model to all ship's locations, taking into account the different systems, both in type and characteristics.

Figure 1 sketches the suggested procedure for applying the fire risk and cost model developed within Task 4.3 of the S@S Project and presented in the following sections.

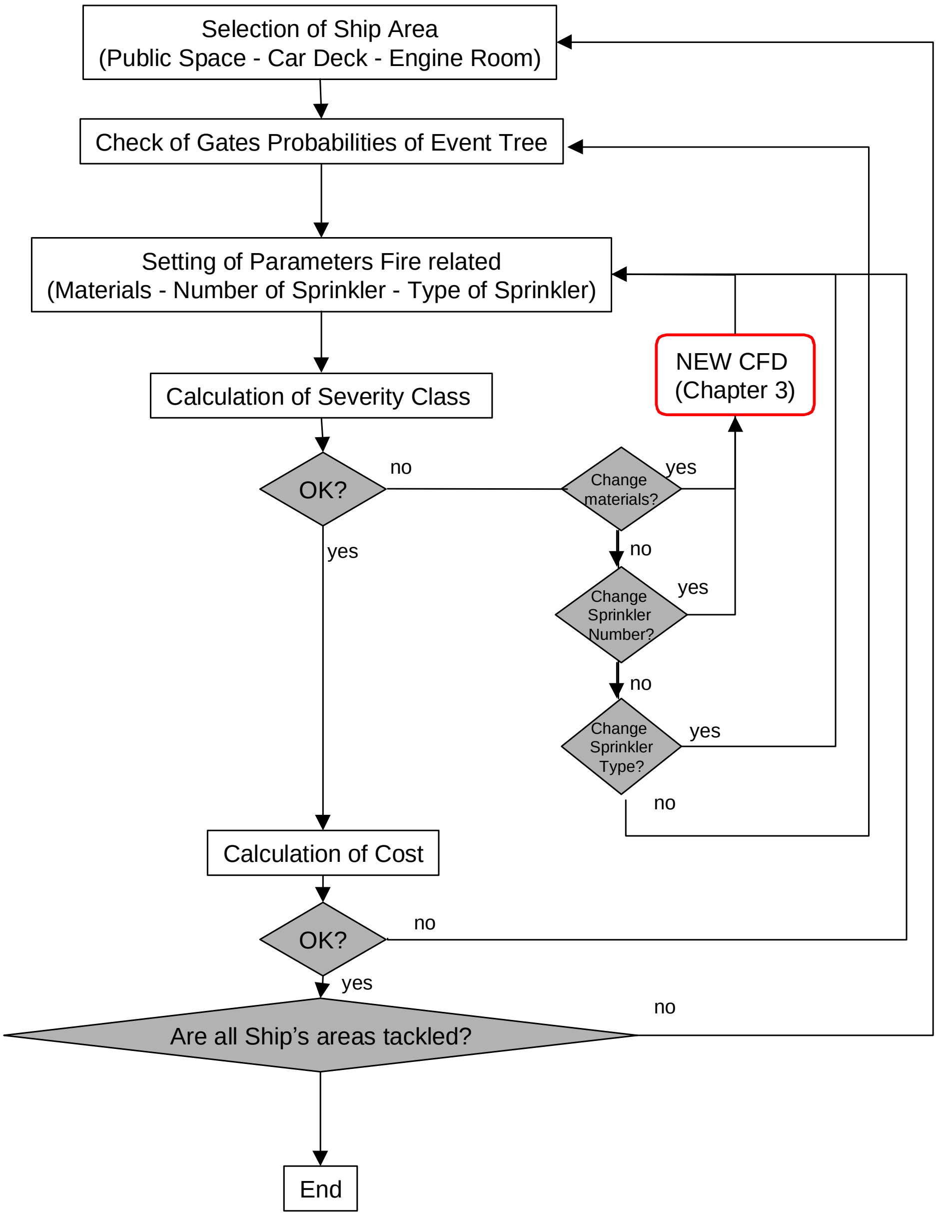

Figure 1: Sketch of Fire and Cost Model Procedure

3. FIRE RISK MODEL - DESCRIPTION

The scope of Task 4.3 is to implement a fire risk model in order to evaluate fire consequences by changing type and characteristics of parameters influencing its development; these consequences are assessed in terms of environmental conditions inside the area in which a fire occurs.

The fire risk model developed by D'Appolonia can be used by designers to evaluate the variation of consequences with the variations of the parameters identified in Task 4.2.

The implementation of the fire risk model comprises the following main steps:

- development of scenarios based on Event Tree Analyses for the quantification of the probability that a fire event occurs (Section 3.1);
- development of CFD simulations for the parametric analysis of fire propagation according to different parameters configurations (Section 3.2);
- analysis of the simulation outcome based on a original approach developed by D'Appolonia (Section 3.2);
- evaluation of the consequences through the definition of class severity (Section 3.3);
- identification of the level of risk for each design options (Section 3.3).

Since the purpose of the work is to demonstrate the validity of the proposed approach described in the report D4.2.0 [1], only a specific HSC area and a limited number of design alternatives have been considered. For each fire scenario obtained through Event Tree Analysis and for each selected design alternatives, CFD simulations have been performed by using the Fire Dynamics Simulator (FDS) model.

Chapter 4 presents the description of fire risk model applied to a lounge of an HSC.

Computational fluid dynamics (CFD) analyses have been carried out (reproducing the scenarios as depicted in the event tree analysis) for estimating the consequences of a fire event occurring on a HSC.

Fire-safety analyst should consider that this model and the values issued from it involve uncertainties and limitations. Nevertheless, these values show tendencies and approximate figures that are useful when describing the comparison between different design options and different HSC.

Furthermore, since no reliable data on active and passive systems' characteristics in HSC are available, the numerical results from the consequences analysis are affected by uncertainty but they can be useful when evaluating, designing and comparing different fire safety measures.

3.1 Event Tree Analyses

The first step of the fire risk analysis a fire event tree analysis involving those parameters influencing the fire development.

The scope of Event Tree Analyses proposed in this Chapter is twofold:

1. to calculate the frequency of occurrence of the outcomes of each scenario in order to evaluate the fire risk level;
2. to support and integrate the consequences analysis.

In the second case, by changing the parameters' characteristics (in terms of frequency or probability associated to a fire event tree gate) it was possible to reduce the number of simulations to be performed and, at the same time, to analyse and evaluate a greater number of design alternatives.

In order to define an appropriate set of events which become determinant during the development of a fire, the identification and the analysis of parameters performed within Task 4.2 have been followed.

The generic event chain, starting from the risk that a fire outbreaks, is shown in Table 2 showing that a fire event is mainly controlled by active design systems (i.e. detectors, sprinklers and ventilation systems). In other words, the different outcomes of the fire event tree and therefore the frequency of each event depend primarily on the presence and functioning of the active design systems (in terms of detection systems and suppression systems).

CODE	EVENT	DESCRIPTION
1	Ignition's event	
2	Rapid Self Termination	Fire self terminates at the early instants subsequent the ignition
3	Automatic Detection	Equipment are able to detect fire
4	Human Detection	People awake in the space are able to detect fire
5	Forced Ventilation Shut Down	Forced ventilation shut down
6	Natural Ventilation Prevented	Whether windows are opened/closed
7	Automatic Fire Extinction	Fixed equipment are able to extinguish fire
8	Manual/Natural Fire Extinction	People into the space are able to extinguish fire

Table 2: Fire Event Tree Framework

Figure 2 presents the fire event tree that represents the causal chain of events occurring between the hazard and the final outcomes.

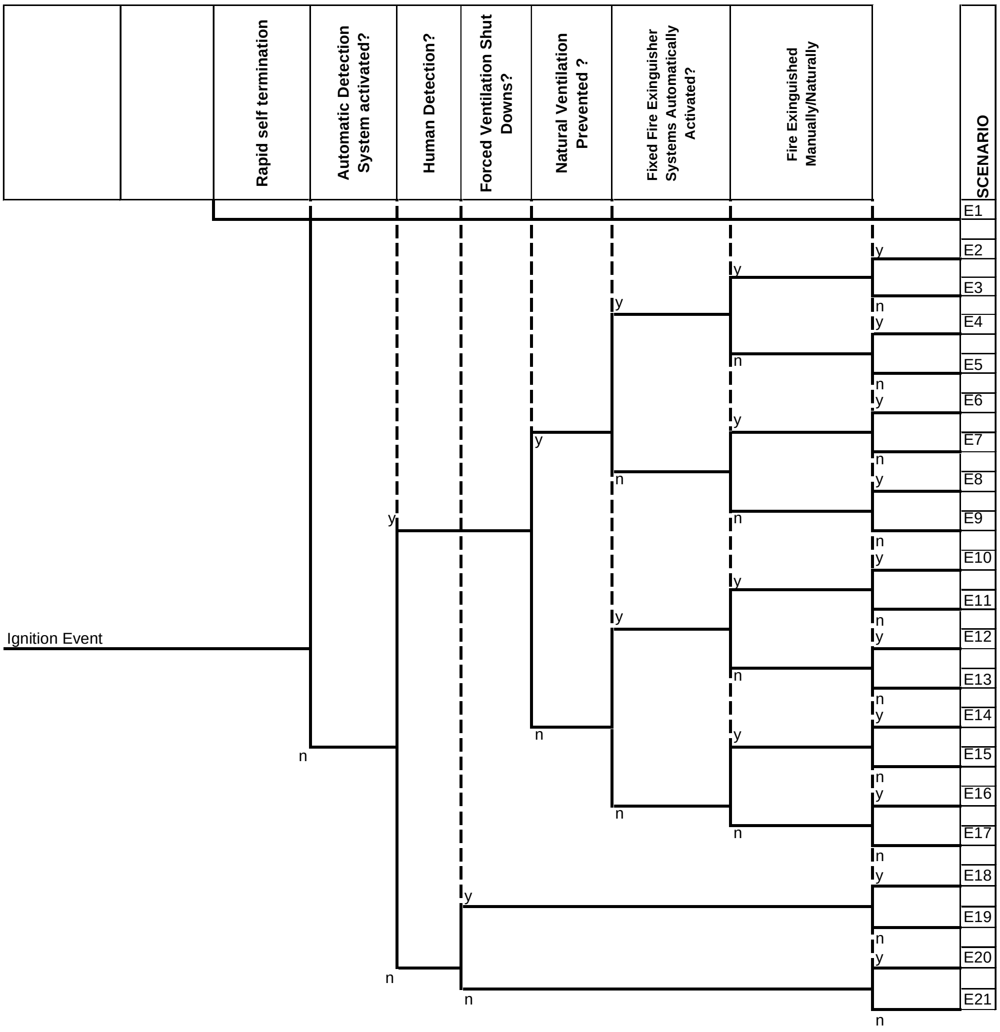

Figure 2: Fire Event Tree – Event Chain

Passive design systems (that are permanent fixtures such as materials for floors, ceiling, walls and furniture) do not appear in the event tree. They influence the development of a fire only in terms of probability of its outbreaks and growth and environmental conditions reached inside the area where the fire occurs.

3.1.1 Quantification of Fire Event Tree

The quantification of the event tree has been performed by using statistical data and expert judgement.

Through the quantification of the fire event tree, the likelihood or frequency of the different fire scenarios has been calculated.

The data of the probability of events selected for the Event Tree Analysis are presented in Table 3.

CODE	PROBABILITY	DESCRIPTION
1	$1.6806*10^{-4}$	Frequency of fire ignition [event/year]
2	0.19	Probability of rapid self termination
3	0.85	Availability of automatic detection system
4	0.12	Probability of people awake and able to detect the fire

5	0.90	Availability of forced ventilation shut-down
6	0.90	Availability of natural ventilation prevention
7	0.96	Availability of automatic suppression system
8	0.30	Probability of success of local manual suppression

Table 3: Fire Event Tree – Probability of Events

Figure 3 sketches the quantification of each scenario of the fire event tree performed by taking into account the probability of occurrence of the events presented in Table 3.

The fire risk model herein proposed foresees that the characterisation of the outcomes in terms of severity is performed trough the quantification of consequences, as explained in Section 3.2.

As above-mentioned, the scope of the fire event tree analysis is twofold. In case fire event tree is used to support consequence analysis, values associated to the probability of gates presented in Table 3 can be changed.

For instance, in Table 3 a reliability of 96% has been associated to the automatic sprinkler system based on a review of statistical data. This value can be improved to 99% through proper design, inspection and maintenance of systems.

In this case, the change in the “status” of parameters, in terms of system’s reliability, affects the fire safety level by changing the frequency of the events instead of the consequences.

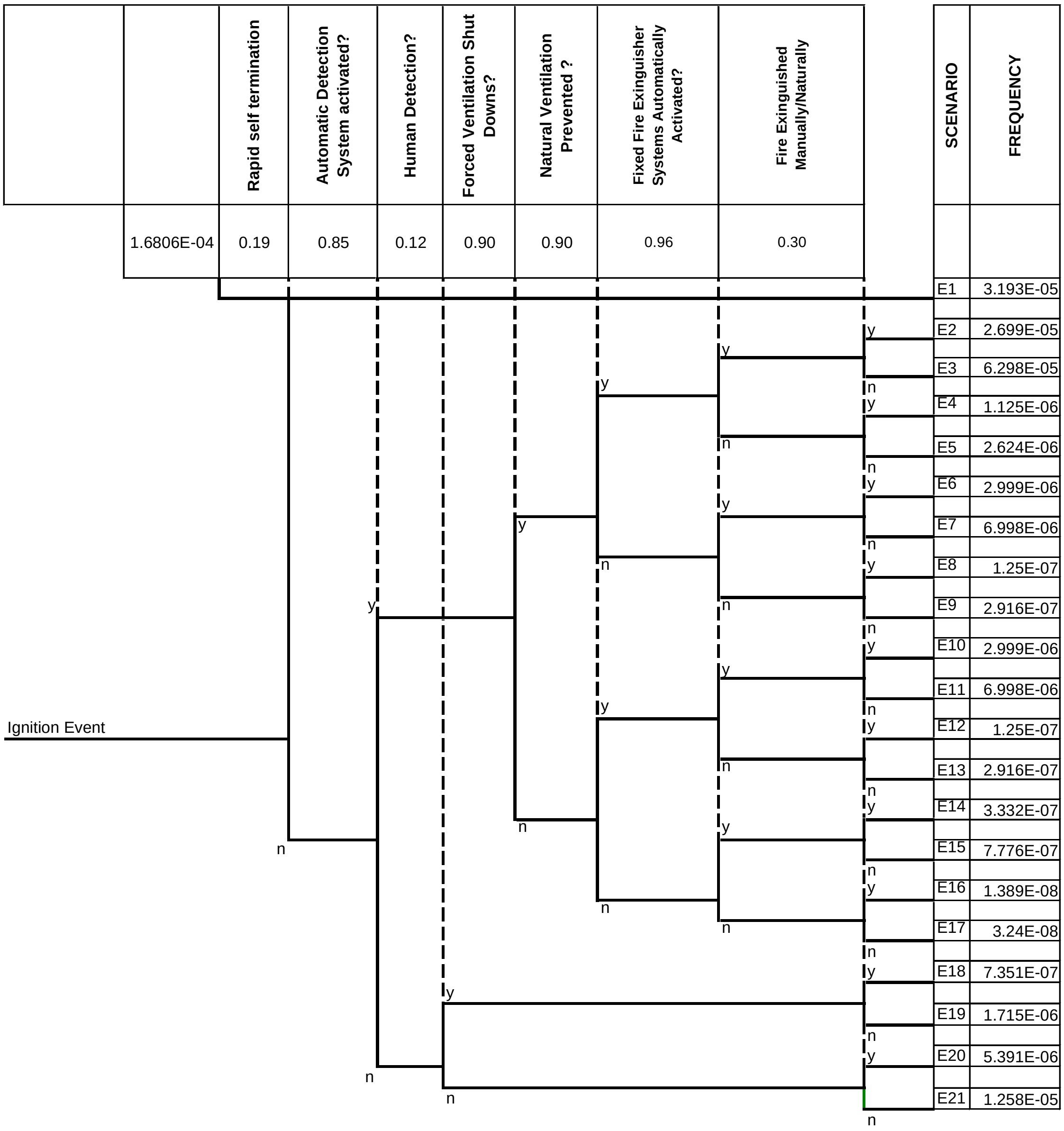

Figure 3: Fire Event Tree - Quantification

3.2 Quantification of consequences

The quantification of consequences has been performed through the computational fluid dynamics (CFD) analyses, supported by the NIST[1] Fire Dynamics Simulator (FDS).

FDS is a CFD model of fire-driven fluid flow. The software has been developed following the "Large Eddy Simulation" (LES) principles.

FDS numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. Combustion equations are based on a "Mixture Fraction" model.

Since the software solves the Navier-Stokes equations for each single cubic cell in the domain, the precision of the solutions depends mainly on the dimensions of the

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[1] National Institute of Standards and Technology

computational grid: decreasing the mesh of the grid (then increasing the number of cells) the obtained solutions will be more accurate. It has been demonstrated that good solutions may be obtained using mesh of about 0.1m and as close to cubes as possible.

Smokeview is a software tool designed to visualise numerical predictions generated by FDS. Smokeview performs this visualisation by presenting animated tracer particle flow, animated contour slices and isosurfaces of computed gas variables and animated surface data and flow vector fields.

Smokeview also presents contours and vector plots of static data anywhere within a simulation scene at a fixed time.

Normally Smokeview is used in a post-processing step to visualise FDS data after a calculation has completed. Smokeview may also be used during a calculation to monitor a simulation's progress and before a calculation to visualise blockage, vent, sprinkler and/or heat detector placement etc. in order to correctly set up the model.

The FDS and Smokeview results have been used in order to obtain a classification of the fire event's consequences in terms of severity.

Severity class associated to each scenario for each design alternatives can be derived from the consequence analysis by using two different approaches herein proposed:

- the Heat Release Rate (HRR) Curve method;
- Tenable conditions method.

The proposed approaches are two ways to observe the same phenomenon. Temperature profile is related with the fire growth rate while the peak of temperature reached is related with the size of fire.

The fire risk methodology developed within Task 4.3 applies the first approach. The second approach is described only for reference purpose.

3.2.1 The Heat Release Rate Curve Method

The first approach consists in associating the scenario's severity to the HRR Curve (obtained as output of FDS simulations) by means of a coefficient 'α' defined as the ratio between the peak of HRR and the time to reach it. Therefore α represents a measure of the fire's growth rate and of its size.

On the basis of the resulting coefficient's value, it is then possible a classification of the consequences, by assuming that a direct relation exists between α (growth rate and size of the fire) and magnitude of the consequences.

Two peaks are relevant for the scope of this analysis. The first peak is reached before the flashover occurs and it is mainly related to passengers' safe evacuation from the room (tied to unsafe evacuation conditions). The second peak follows the flashover and is mainly related to the achievement of the extreme unsafe conditions involving the whole vessel (fire propagation, structural collapse, etc.).

Accordingly with these considerations, two α coefficients (α_I and α_{II}) are calculated being α_I related to local consequences and α_{II} to the safety of the entire vessel.

Once all values are obtained from simulations for each scenario, they will be put in a XY plane where Y axe represents the α_{II} values and X axe α_I so that each scenario is represented by a point in the plane.

The plane will be divided in zones, each of ones is associated to a consequences severity level as further explained in Section 3.3.

The α_I and α_{II} coefficients have been calculated by recognising HRR peaks through the drawing of a line connecting the more significant points may that approximates the Heat Release Rate Curve as in the following examples.

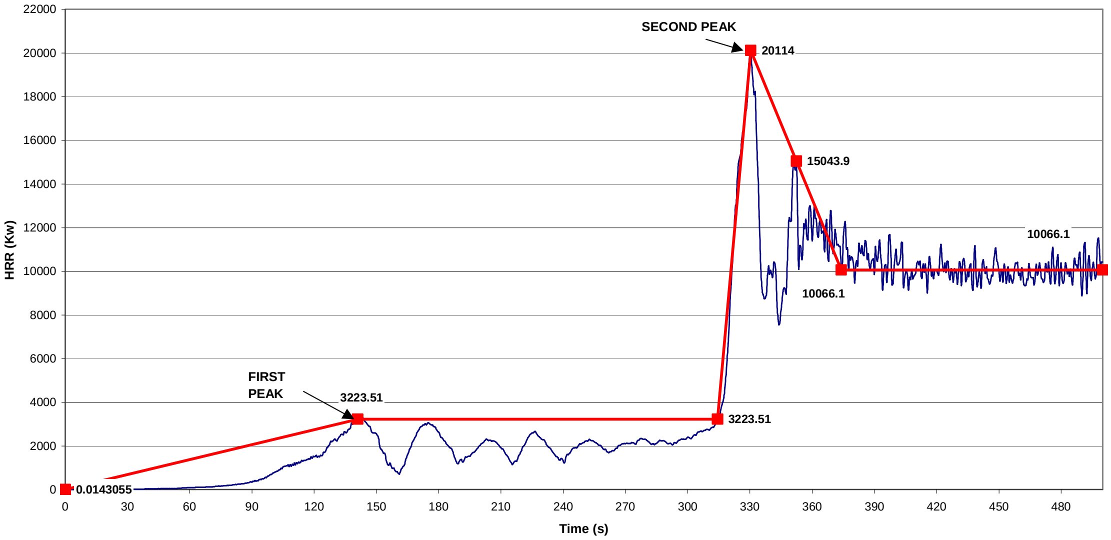

Figure 4: Heat Release Rate Curve Method – First Example

The HRR curve presented in Figure 4 is typical for scenarios where no automatic extinguisher system is available.

Figure 5 shows a HRR curve typical for scenarios where the sprinkler system operates.

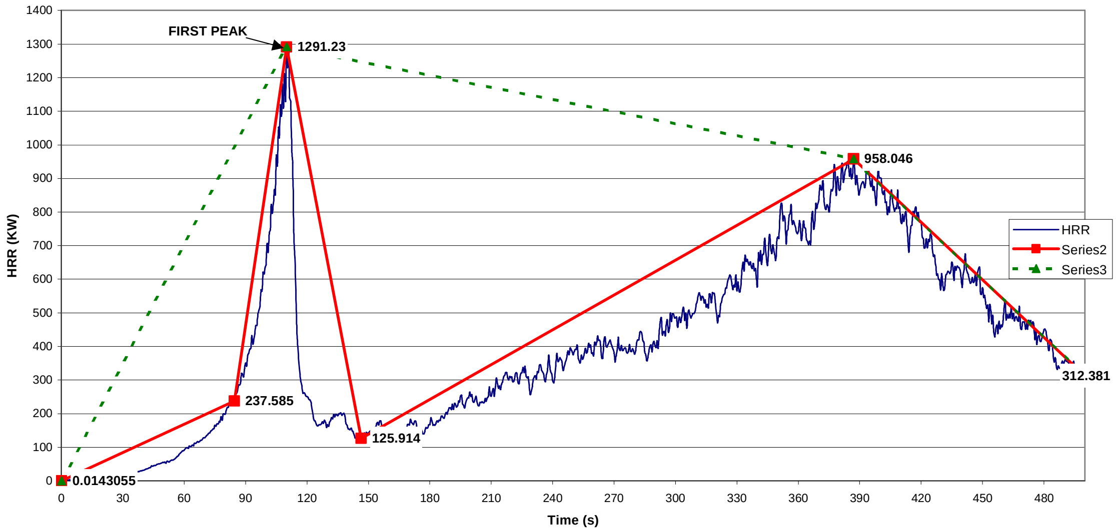

Figure 5: Heat Release Rate Curve Method – Second Example

Comparing the two curves (Figure 4 and Figure 5), it can be noted that, in the first phase of fire growth, the HRR increases with the same ramp but, if sprinkler systems work properly, the HRR, after the sprinklers' activation, starts to decrease to very low values without reaching the flashover point.

In the second case, the α_{II} coefficient is not applicable. In that case and in the other similar cases, the evaluation of consequences of each scenario and of different design configuration is performed only through α_{I} coefficient.

3.2.2 Tenable Conditions Method

The second approach is related with the concept of tenable conditions for the evacuating people.

Accordingly to consolidate risk assessment techniques, the severity of consequences in case of fire is expressed in terms of number of victims or damage to people which depend mainly on time available for escape. At the moment in which the untenable conditions are reached in the room, people cannot escape any longer.

The time needed for escape is to be calculated considering the maximum passengers' capacity of the lounge, an escape velocity of 1.5 m/s (conservative value taking into account the bad conditions and panic situation), dimensions of the room, number, dimension and location of exits.

As criteria assumed to define tenable conditions for a safe evacuation, may be considered:

- temperature;
- visibility;
- concentration of toxic gases.

After the ignition, the fire grows and develops, until it becomes so large that people cannot escape any longer. This defines the end of the time available for escape when untenable conditions appear.

Hence, on these bases, the main parameters influencing the evacuation conditions to be monitored in the simulations are:

- the peak of heat release rate and the time to reach it;
- the maximum temperature reached in the room (potentially leading to structural collapse of the vessel);
- the distance of visibility (m) along the main escape route and the time to reach it;
- the time to the limiting temperature along the escape route at a fixed height.

For this scope, it would be measure temperature and visibility point by point during the simulations by means of a suitable number of virtual thermocouples.

The outputs from each simulation may be presented and visualised in different forms:

- thermocouples giving point values each 0.5 s in form of table from which it is simple obtaining curves and graphs;
- slice files giving animated visualisation of the temperature's growth in a plane by means of a colours' scale (see Figure 6).

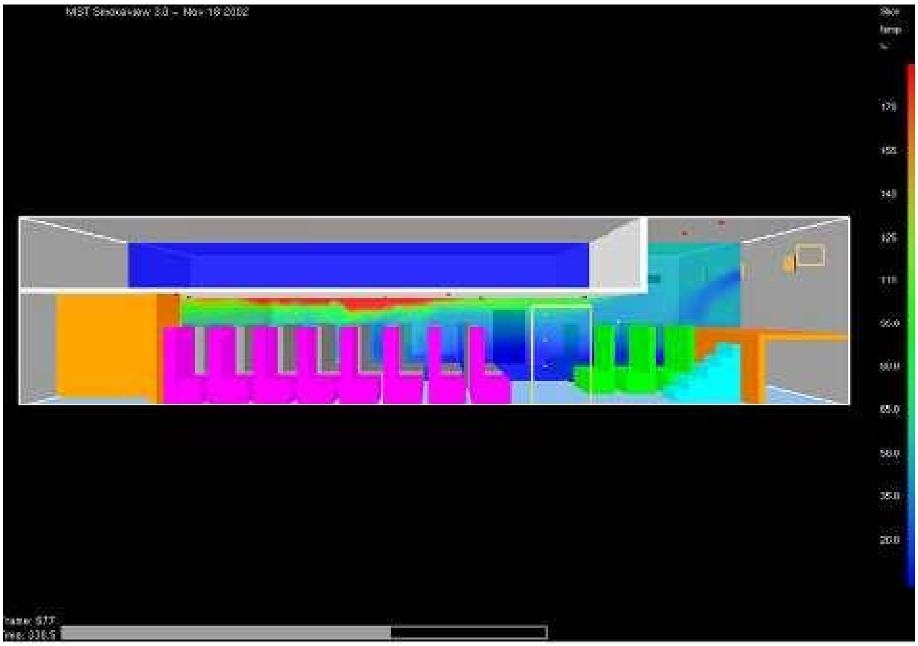

Figure 6: Example of Temperature's Growth

- isosurface files allow to save the Heat Release Rate per Unit of Volume and the Mixture Fraction and render them as an animated sequence;
- Plot3D visualises on each plane the visibility or temperature data, recorded every 30s, by means of a colours' scale (see Figure 7).

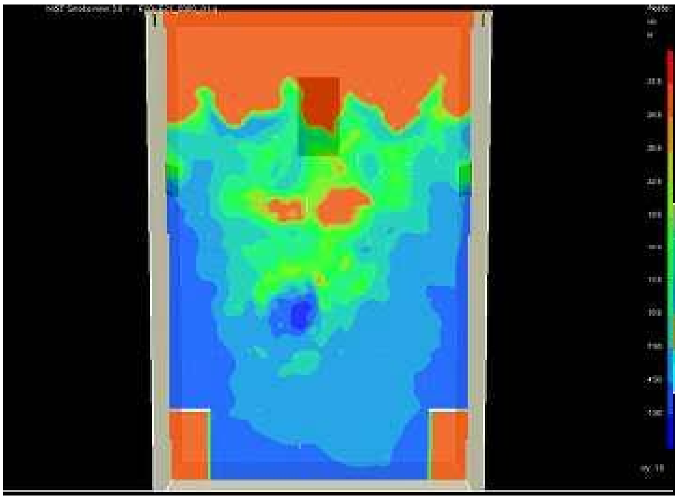

Figure 7: Visualisation of Visibility

Once all outputs parameters are estimated, the time available for escape is known and can be compared with the evacuation time calculated for the room in order to have a likely prevision on the number of people eventually involved in fire.

The risk level of the scenarios will be defined on the basis of the number of people involved.

As previously explained, this method is presented for reference only.

If the designer decides to use this method, the output data can be summarised as in Table 4 that presents an example of the relationship between simulation outputs and estimated risk level obtainable for each scenario.

Scenario	Simulation Output				Risk Level
	Temperature Profile – Time to unsafe temperature	Visibility Profile – Time to unsafe visibility	Maximum Temperature (°C)	…	
…					

Table 4: Relationship between Simulation Outputs and Fire Risk Level

3.2.3 Advantages and Limits of Two Methods

A comparison of advantages and limits of each of the two methods is summarised in Table 5.

METHOD	ADVANTAGES	LIMITS
Heat Release Rate (α coefficient)	- Direct correlation between output data and consequences severity classes; - Independence from evacuation analysis; - Independence from geometry; Large and immediate applicability for all spaces; - Possibility of developing an easy and generic software application for the consequences' assessment; - Immediate comparableness of the results.	- Requires an investigation in order to find a relation between coefficient and number of victims;
Tenable Conditions	- More detailed analysis of scenario's evolution; - Accurated results; - Possibility of express the results directly in terms of number of victims.	- A preventive evacuation analysis is necessary; - Space geometry dependence ; - A large number of data is required; - Dependence from parameters' measuring choices and evacuation criteria applied (i.e. Position and number of thermocouples; assumptions in the definition of extreme conditions; choice of the escape route, hypothesis on features of passengers, ecc.); - Applicable only to the specific space under analysis and do not take into account possible consequences out of the room.

Table 5: Limits and Advantages of Two Methods

Table 5 shows that the second approach is more specific and accurate, whilst the first appears more largely and easily applicable to all spaces.

Nevertheless, for completeness of analysis, also the temperature's data have been monitored. It will be prerogative of the designer choosing the best approach for his/her scopes.

3.3 Class of severity

The class of severity assigned to each scenario for each design alternatives has been defined on the basis of the values of α_I and α_{II} parameters determined as explained in Section 3.2.1.

The XY plane containing the points representing the values of α_I and α_{II} parameters has been divided in nine zones, each of ones is associated to a class of severity.

Five classes of severity have been highlighted: the first class of severity is associated to scenarios or alternative designs in which the consequences in case of fire are the best one. Class 5 of severity represents a scenario with very bad consequences in case a fire event occurs.

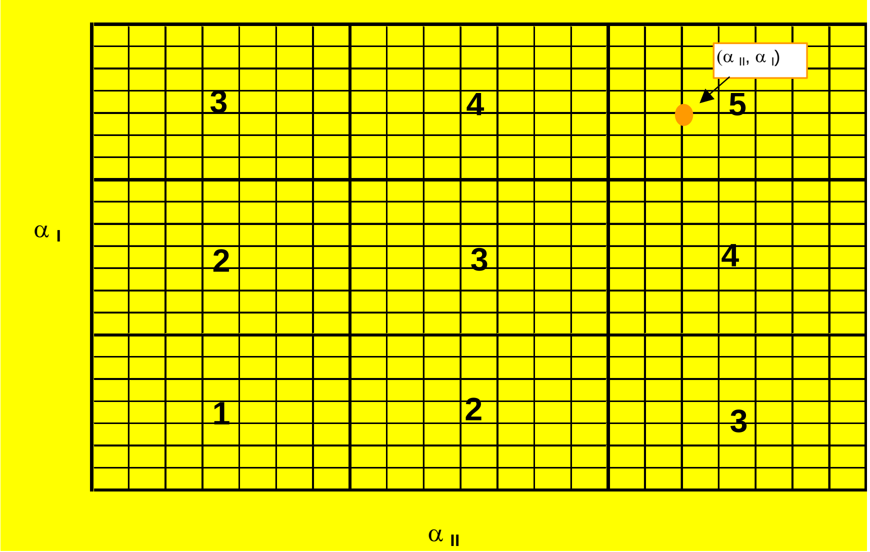

Figure 8: Class of Severity

4. FIRE RISK MODEL – APPLICATION TO A PUBLIC SPACE

This chapter describes in detail the application of the risk model to a representative case of public space, the involved parameters and the results.

4.1 Geometry and Equipment

The public space under analysis (a lounge in this case) needs to be modelled as realistically as possible for performing the evaluation of consequences of a fire event by means of CFD simulations.

The following assumptions have been made to define the basic geometry and have been applied to all the simulations carried out for the public space.

The public space has been represented by a sitting room whose geometry and furniture were derived from design drawings of a real vessel (SuperSeaCat Three).

The dimensions of the lounge are about 15.65 m x 10 m with a variable height from 2.2m to 3.7m.

The number of cells applied to the simulations is 128 x 80 x 32 and is deemed sufficiently high to have an accurate solution of the equations in FDS simulations.

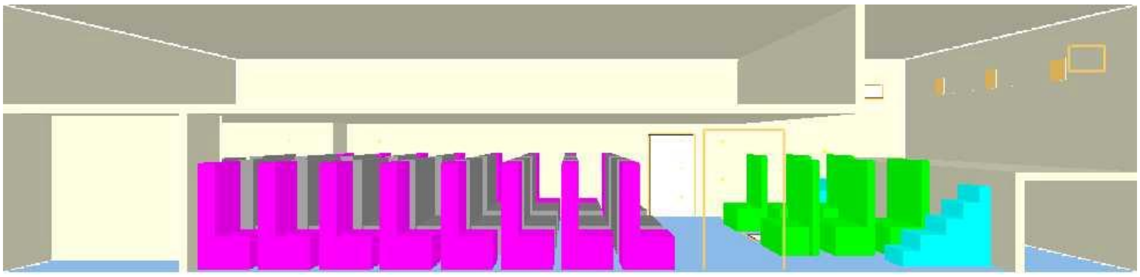

Figure 9: Public Space Geometry

The room is equipped with two emergency exits located on the lateral walls and with a stair connected to the lower floor.
Accordingly with the Event Tree gates, the lounge is also provided with the following equipment:

- automatic detection system;
- ventilation system;
- fixed fire extinguisher system;
- manual fire extinguisher system.

Automatic detection system consists in a certain number of heat detectors located on the ceiling. Each detector is connected with an alarm system and with the forced ventilation equipment so that as soon as the fire is detected, the forced ventilation should be shut off automatically. With the aim of limiting the number of design variables in the analysis, the number of detectors has been assumed fixed of 15 units located on the ceiling in the area where its height is reduced at 2.2 m.

The ventilation system consists of:
- forced ventilation;
- natural ventilation.

The forced ventilation is supplied by three openings of 0.3 x 0.5 m, located at 2.8 m from the floor, blowing air at 15 °C with a velocity of 1.2 m/s. This ventilation is connected with the heat-sensitive apparatuses (detectors or sprinklers) and should be automatically shut off as soon as the fire is detected.

Natural ventilation is provided by two openings, with the same dimensions of the previous ones, and by two emergency exits (1.2 m x 2.0 m). The natural ventilation is assumed always present in the simulated scenarios.

The fixed fire extinguisher system consists of a certain number of sprinklers located on the ceiling. For the scope of this work the number and typology of sprinklers are considered as design parameters and will be changed case by case in order to estimate its impact on risk level as better explained in the following paragraph.

For the fire event definition, it has been assumed that the initial fire is due to the ignition of an upholstered seat cushion (e.g., by a cigarette). Its development, as time function, has been supposed following the heat release rate curve per unit of area experimentally determined by NIST for a three settle and adapted to this case.
The following relation expresses the ramp of the initial fire as time function:

HRRPUA=1700 (Kw/m^2) T= 0.0, F=0.0 /
T= 200.0,F=0.34 /
T= 300.0,F=0.54 /
T= 380.0,F=1.0 /
T= 550.0,F=0.16 /
T=1000.0,F=0.0

Where T = time from ignition (s)
F = HRRPUA fraction

No heat flux is foreseen trough the external walls (for a conservative approach the room is assumed insulated).

4.2 Design Configurations

This sub-chapter defines the different design configurations to which the proposed approach applies.

Since the scope of this work is only to demonstrate the applicability and validity of the proposed fire risk methodology, the number of design parameters analysed and changed is limited. It should be again highlighted that, in a real case, the number of design variables influencing the risk level of the vessel is larger.

In the application here described, the following parameters have been assumed as representing the design options:

- materials;
- number of Sprinklers;
- type of Sprinkler.

4.2.1 Materials

Accordingly to the approach proposed in the report D 4.2.0 [1], the fire's size and its development depends on the combustible materials (furniture, bulkhead panels, structural items, internal finishes, etc.) in the room and their behaviour in case of fire.

The change of materials considered as fire's parameters implies the change in severity of consequences as reflected in the results of the simulations.

The FDS simulator, to resolve the Navier-Stokes equations, needs the materials' properties data from a database.

Appendix A present an example of data set needed to run the simulation, highlighting the differences in the definition of combustible and non-combustible materials.

For the scope of this analysis, three different materials' configurations of the lounge are considered and classified on the basis of their expected fire resistance performances; they are defined in Table 6.

Materials' fire performance grade	Seats	Stairs	Bulkhead panels and default structural material[2]	Secondary panels	Floor	Ceiling panel
Low (L)	Upholstery (Tign=280°C)	Steel	Gypsum Board	Gypsum Board	Carpet	Gypsum Board
Medium (M)	Upholstery (Tign=280°C)	Steel	Marinite	Vinyl Siding	Carpet	Combustible Ceiling Tile
High (H)	Upholstery[3] (Tign=450°C)	Steel	Marinite	Vinyl Siding	Sheet metal	Non-combustible Ceiling Tile

Table 6: Description of Material's Configuration

It should be noted that the choice of materials has been subordinated to the availability of thermo-physical data and does not always reflect real cases.

4.2.2 Number of Sprinklers units

Two design options related to the change in the number of sprinkler units have been analysed: the first option consist of 15 sprinklers and the second of 25 sprinklers. In both cases, sprinklers are uniformly distributed along the ceiling panels.

4.2.3 Type of Sprinkler

In order to reduce the number of simulation to be performed, the influence of the type of sprinkler is analysed by means of the Event Tree analysis as explained in the Section 3.1.

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[2] External walls and bulkheads.

[3] The ignition temperature of 450°C has been arbitrarly assumed with the aim of improving the fire perfomances of the materials since the FDS database repots only one type of upholstery with a low ignition temperature (280°C) and no further data were available in litterature.

In this case, the changes of the type of the sprinkler, in terms of reliability of the system, influence the frequency of the scenario and not the consequences.

Two different types λ_1 and λ_2 of sprinklers units are assumed as applicable; the first option considers a reliability of automatic sprinkler system equal to 96%, the second a greater value of reliability equal to 99%.

From the analysis of the design choices of each selected parameter (materials, number of sprinklers and type of sprinkler system) applicable to the lounge, the selected design configurations analysed by applying the fire risk model are summarised in the following matrix (Figure 10).

			Public Space Geometry		
			Passive measures: materials' fire performances		
	Number	Type	Low	Medium	High
Active measures: sprinklers and heat detectors	15	λ_1	$PS_{L,15,\lambda 1}$	$PS_{M,15,\lambda 1}$	$PS_{H,15,\lambda 1}$
		λ_2	$PS_{L,15,\lambda 2}$	$PS_{M,15,\lambda 2}$	$PS_{H,15,\lambda 2}$
	25	λ_1	$PS_{L,25,\lambda 1}$	$PS_{M,25,\lambda 1}$	$PS_{H,25,\lambda 1}$
		λ_2	$PS_{L,25,\lambda 2}$	$PS_{M,25,\lambda 2}$	$PS_{H,25,\lambda 2}$

Figure 10: Scheme of Design Configurations

Figure 10 shows that twelve design alternatives have been obtained: for each one the event tree shall be resolved with the aim of estimating the associated risk level and then the related costs.

It should be highlighted that only the number of sprinkler units is deemed influencing the severity of the fire development whilst typology and features contribute only to the assessment of the scenario's frequency by means of their reliability data and do not require further suitable FDS Simulations. This means that only six simulations for each scenario need to be performed.

4.3 FDS Simulations

This paragraph describes in detail the relation existing between scenarios from the event tree and the simulation's procedures. Accordingly with the previous chapters, the basic event tree has been applied to each design configuration in the matrix above.
From each event tree, twenty-one scenarios are expected and for each one the consequence class should be assessed by means of CFD simulations. In order to limit the number of simulation, the following has been assumed:

- The human factor, related to human detection or portable fire extinguisher intervention, is not considered in the simulation but its contribute on the consequences is estimated by means of experts' judgement;
- The impact of the natural ventilation on fire growth is deemed negligible.

The correspondence of the simulations with the scenarios from the event tree is highlighted in Table 7.

Scenaros	Rapid Self Termination	Detection Activated	Human Detection	Forced ventilation shut-down	Natural ventilation prevented	Sprinkler	Manual Suppression	CFD Simulations
E1	Y	N/R	N/R	N/R	N/R	N/R	N/R	N/A
E2	N	Y	N/R	Y	Y	Y	Y	A
E3	N	Y	N/R	Y	Y	Y	N	A
E4	N	Y	N/R	Y	Y	N	Y	B
E5	N	Y	N/R	Y	Y	N	N	B
E6	N	Y	N/R	Y	N	Y	Y	A
E7	N	Y	N/R	Y	N	Y	N	A
E8	N	Y	N/R	Y	N	N	Y	B
E9	N	Y	N/R	Y	N	N	N	B
E10	N	Y	N/R	N	Y	Y	Y	C
E11	N	Y	N/R	N	Y	Y	N	C
E12	N	Y	N/R	N	Y	N	Y	D
E13	N	Y	N/R	N	Y	N	N	D
E14	N	Y	N/R	N	N	Y	Y	C
E15	N	Y	N/R	N	N	Y	N	C
E16	N	Y	N/R	N	N	N	Y	D
E17	N	Y	N/R	N	N	N	N	D
E18	N	N	Y	N/R	N/R	N/R	Y	D
E19	N	N	Y	N/R	N/R	N/R	N	D
E20	N	N	N	N/R	N/R	N/R	Y	D
E21	N	N	N	N/R	N/R	N/R	N	D

Table 7: Relationship between Fire Event Tree and FDS Simulations

Thus, some gates of the event tree have no impact on the development of fire with respect to the simulations and therefore the same simulation will cover more than one scenario[4].

Since an event tree is to be resolved for each design configuration, on the basis of the assumption above, the total number of simulations which is to be performed is 18 considering that simulations named D and B are not relevant to sprinklers' number.

4.3.1 Example of FDS Simulation of a Selected Design Configuration

In the following a single representative simulation is discussed for demonstrative purpose. The simulation is named C-M-15 where C indicates the scenarios covered by the simulation with reference to Table 7, M indicates the materials' configuration and 15 is the number of sprinkler. The reference scenario foresees that all the protective automatic equipment work but the forced ventilation shut down system fails.

Appendix A presents the FDS input data files as used in the software.

Figure 11 and Figure 12 present typical outputs that can be obtained from an FDS simulation. In particular, these figures present respectively:

- the heat Release Rate Curve;

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[4] CFD simulation "A" covers E2 and E3 scenarios due to the first assumption and E6 and E7 scenarios due to the second one.

- the temperature Profile, as time function, measured in proximity of both the emergency exits (2 m from the openings) at 1.8m from the floor by means of thermocouples.

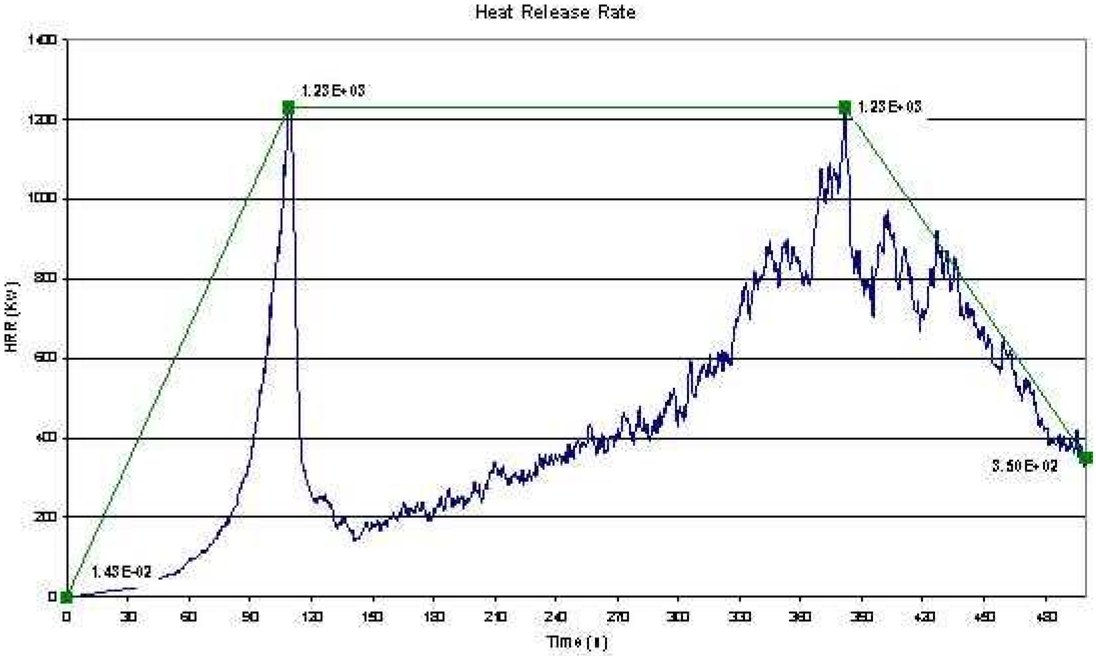

Figure 11: Heat Release Rate Curve for Selected Design Configuration

Appendix B presents the Heat Release Rate Curve obtained from all the simulations performed within Task 4.3.

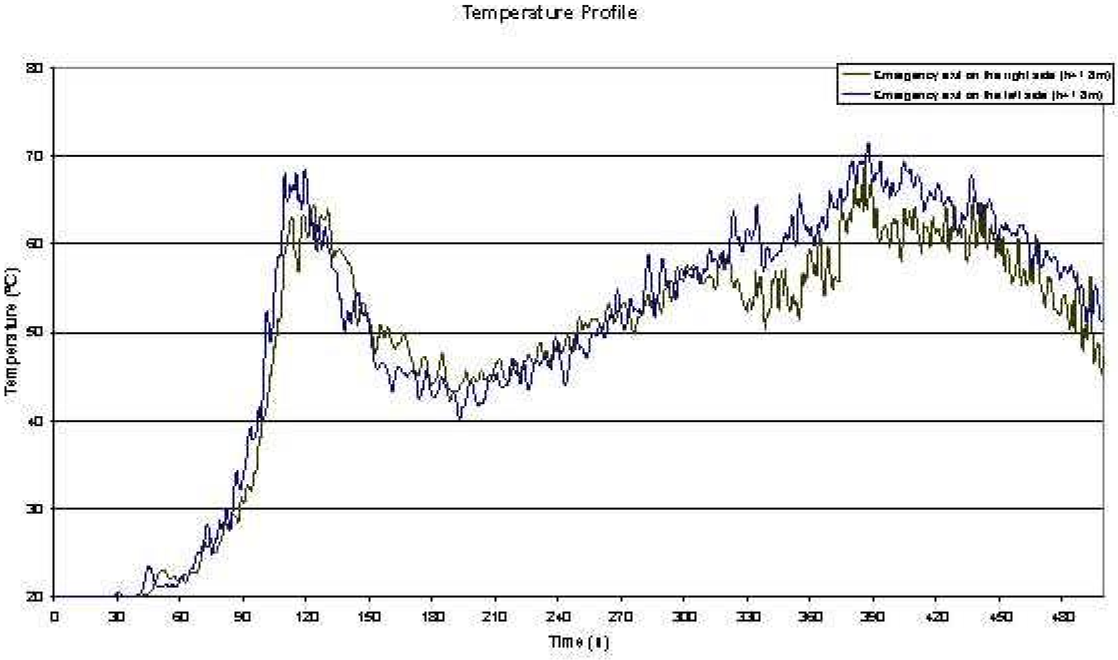

Figure 12: Temperature Profile

The Heat Release Rate method has been applied to the selected design configuration in order to calculate the α coefficients as explained in Section 3.2.1. At this point, the class of severity of all scenarios of the fire event tree, attributable to the selected design configurations can be evaluated as described in Section 3.3.

The results obtained from this FDS simulation have permitted to define the class of severity to a set of fire event tree scenarios (indicated as C in Table 7) for the selected design configuration.

Appendix C presents the determination of frequency and class of severity for each scenarios of the fire event tree and for each design configuration analysed as summarised in Figure 10.

Moreover a movie representation of the current situation can be constantly monitored as shown in Figure 13.

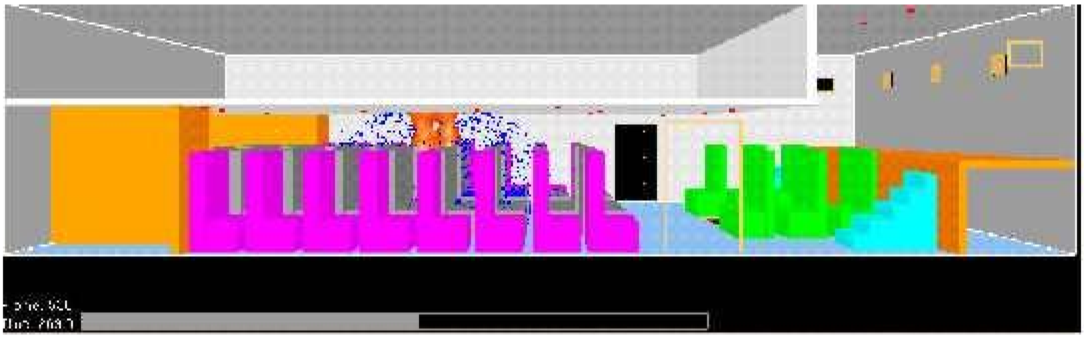

Figure 13: Fire Spread inside a Public Space

5. DISCUSSION OF RESULTS

This Chapter schematises the results obtained from the eighteen simulations performed by using FDS.

Table 8 associates each event tree's scenario to the name of the simulation. Each simulation has been done repeated several times in order to take in account the selected design configurations. From each simulation, identified with a simulation code, coefficients α_I and α_{II} have been calculated applying the Heat Release Rate Curve Method.

Scenarios	Simulations	Materials	N° of Sprinklers	Simulation Code	Coefficient α_I	Coefficient α_{II}	Severity Class
E2-E3 E6-E7	A	L	15	A-L-15	10.07	N/A	2
		M		A-M-15	11.24	N/A	2
		H		A-H-15	1.88	N/A	1
		L	25	A-L-25	10.93	N/A	2
		M		A-M-25	10.39	N/A	2
		H		A-H-25	1.64	N/A	1
E4-E5 E8-E9	B	L	N/A	B-L	18.49	103.34	5
		M		B-M	20.93	102.25	5
		H		B-H	5.75	N/A	1
E10-E11 E14-E15	C	L	15	C-L-15	11.74	N/A	2
		M		C-M-15	11.28	N/A	2
		H		C-H-15	1.88	N/A	1
		L	25	C-L-25	10.93	N/A	2
		M		C-M-25	10.46	N/A	2
		H		C-H-25	1.68	N/A	1
E12-E13 E16-E17 E18-E19 E20-E21	D	L	N/A	D-L	22.86	60.86	3
		M		D-M	16.87	105.54	5
		H		D-H	5.97	N/A	1

Table 8: Values of α Coefficients and Class of Severity for Each Simulation

Table 8 presents also the severity class associated to each simulation by putting in the XY plane the points (α_{II}; α_I) as presented in Figure 14.

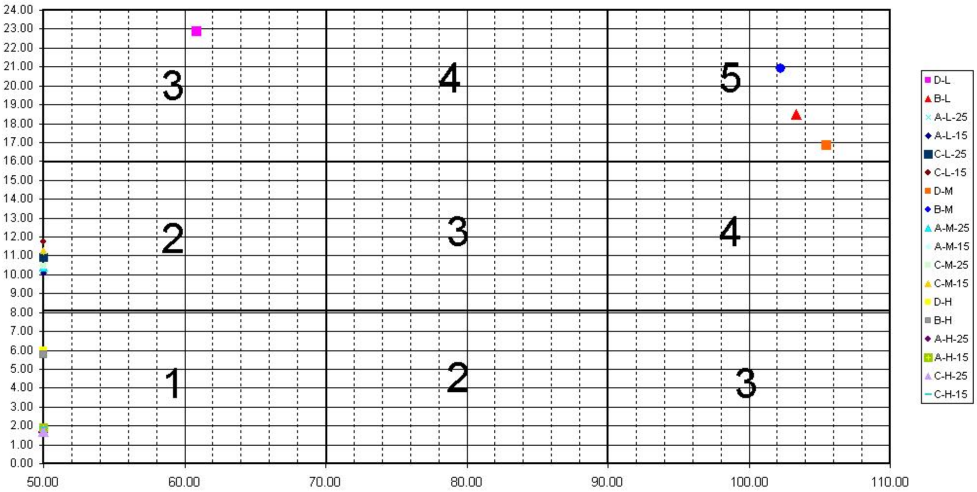

Figure 14: Class of Severity per Simulation Code

The results obtained from the consequence analysis have been analysed in order to comprise which of the selected parameter most weights in the definition of the risk level attributable to a selected design configuration.

From the results presented in Table 9, Table 10 and Table 11, it can be derived that the materials used can change considerably the risk level by changing completely the class of severity of each scenario.

	Number of Sprinklers									
	15					25				
Fire Performance of Materials	Class 1	Class 2	Class 3	Class 4	Class 5	Class 1	Class 2	Class 3	Class 4	Class 5
H	1.361E-04					1,361E-04				
M		1,111E-04			2,505E-05		1,111E-04			2,505E-05
L		1,111E-04	2,088E-05		5,165E-06		1,111E-04	2,088E-05		4,166E-06

Table 9: Analysis of Results – Fire Performance Materials versus Number of Sprinklers

	Type of Sprinklers									
	λ_1					λ_2				
Fire Performance of Materials	Class 1	Class 2	Class 3	Class 4	Class 5	Class 1	Class 2	Class 3	Class 4	Class 5
H	1.361E-04					1.361E-04				
M		1,111E-04			2,505E-05		1,146E-04			2,158E-05
L		1,111E-04	2,088E-05		5,165E-06		1,146E-04	2,053E-05		1,041E-06

Table 10: Analysis of Results – Fire Performance Materials versus Type of Sprinklers versus

	Type of Sprinklers									
	λ_1					λ_2				
Number of Sprinkler	Class 1	Class 2	Class 3	Class 4	Class 5	Class 1	Class 2	Class 3	Class 4	Class 5
15		1,111E-04	2,088E-05		5,165E-06		1,146E-04	2,053E-05		1,041E-06
25		1,111E-04			2,505E-05		1,146E-04			2,158E-05

Table 11: Analysis of Results – Number of Sprinklers versus Type of Sprinklers

During the simulation, the temperature profile inside the lounge and the values reached near the exits near the exit have been monitored. The temperature is locally measured by means of simulated thermocouples positioned near the exits.

Table 12 presents the values of temperatures measured for each simulation. Data reported in Table 12 are useful in case the designer wants apply the tenable conditions method (refer to Section 3.2.2). Table 12 is for reference only.

Simulation Code	Time (s) to reach T=70°C		Temperature Profile (°C)			
	T_1[5]	T_2[6]	t = 60 s	t = 180 s	t = 300 s	t = 420 s
A-L-15	-	-	21.6	52.4	52.8	NR
A-M-15	388.5	382.5	22	48.1	55.7	68.8
A-H-15	248.5	245	21.4	47.3	56.3	55.7
A-L-25	-	-	21.6	34.9	39.3	39.6
A-M-25	-	-	22	35.9	40.4	42

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[5] Values measured at 2m from the exit on the right wall and 1.8m from the floor

[6] Values measured at 2m from the exit on the left wall and 1.8m from the floor

Simulation Code	Time (s) to reach T=70°C		Temperature Profile (°C)			
	T_1[5]	T_2[6]	t = 60 s	t = 180 s	t = 300 s	t = 420 s
A-H-25	-	-	21.4	47.3	58.6	41
B-L	120	115.5	22.1	197.5	592	613
B-M	115.5	111	22	198	360	600
B-H	251	246	21.6	45.6	117	235
C-L-15	-	116.5	21.6	41.4	54.9	63.7
C-M-15	-	387	21.9	44.2	56.6	66.2
C-H-15	248.5	245	21.4	47.3	55	57.6
C-L-25	-	-	21.6	35.2	36.7	39.1
C-M-25	-	-	22	36	38	41.3
C-H-25	-	-	21.4	47.3	57.4	40
D-L	114.5	112.5	21.9	220	209	578
D-M	113	110	22.2	191	372	603
D-H	245	245.5	21.6	45.6	109	238

Table 12: Temperature Inside the Lounge

6. COST MODEL

The cost model related to systems for containment of fire has been implemented in order to calculate the change on costs attributable to the change of parameters' characteristics in terms of fire behaviour.

According to the cost estimation methodology prepared by UNEW, the total cost associated to a parameter can be splitted in:
- Material Cost (C_m);
- Labour Cost (C_l);
- Maintenance Cost (C_{ma});
- Average Crew Cost (C_c).

Considering that the labour cost (C_l) and the maintenance cost (C_{ma}) can be expressed as function of the material cost C_m and that the crew cost (C_c) is not relevant to this case, the cost model will be implemented in order to evaluate only the material cost.

6.1 Development of Cost Model

The material cost C_m will be evaluated for:
- passive systems: materials typically used on board HSC for furnishing, ceiling, lining and resisting divisions;
- active systems: systems typically used on board HSC for containment of fire: smoke and heat detectors, automatic and manual alarms, sprinklers, fixed and portable fire fighting systems.

Therefore, the cost model will be developed in order to evaluate the material cost related to both passive design systems ($C_{m,p}$) and the active design systems ($C_{m,a}$).

Costs related to passive systems and active systems depend on the parameters' costs.

Parameters related to passive and active design systems typically used in the HSC public spaces have been identified within Task 4.2.

Parameters related to passive design systems are materials used for:
- furnishings including: case furniture, draperies/curtains, upholstered furniture, deck finish materials;
- linings;
- ceilings;
- separating divisions.

The material costs related to passive design systems used in HSC public spaces is named $C_{m,p,p.}$

The following parameters related to active systems have been identified:
- detection systems,
- alarm systems;
- ventilation shut-down systems;
- fixed fire extinguisher systems;
- portable fire extinguisher systems.

Costs related to active design systems will be named $C_{m,p,a}$.

The objective of the cost model is to identify changes on costs attributable to the change of parameters' characteristics.

In order to perform the cost estimation, the following activities are needed, for each parameter identified:

- definition of "default values" for each parameter where the default values are values usually associated to parameters in the design phase. Default values represent the type, quantity (expressed in meters or kilograms) and cost of materials/products used in the "basic vessel" (Super Sea Cat);
- identification of parameters to be changed (new materials with better characteristics of reaction to fire, minor quantity, etc.);
- identification of materials/products to be evaluated for use in the "new vessel";
- definition of quantity and cost of materials/Product for the "new vessel";
- evaluation of variation related to "new" materials/products.

The cost model has been implemented in order to allow designers to evaluate the change on costs attributable to use of different types of materials/products for a single item/parameter.

In other terms, if the ceiling material used in all public spaces of the "basic vessel" is always the same, the designer can evaluate the change on costs related to the use of various ceiling materials instead of one.

The change on costs will be expressed as $\delta_{m,p,p}$ for passive systems and as $\delta_{m,p,a}$ for active systems.

$$\delta_{m,p,p} = [C_{m,p,p}\text{ (new vessel)} - C_{m,p,p}\text{ (basic vessel)}]/ C_{m,p,p}\text{ (basic vessel)}$$

$$\delta_{m,p,a} = [C_{m,p,a}\text{ (new vessel)} - C_{m,p,a}\text{ (basic vessel)}]/ C_{m,p,a}\text{ (basic vessel)}$$

Total changes on costs related to passive and active systems in the public spaces, can be expressed as follows:

$$\delta_{m,p} = \delta_{m,p,p} + \delta_{m,p,a}$$

Appendix D shows an example of cost model applied to public spaces. Data concerning quantity and cost of materials/products for basic vessel and new vessel are not real.

7. CONCLUSION

The aim of this report is to present the work performed by D'Appolonia within Task 4.3 of the S@S project. The activities undertaken consist of the implementation of a fire risk-cost model in order to evaluate the safety level on board an HSC and the related costs associated to different alternative design.

The report presents the methodology developed by D'Appolonia for the analysis and assessment of risk and cost relevant to the containment of fire, suitable for application at the early stages of design.

The report includes also a suggested procedure to be followed by the designer for applying the fire risk and cost model.

8. REFERENCES

[1] Dimitris Konovessis, 2002, Formulation of Models Containment of Damage and Fire, Safety at Speed Project, Deliverable No. D4.2.0, Document ID Code S104.20.09.054.001A, December 2002.

PART 2
RISK/COST MODEL FOR DAMAGE RESISTANCE

9. INTRODUCTION

In the second part of Deliverable D430, the work performed on the implementation of a probabilistic risk/cost model for large-scale flooding consequence analysis of high-speed monohulls is reported. Following a brief note on risk-based design, methods/tools and data appropriate for this development are presented for the initiating events considered. Limitations of applicability and areas that further research is needed are highlighted.

10. RISK-BASED DESIGN

For a period of more than ten years a safety culture approach is being promoted through the theme "Design for Safety", which aims at integrating safety cost-effectively in the ship design process [1]. However, the lack, thus far, of a systematic and all-embracing approach to ship safety, offering a framework that allows for a strategic overview of safety and the derivation of effective solutions, meant that the wealth of information amassed over many years of research and development on stand-alone safety-critical areas remains under-utilised, whilst ship safety continues to being unnecessarily undermined. One of the main elements of the above mentioned R&D work is the assurance of safety within the ship design process, in the continuous search for improving the current state-of-affairs. Through small, albeit bold steps in the direction advocated by "Design for Safety", it is slowly but steadily being recognised that this approach can greatly contribute to the overall cost-effective improvement of safety in shipping whilst nurturing the evolution of a more scientific approach to this field.

Risk-based design is a formalised design methodology that integrates systematically risk analysis in the design process with prevention/reduction of risk (to life, property and the environment) embedded as a design objective, alongside standard design objectives (such as speed, cargo capacity, passenger capacity, and turnaround times). This implies the adoption of a holistic approach that links risk prevention/reduction measures to ship performance and cost by using relevant tools to address ship design and operation. This is a radical shift from the current treatment of safety (risk) as a design constraint imposed by rules and regulations. Risk-based design offers freedom to the designer to choose/identify optimal solutions to meet safety targets. For risk-based design to be realised, safety must be treated as a life cycle issue, which in turn implies focus on risk-based operation and need for a risk-based regulatory framework.

Risk-based design, operation and regulation open the door to innovation, as radically novel and inventive design solutions become feasible. It is strongly believed that risk-based design is a key element for the industry to enhance its competitiveness, as the focus shifts towards knowledge-intensive products. On the other hand, the same approach will inherently lead to safer products cost-effectively, because safety can be incorporated into the design process as just another design objective, instead of being treated as a constraint as is the case today.

Risk-based design in the maritime industry follows the well-established path of quantitative risk assessment used in other industries. The term 'risk based design' is also in common use in other industries. The following steps are needed to identify the optimal design solution:

- Set mission objectives
- Identify hazards and scenarios leading to losses
- Determine risks associated with hazards
- Identify means to prevent/reduce risks
- Select safety enhancing features/measures that are cost-effective and designs that meet objectives
- Approve design solutions or change main parameters

The key for a successful risk-based design is to use advanced tools to determine the risks involved and to quantify the effects of risk preventing/reducing measures, as well as to develop acceptance (evaluation) criteria to judge their cost-effectiveness [2].

11. OVERVIEW OF THE RISK/COST MODEL

Of particular importance within the risk-based design methodology, outlined in the foregoing, is the model for the estimation of risk and associated cost appropriate for the ship type in question and mission objectives.

With reference to the focus of this report, as primary initiating events (hazards) for incidents with potential to lead to large scale flooding the following are considered: collision; grounding; impact; failure of bow or stern door; mechanical failure of watertight barriers; and operational safety management systems failure / human error. These initiating events lead to the identification of scenarios, which risk analysis is based upon.

In general, such a model comprises the following elements (Figure 16 illustrates the interrelations between the various elements):

1. Frequency estimation tool for incidents that lead to flooding after damage
2. Consequence estimation tool following flooding
3. Estimation of resulting risk level
4. Assessment of the effect of possible means for containment of damage (RCOs), using the above tools
5. Cost-effectiveness analysis of RCOs

The frequency of incidents that may lead to large scale flooding is closely associated to the expected extent of damage. This is represented by distributions of the longitudinal, vertical and transverse extent of damage for different ship types, using statistical data and first-principles structural analysis. For high speed craft these distributions are not available, rendering future research in this area important. In this respect, the focus will be in presenting methods and tools for the estimation of consequences of large-scale flooding following damage of high speed monohulls.

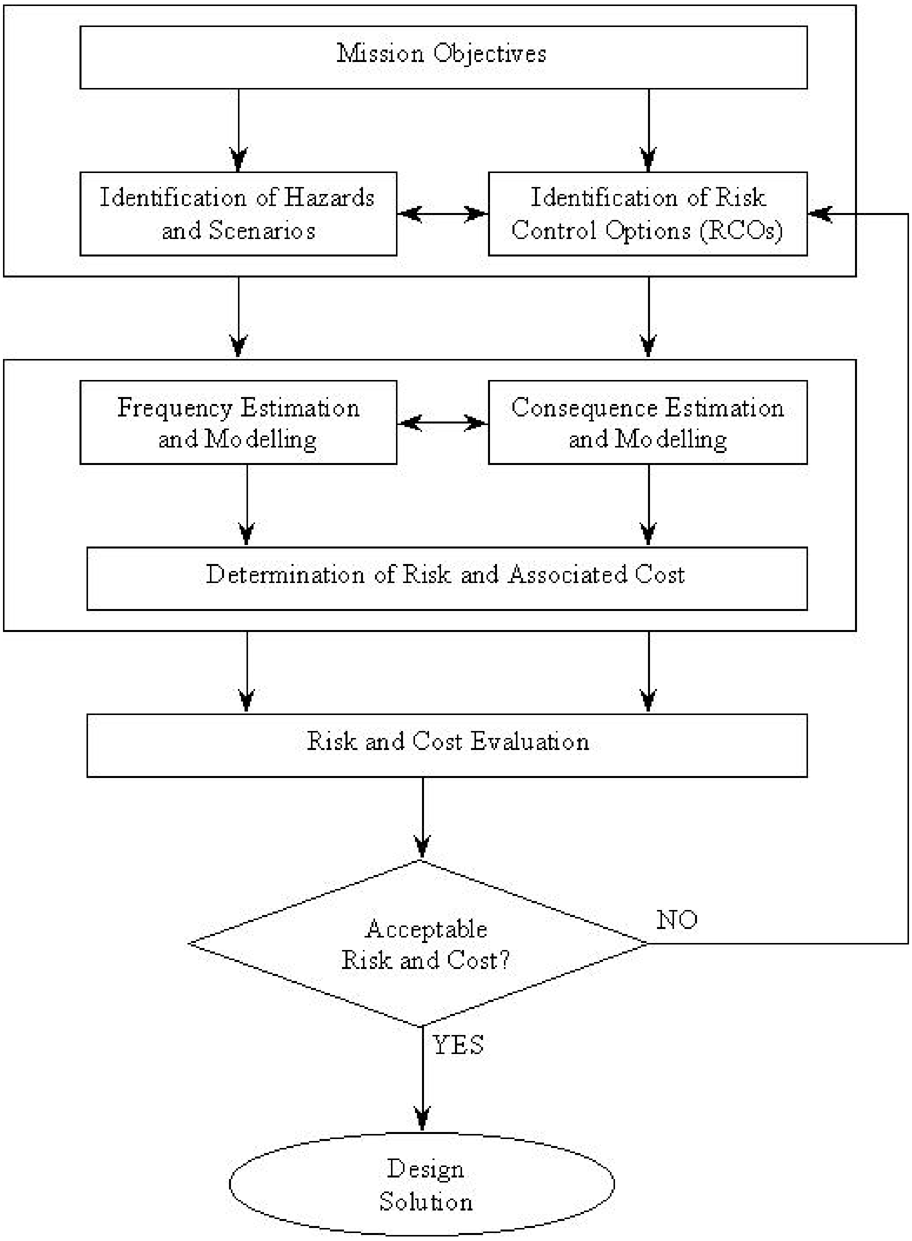

Figure 16: Risk-Based Design Methodology

12. RISK MODEL FOR THE CONTAINMENT OF DAMAGE

The various elements, and their interrelations, of the risk model appropriate for containment of damage during high-speed craft operation are described in this section of the report. The focus is on the applicability of the model during the design process. Guidelines for the utilisation of the model are given, as well as the required input for its full implementation.

12.1 First Principles Tools for Assessing Damage Survivability

12.1.1 Static Equivalent Method (SEM)

An estimate of the volume and height of water accumulated on large undivided spaces close to the damaged waterline can be made using the SEM. In principle, the method statically develops the volume of water that will reduce the damage GZ curve to exactly zero, see Figure 17. From this neutral stability position, any less water volume will be survivable and any more water will cause a capsize. For the re-analysis of the SEM, at this critical heel angle, two parameters h – the dynamic water head, and f – the freeboard at the θ critical angle are calculated, see Figure 18.

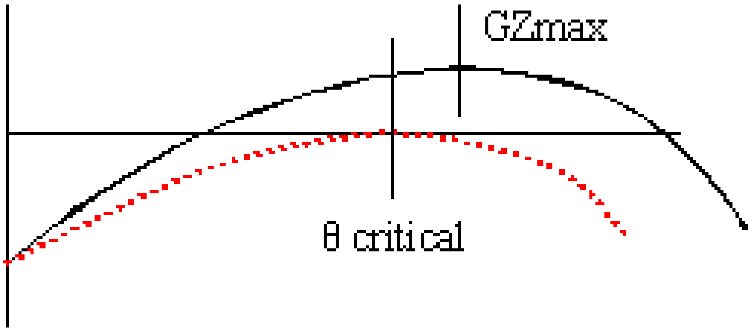

Figure 17: Reduction of GZ Cruve

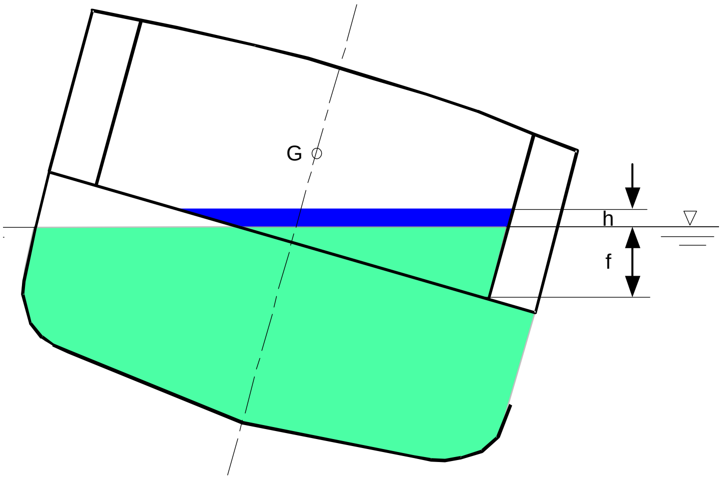

Figure 18: SEM Parameters "h" and "f"

These values of h and f are then statistically correlated with a survival seastate derived from damage stability tests, numerically or experimentally.

Three items should be noted about the static calculation required to determine the SEM parameters. First, the damaged compartments above the open deck space and any damaged wing spaces are considered free flooding as in a standard damage stability calculation, with contribution to buoyancy by intact wings or casings. Second, the development of the reduced GZ lever curves should be-based on constant volume of flood water, not a constant dynamic head (h). Three, it should be noted that the critical angle (θ critical) is generally solved iteratively, and is typically less then the calm water GZmax angle.

In this respect, the statistical relationship between dynamic water head (h), the freeboard at θ critical (f), and the mean significant survival wave height (H_S) has been established in the form of a planar regression given below [3], [4]:

$$H_S = 6.7 \times h - 0.8 \times f - 0.9 \qquad (1)$$

12.1.2 Probability of Survival

Deriving from the above, the probability of survival can be defined as the probability of the significant wave height H_s, calculated for a given damage condition, not exceeding a predetermined significant wave height H_{s^*} that characterises the area of operation of the vessel, i.e.

$$P_{survival} = P\,[H_s < H_{s^*}] \qquad (2)$$

Accordingly, the probability of capsize, which includes every accident that may occur (for example, slow sinking or rapid capsize), is determined as:

$$P_{capsize} = P\,[H_s \geq H_{s^*}] = 1 - P_{survival} \qquad (3)$$

The probability of survival is calculated using SEM results over a suitably weighted range of input parameters. This is done using the well-established technique of Monte Carlo simulations. Monte Carlo methods have been used extensively for the quantification of the uncertainty levels of various systems in fields as diverse as accounting, engineering, marketing, operations management and strategy development. The methods develop through the building of a probabilistic model of the system under investigation and recording of the performance of predetermined parameters, during successive runs of a simulator. The latter are achieved utilising random generators of the uncertain characteristics of the system, which are either discrete or follow known statistical distributions. The outcome of the simulations is usually presented as averages and as risk levels in histograms and cumulative graphs of the predetermined parameters.

Adopting the formulation of the Static Equivalent Method (SEM) as the means for the calculation, it should be noted that since the calculated height of water on deck for a given damage condition depends on every design parameter and their interrelations (principal dimensions and ratios, subdivision, car deck arrangement etc.), as well as on the possible extent of damage, any uncertainty that is determined as influential can be examined through this very calculation, which in turn leads to the determination of the probability of survival.

Distributions of the operational profiles of intact draught and associated vertical and longitudinal centres of gravity form the necessary input to this model. Table 14 contains particulars of the loading conditions of the S@S basis monohull high speed craft, which is used to derive initial conclusions regarding the nature of the input distribution. From these figures, it can be concluded that the deviations in the values are not significant (mean values and deviations from the mean; intact draught: 2.552 m, +5% / -11%; GM: 5.286 m, +10% / -13%; displacement: 1,173.9 tonnes, +10% / -21%).

Table 14: Draught distribution for the S@S basis monohull HSC

Loading Conditions	Δ [tonnes]	T_M [m]	Trim [m]	GM [m]
L.S.	927.4	2.271	-0.344	5.763
1	1,239.4	2.627	0.159	5.272
2	1,221.3	2.607	0.147	5.243
3	1,239.4	2.627	-0.004	5.253
4	1,221.3	2.607	-0.017	5.223
5	1,267.4	2.657	0.054	5.260
6	1,250.0	2.639	0.042	5.236
7	1,038.1	2.402	-0.229	5.399
8	1,009.2	2.368	-0.258	5.331
9	1,295.9	2.688	-0.454	5.165
10	1,295.9	2.688	-0.208	5.202
11	1,295.9	2.688	0.677	4.575
12	960.5	2.311	-0.317	5.796

Figure 19 focuses on the outcomes of a side damage onto the struck vessel when flooding occurs. For the calculation of the branch probabilities, the following approach is adopted [5]:

- The probability of survival s_i of any given damage case is considered to be the product of factor s_a, which reflects the survival probability as affected by various effects that could in the main be assessed using residual stability curves, as described above, with factor s_w, which reflects the survival probability in the event of large scale flooding on the main vehicle deck due to wave action.

- The factor s_a can be used as the branch probability for the scenario where the struck vessel remains afloat after flooding, whilst its complementary probability $(1-s_a)$ can be used for the binary event of this scenario (struck vessel sinks after flooding).

- The Static Equivalent Method can be utilised to calculate the branch probabilities for the final outcomes of a vessel sinking after flooding has occurred. The resulting factor s_w can be used as the branch probability for the scenario where slow sinking following flooding occurs, whilst its complementary probability $(1-s_w)$ is assigned to its binary event (rapid capsize following flooding).

- In order to take into account the probability of extent and location of damage, appropriate damage distributions should be used. For high speed carft these distributions do not exist at present. This probability can be generally represented by the factor p_i, as shown in Figure 19.

- The assumption that factor s_w takes unity value in case the vessel remains afloat is reflected by the formulation proposed in Figure 19. The overall formulation can be considered in a cumulative sense, i.e. including every possible damage case.

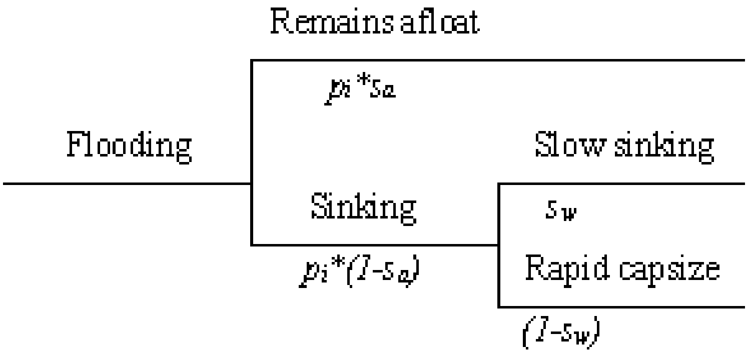

Figure 19: Event Tree for Struck Ship, Flooding Occurring

12.1.3 Implementation of the Risk Model

The risk model described above has been implemented on the S@S basis high speed monohull (length between perpendiculars 88 metres, breadth 17.1 metres, depth to car deck 6 metres, carrying capacity 750 passengers and 175 cars). A damage survivability analysis was carried out for three altenative configurations (for eight, nine and ten transverse bulkheads considered installed below the vehicle deck) for a number of scenarios involving two and three adjustent compartments being flooded. Appendix E contains the plans of these alternative arrangements. The calculations have been carried out for two initial loading conditions, namely INI1 (draught 2.6 metres, GM 5.3 metres and trim 0.16 metres by the stern) and INI2 (draught 2.3 metres, GM 5.6 metres and trim 0.43 metres by the bow). Tables 15 to 20 summarise these calculations. Appendix F contains the SEM calculations obtained using NAPA.

Table 15: Results for two-compartment damage cases, Alternative with 8 bulkheads

Damage Code	Initial Conditions	Hw [m]	f [m]	Hs [m]
D0827	INI1	0.7	-2.017	5.40
	INI2	0.864	-1.448	6.05
D0826	INI1	0.865	-1.731	6.28
	INI2	1.023	-1.137	6.86
D0825	INI1	0.831	-1.68	6.01
	INI2	0.886	-1.429	6.18
D0823	INI1	0.745	-2.886	6.40
	INI2	0.821	-2.358	6.49
D0822	INI1	0.885	-2.11	6.72

	INI2	0.989	-1.749	7.13
D0821	INI1	1.157	-0.769	7.47
	INI2	1.161	-0.605	7.36

Table 16: Results for three-compartment damage cases, Alternative with 8 bulkheads

Damage Code	**Initial Conditions**	**Hw [m]**	**f [m]**	**Hs [m]**
D08376	INI1	0.552	-2.579	4.86
	INI2	0.674	-2.31	5.46
D08365	INI1	0.537	-2.25	4.49
	INI2	0.677	-1.695	4.99
D08354	INI1	0.453	-2.724	4.31
	INI2	0.547	-1.991	4.36
D08321	INI1	0.856	-2.789	7.07
	INI2	0.954	-2.478	7.47

Table 17: Results for two-compartment damage cases, Alternative with 9 bulkheads

Damage Code	**Initial Conditions**	**Hw [m]**	**f [m]**	**Hs [m]**
D0928	INI1	0.7	-2.017	5.40
	INI2	0.864	-1.448	6.05
D0927	INI1	0.865	-1.731	6.28
	INI2	1.023	-1.138	6.86
D0926	INI1	0.933	-1.463	6.52
	INI2	0.95	-1.335	6.53
D0925	INI1	0.789	-1.695	5.74
	INI2	0.829	-1.556	5.89
D0923	INI1	0.835	-1.614	5.98
	INI2	0.905	-1.197	6.12
D0922	INI1	0.922	-1.859	6.76
	INI2	1.034	-1.55	7.27
D0921	INI1	1.157	-0.753	7.45
	INI2	1.173	-0.535	7.39

Table 18: Results for three-compartment damage cases, Alternative with 9 bulkheads

Damage Code	**Initial Conditions**	**Hw [m]**	**f [m]**	**Hs [m]**
D09387	INI1	0.552	-2.579	4.86
	INI2	0.674	-2.31	5.46
D09376	INI1	0.627	-2.049	4.94
	INI2	0.769	-1.515	5.46
D09365	INI1	0.653	-1.966	5.05
	INI2	0.718	-1.726	5.29
D09332	INI1	0.712	-3.782	6.89

	INI2	0.801	-3.447	7.22
D09321	INI1	0.891	-2.521	7.09
	INI2	0.995	-2.229	7.55

Table 19: Results for two-compartment damage cases, Alternative with 10 bulkheads

Damage Code	Initial Conditions	Hw [m]	f [m]	Hs [m]
D1028	INI1	0.865	-1.731	6.28
	INI2	1.023	-1.138	6.86
D1027	INI1	0.957	-1.44	6.66
	INI2	0.972	-1.297	6.65
D1026	INI1	0.844	-1.582	6.02
	INI2	0.862	-1.529	6.09
D1025	INI1	0.789	-1.661	5.72
	INI2	0.857	-1.469	6.02
D1024	INI1	0.866	-1.474	6.08
	INI2	0.93	-1.367	6.42
D1023	INI1	0.986	-0.929	6.45
	INI2	1.032	-1.147	6.93
D1022	INI1	1.075	-1.031	7.13
	INI2	1.12	-0.906	7.33
D1021	INI1	1.206	-0.384	7.49
	INI2	1.192	-0.161	7.22

Table 20: Results for three-compartment damage cases, Alternative with 10 bulkheads

Damage Code	Initial Conditions	Hw [m]	f [m]	Hs [m]
D10398	INI1	0.552	-2.597	4.88
	INI2	0.674	-2.31	5.46
D10387	INI1	0.662	-1.962	5.11
	INI2	0.796	-1.47	5.61
D10376	INI1	0.705	-1.839	5.29
	INI2	0.765	-1.632	5.53
D10365	INI1	0.575	-2.169	4.69
	INI2	0.68	-1.691	5.01
D10343	INI1	0.742	-2.976	6.45
	INI2	0.838	-2.437	6.66
D10332	INI1	0.863	-2.278	6.70
	INI2	0.963	-1.932	7.09
D10321	INI1	1.045	-1.332	7.17
	INI2	1.092	-0.974	7.19

The derived survivability levels presented in Tables 15 to 20 demonstrate that the S@S basis high speed monohull possesses very high survivability characteristics. A point that should be highlighted is that the HSC Code requires only the examination of damage cases involving up to two adjacent compartments for a vessel of this size. As has already indicated, the lack of distributions of the extents of damage for high speed craft, renders derivation of probabilities of capsize not possible, which, in any case, would be small, judging from the survivability analysis results obtained.

Figure 20 illustrates the attitude of the vessel when additional water on deck calculations with the SEM method have been carried out, at the point where the vessel looses stability (GZ = 0), in the case of a very large damage case, comprising four compartments flooded below the vehicle deck. Due to the very extreme nature of this case, from a damage survivability assessment point of view the vessel is not capsizing, but is sinking instead. The very important element with this kind of damage cases is to estimate the probability of structural failure as well as to have available distributions of the probabilities of the extent of damages applicable to HSC.

Figure 20: Very Large Damage Case

Finally, the effect on damage survivability of varying GM values has been examined. For this purpose, attained subdivision index calculations have been carried out for GM values ranging from 0.5 metres to 5.5 metres, for the three variants of the S@S basis ship used above. SLF42 proposal for the probabilistic harmonised regulations have been used, and it should be highlighted that any probabilistic formulation for damage survivability only takes into account damage cases with extent up to 24% of the vessel's length. The results obtained using NAPA are contained in Appendix G. These results show that significant reduction in survivability is evident for a substantial reduction in the operational GM value (of around 2 metres), which may be considered impractical from an operational point of view.

12.1.4 Event Trees – Severity of Consequences

Figures 21 to 23 contain the event trees for collision, grounding and impact incidents developed as part of the Joint North West European Project for conventional passenger Ro-Ro vessels [6]. The branch probabilities of these event trees have been derived from statistical data and expert judgement.

With reference to the event tree for collision outcomes, in the absence of other relevant data, it is proposed that this event tree is used as it is, expect for the branch probabilities for large scale flooding outcomes (part of the event tree presented in Figure 19). This is due to the results of the survivability analysis presented above. Given the limitations discussed, it is not possible to propose a concise method to derive varying levels for these branch probabilities, however, assumed values of 0.9, 0.05 and 0.05 as branch probabilities for the vessel remaining afloat, slowly capsizing and rapidly sinking, respectively, are considered to be appropriate.

With reference to the event trees for grounding outcomes, in the absence of other relevant data, it is proposed to be used as it is, in the case of a vessel with a double bottom, otherwise a combination of the branch probabilities for double bottom flooding only and flooding above double bottom is proposed.

The event tree for impact incidents, in the absence of other relevant data, is proposed to be used as it is.

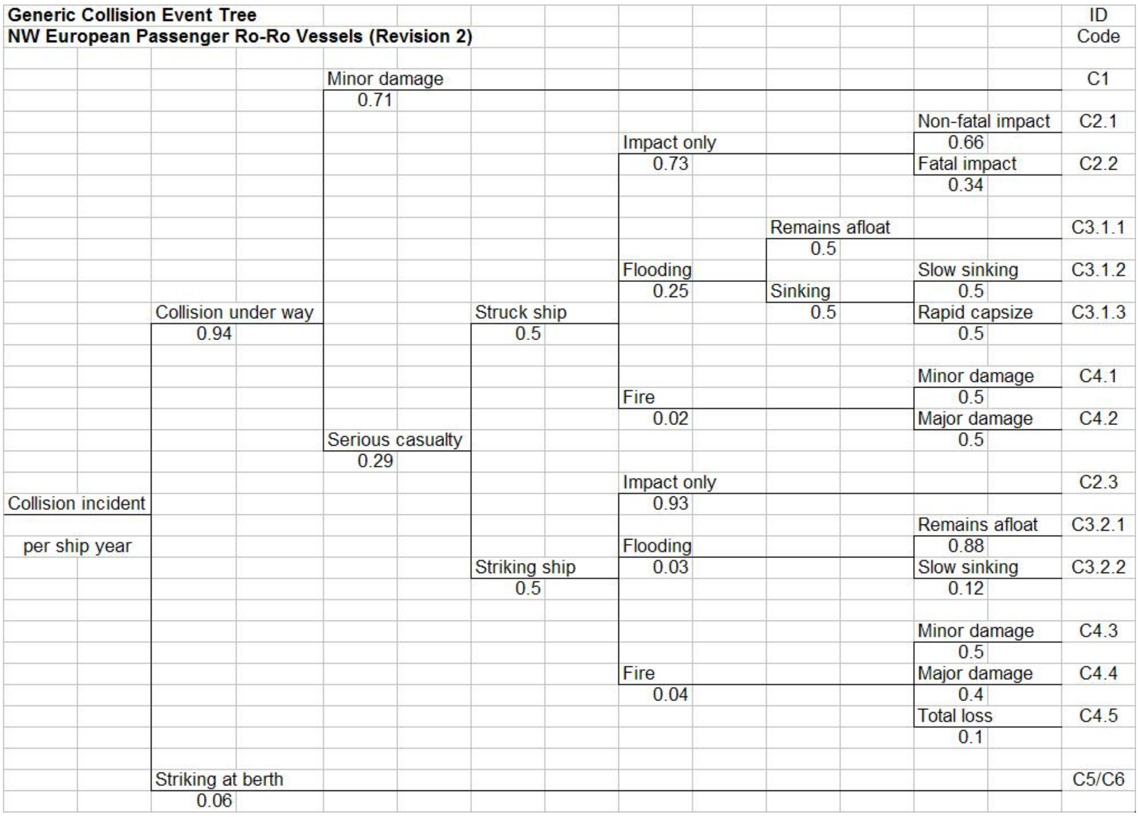

Figure 21: Event Tree for Collision Outcomes [6]

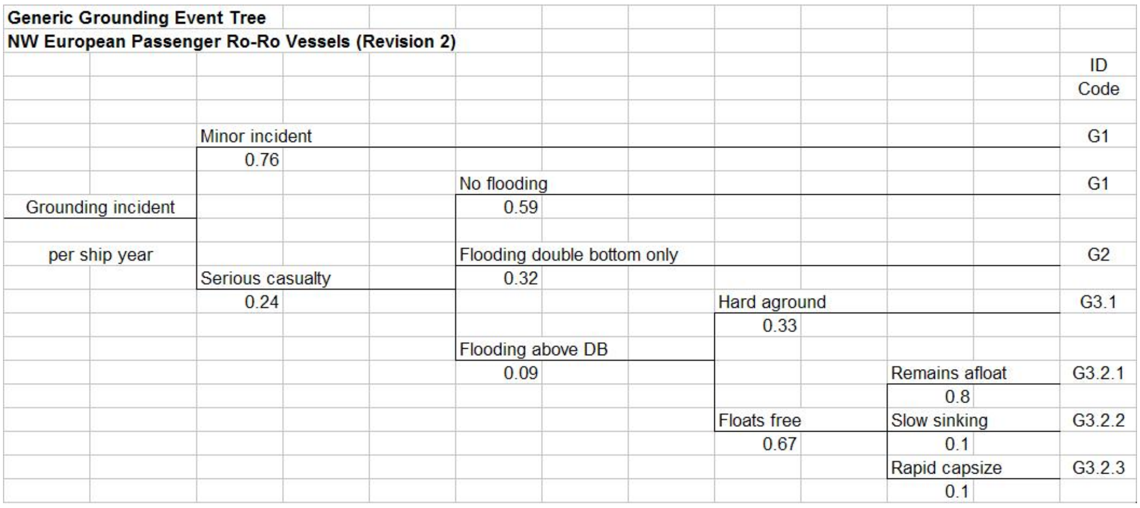

Figure 22: Event Tree for Grounding Outcomes [6]

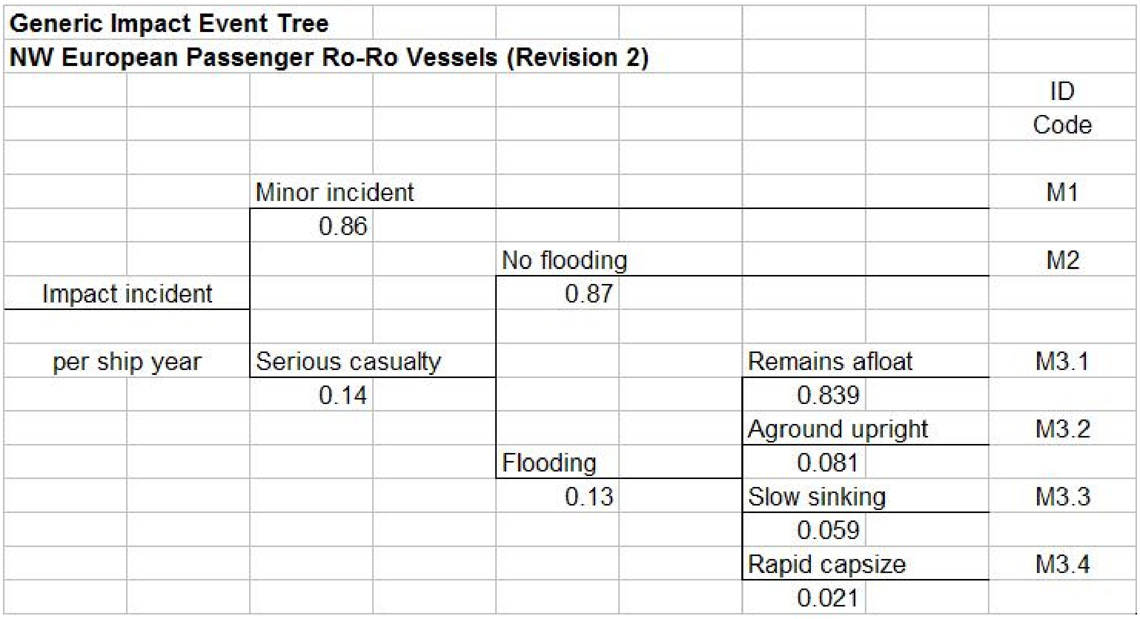

Figure 23: Event Tree for Impact Outcomes [6]

Table 21 contains the severity index, as proposed in the latest IMO Guidelines for FSA Application [7]. Association of the possible outcomes contained in Figures 21 to 23 is possible with the severity scales of this index, based on expert judgement.

Table 21: Severity Index [7]

Severity Index				
SI	SEVERITY	EFFECTS ON HUMAN SAFETY	EFFECTS ON SHIPS	S (Equivalent fatalities)
1	Minor	Single or minor injuries	Local equipment damage	0.01
2	Significant	Multiple or sever injuries	Non-severe ship damage	0.1
3	Severe	Single fatality or multiple severe injuries	Severe damage	1
4	Catastrophic	Multiple fatalities	Total loss	10

12.2 Raking Damages

High-speed craft with single bottom structure are vulnerable to bottom raking and the consequences can be disastrous. Safe operation is critically dependent on the integrity of the hull structure under extreme sea conditions and/or accidental operational conditions. This requires an accurate assessment of physical and mechanical behaviour of the hull structure.

The UK submitted a proposal at the start of the recent revision of the 2000 HSC Code suggesting that the extent of bottom raking damage should take into account the effects of variations in craft speed, displacement, hull material and scantlings. It is clear that the extent of damage should be related to these factors, especially craft speed.

However, in the absence of any scientifically supported research, a rather simplistic approach of 100% length bottom damage requirement for all Category B craft regardless of speed, size, etc was adopted by the IMO Stability Load Line and Fishing Vessel (SLF) Working Group. Similar simplistic requirements for Category A craft expressed solely as percentage of craft length were also agreed. However, higher speed Category A craft do not currently achieve a level of safety equivalent to slower speed craft. This calls for further research for the purpose of code amendment.

12.3 Other Initiating Events

As already mentioned, large scale flooding may also occur through the bow or stern doors on the car deck, whilst progressive flooding may occur through watertight internal doors left open or purely maintained. In these cases, advanced tools need to be applied to simulate the behaviour of the vessel following damage. Developments in these areas are still on-going and in this respect, results based on first-principles are not available.

12.3.1 Additional Causes of Flooding

Appendix H contains a fault tree that can be used for the case of flooding in any other case other than collision, grounding or impact. This fault tree has been developed for conventional passenger Ro-Ro vessels as part of the work carried out during the Joint North West European project [6]. In the absence of data from HSC operations, the results of this work can be used. In the following the assumptions made are reproduced, from [6].

The following main scenarios have been considered:

CODE	SCENARIO
L1.1	Flooding due to wave damage, through bow door
L1.2	Flooding due to wave damage, through stern door
L1.3	Flooding due to wave damage, through hull
L1.4	Flooding due to wave damage, into bridge/superstructure
L2.1	Flooding through open bow door
L2.2	Flooding through open stern door
L2.3	Flooding through open side door
L3	Flooding through down-flooding openings
L4	Flooding through vehicle deck

Flooding due to wave damage

The average frequencies of bow door damage requiring immediate repair for NW European passenger Ro-Ro vessels are estimated to be:

Pre-1982 IACS rules	2×10^{-2} per ship year
Current classification society rules	2×10^{-3} per ship year

The frequency for pre-1982 IACS rules compliance is derived from reported damage experience in the Baltic. Compliance with the current rules is assumed to achieve an order of magnitude improvement for these ships. However, the effects of operation in different sea areas could be represented by the frequencies in the table below, increased by a factor of 20 to give an average value of 2 x 10^{-3}.

SEA AREA	20-YEAR SIGNIFICANT WAVE HEIGHT (m)	FREQUENCY OF 19.6 m WAVE HEIGHT (per year)
North Atlantic	19.6	5.0 x 10^{-2}
Norwegian Sea	14.9	2.3 x 10^{-3}
Mid North Sea	11.9	3.2 x 10^{-4}
Skagerak	9.6	6.9 x 10^{-5}
Kattegat	8.7	3.8 x 10^{-5}
Baltic Sea	8.5	3.4 x 10^{-5}

Based on Lloyd's data, the effect of door configuration, reflecting the difficulty of securing the bow visor type, could be assumed as follows:

Bow visor	x 1.2
Bow doors	x 0.5

The effects of the captain's willingness to reduce speed in rough weather could be represented by the following assumed modification factors:

Services with time pressure (less than 1 hour in port between sailings)	x 2
Ships with ISM Code safety management systems	x 0.5

The probability of failure of the bow door is estimated to be 0.06 per damage incident. This probability will be assumed to be independent of bow door configuration, operating area or service type.

The following are the assumed probabilities of bow damage resulting in complete failure and flooding of the vehicle deck:

Two barriers overlapping	0.5
Two independent barriers	0.1
Three independent barriers	0.05

The frequencies of wave damage other than to the bow door are derived from accidental data of passenger Ro-Ro vessels in NW Europe known during 1978-94, and are as follows:

Damage to bridge	6 x 10^{-4} per ship year
Damage to garage deck	3 x 10^{-4} per ship year
Damage to stern door	6 x 10^{-5} per ship year
Damage to hull	6 x 10^{-5} per ship year

Since there are no second lines of defence these are equivalent to flooding frequencies. Modification factors could be applied as for bow door damage. It should be noted that, except otherwise stated, these values are highly judgemental, and should be used with caution.

Flooding through Open Doors

Generic human error rates are used to determine the frequency that a door will remain open during its closure process. Depending on the reporting system that is applied, these error probabilities are as follows:

Negative reporting system	10^{-5} per door closure
Positive reporting system	10^{-6} per door closure
Positive reporting system and ISM Code compliance	10^{-7} per door closure

Positive reporting procedures are required by SOLAS 90, but in fact largely adopted since 1987. The loading officer is required to make a positive report to the bridge that the doors are closed, and this must be noted in the log. The status of the doors is also shown by indicator lights on the bridge. Possible modification factors are:

Ship has bow visor, which obstructs vision from the bridge when open	x 0.2
Ship has doors, which do not obstruct vision from bridge	x 2
Turn-around time in port less than 1 hour	x 2
Turn-around time in port more than 6 hours	x 0.5

These are based on judgement, and improved estimates would be desirable.

The probability of vehicle deck flooding through open doors is estimated to be 0.25 per damage incident for bow and side doors, and 0.1 per damage incident for stern doors. Modifications can be made as follows:

Loading procedures meeting the ISM Code	x 0.5
Port approaches deep enough to avoid squat	x 0.75
Sheltered water routes	x 0.5
Freeboard less than 2 metres	x 2
Freeboard more than 4 metres	x 0.5

Flooding though Down-Flooding Openings

The frequency is estimated to be 2.9 x 10^{-4} per ship year, which however is based on the experience of only one accident.

Theoretical capsize models can be used to predict the effect of wave climate, ship route, and ship stability parameters on the capsize frequency.

Flooding below Vehicle Deck

Flooding below the vehicle deck may be due to corrosion, faults in the ballast or cooling water systems, or fault in the shaft seals (experience with passenger Ro-Ro vessels in NW Europe during 1978-94).

The frequency is estimated to be 8.6 x 10^{-4} per ship year, which is based on the experience of three accidents (experience with passenger Ro-Ro vessels in NW Europe during 1978-94).

12.3.2 Failure of internal doors

Generic data on failure of internal doors due to negligence or poor maintenance has not been possible to obtain. Work carried out as part of the S@S project on human reliability can be used to obtain data on frequencies of such actions.

12.3.3 Human Error

Generic human error rate data may be used to indicate likely probabilities of failure to close the doors, in the absence of a more detailed human reliability analysis. A simple approach to assigning human error rates is given in Table 22 (from Swain and Guttman, 1985). The task under study is matched to the generic task descriptions in the table, and the corresponding error probability is used. This is taken as a probability of error per task for operators with average levels of training and experience and motivation.

Table 22: Selected Generic Human Error Rates [10]

ERROR TYPE	TYPE OF BEHAVIOUR	HUMAN ERROR PROBABILITY
1	Extraordinary errors: of the type difficult to conceive how they could occur: stress free, powerful cues initiating for success	10^{-5}
2	Error in regularly performed, commonplace simple tasks with minimum stress	10^{-4}
3	Errors of commission such as operating wrong button or reading wrong display. More complex task, less time available, some cues necessary	10^{-3}
4	Errors of omission where dependence is placed on situation cues and memory. Complex, unfamiliar task with little feedback and some distractions.	10^{-2}
5	Highly complex task, considerable stress, little time to perform it	10^{-1}
6	Process involving creative thinking, unfamiliar complex operation where time is short, stress is high	10^{-1} to 1

Treating the entire door closure process as a single operation, the pre-1987 procedures could be equated to Type 2 with an error probability of 10^{-4}, while the more modern procedures could be equated to Type 1 with an error probability of 10^{-5}. Alternatively, the closure and checking could be treated as separate operations, producing lower probabilities.

12.3.4 Event Tree – Severity of Consequences

Figures 24 contain the event tree for flooding incidents for all incidents other than collision, grounding or impact developed as part of the Joint North West European Project for conventional passenger Ro-Ro vessels [6]. The branch probabilities of this event tree have been derived from statistical data and expert judgement.

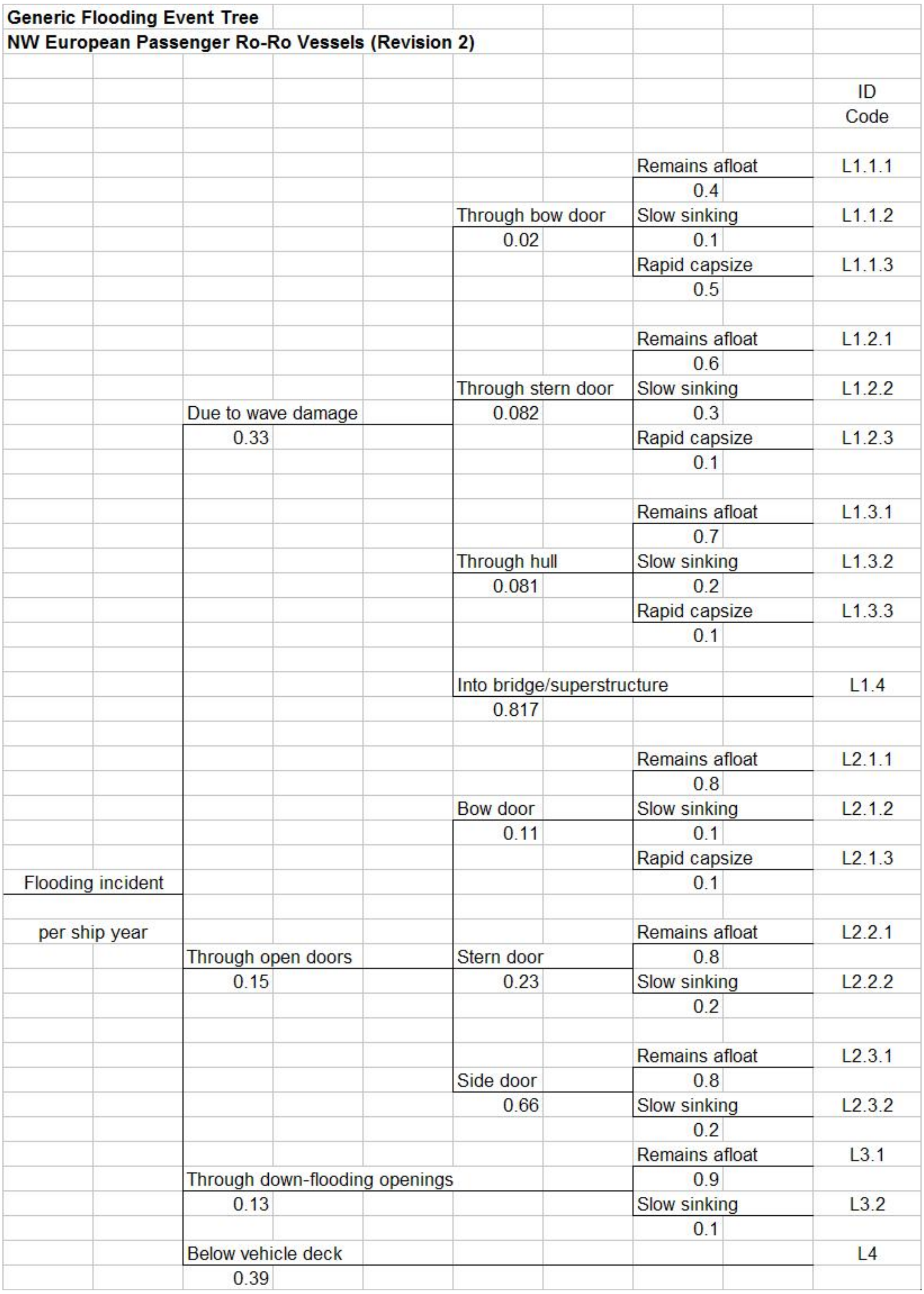

Figure 24: Event Tree for Other Flooding Incidents [6]

In the absence of other data, the event tree of Figure 24 is proposed for use. In the case of absence of any design feature contained in the event tree, it is proposed that the branch probabilities are averaged over the remaining branches (for example, in the case the design configuration does not include side doors, the branch probabilities for flooding through bow and stern doors is proposed to be considered with a ratio 1:2 for all possible flooding incidents through open doors).

With reference to severity of consequences the severity index contained in Table 21 is also proposed for use.

13. COST MODEL FOR THE CONTAINMENT OF DAMAGE

13.1 Elements of the Cost Model

Estimates to demonstrate whether a risk reduction measure is reasonably practicable, are usually given with reference to Gross Cost of Averting Fatality (Gross CAF) and Net Cost of Averting Fatality (Net CAF). Their definitions are:

$$Gross\ \ CAF = \frac{\Delta C}{\Delta R} \text{ and } Net\ \ CAF = \frac{\Delta C - \Delta B}{\Delta R}$$

where:

ΔC	is the cost per ship of the risk control option
ΔB	is the economic benefit per ship resulting from the implementation of the risk control option (this may also include pollution prevented)
ΔR	is the risk reduction per ship, in terms of the number of fatalities averted, implied by the risk control option

Costs of risk control options such as training, maintenance, repair, could be sought and the effects on commercial performance of these options quantified.

Benefits of risk control option such as:

- Safety (life, health, injury) improvement,
- Environmental protection
- Commercial benefit

can be calculated using risk free rate of return to discount to present values.

One way to present the results can be as "Risk Profiles" i.e. in the form of "F-N" like diagrams and integrated results could be generated in the following schematic form [7]:

Risk control option I: Costs		
Consequence mode	**Without risk control options**	**Using control option I**
Total loss of the ship	Present value €	
Repair of structural damage	Expected value €	Monetary units €
Environmental pollution	Expected value €	
Loss of human life	Expected value (number)	(Number)
Loss of reputation	Expected value €	
Additional building cost		

Loss of cargo	Expected value €	
Loss of revenue	Expected value €	
Total	€	

In this respect, when quantifying the effectiveness of risk control options relevant to containment of flooding following damage, trade-offs between design characteristics (for example, the available carrying capacity and the weight of the structure) ought to be performed in order to calculate the marginal costs of the corresponding risk control options. Models for structural weight and building cost, will be presented in the following.

13.2 Structural Weight and Building Cost

As briefly discussed in the foregoing, is it more appropriate to have an indicator of the difference on the structural weight among the various subdivision alternatives considered. A formulation for the weight of decks and bulkheads is appropriate for this scope is as follows:

$$\Delta WEIGHT_{decks} = \rho_{material} \cdot e_{decks} \cdot \left(\sum_{decks} S - \sum_{decks} S_{ini} \right)$$

$$\Delta WEIGHT_{bulkheads} = \rho_{material} \cdot e_{bulkheads} \cdot \left(\sum_{bulkheads} S - \sum_{bulkheads} S_{ini} \right)$$

$$\Delta WEIGHT = \Delta WEIGHT_{decks} + \Delta WEIGHT_{bulkheads}$$

The formulation should also account for the stiffeners of the decks and bulkheads, which can be considered as 30% of the plating weight.

Material and labour costs for additional material weight can be calculated from formulae available in the literature, which are producing reasonable results in general, or based on the experience of members of the project consortium.

13.3 Required Freight Rate Model

A model appropriate for the calculation of the Required Freight Rate has been developed. An initial estimate of the design development and building cost is required for the techno-economic calculations. Having defined this, the variation of the steel weight cost related to exploration of alternatives configurations can be considered in the following manner:

[Initial Cost] = [Design Development and Building Cost] ± [Δ(Material Weight Cost)]

Full details of the Required Freight Rate model can be found in Deliverable D420. Appendix I contains the implementation of this model in a Excel spreadsheet.

14. CONCLUSIONS

Elements of a probabilistic risk/cost model for consequence analysis of large-scale flooding have been presented in this report. This risk/cost model forms an integral part of a risk-based design methodology, targeting holistic design solutions, by setting global design goals, through the integration of safety-related considerations in the design process.

As primary initiating events (hazards) for incidents with potential to lead to large scale flooding the following have been considered: collision; grounding; impact; structural failure of bow or stern door; mechanical failure of watertight barriers; and operational safety management systems failure / human error. Specifics of the work carried out include the following:

1) A full survivability assessment of the project's basis ship and variants has been carried out, with the view to provide risk data for the assessment of collision, grounding and impact incidents. It should be noted that the basis ship has very high stability characteristics, which combined with the lack of data on distributions of extent of damages for high speed craft, renders the derivation of probabilities of capsize difficult, which in any case would be very low.
2) In the case of failure of bow or stern doors a fault tree has been proposed. This fault tree is populated with data deriving from experience of operation of passenger Ro-Ro vessels, due to lack of data from operation of high-speed craft and the proximity in the patterns of operation.
3) Failure of watertight barriers and human errors have been treated as factors contributing to the severity of the potential incidents above, using data from operation of passenger Ro-Ro vessels and human reliability analysis, respectively.
4) For the assessment and evaluation of the severity of the consequences the severity scale contained in the IMO's Formal Safety Assessment guidelines is proposed.
5) Finally, with reference to the cost element of the model, for the quantification of the effectiveness of risk control options relevant to containment of flooding following damage, trade-offs between design characteristics (for example, the available carrying capacity and the weight of the structure) have to be performed in order to calculate the marginal costs of the corresponding risk control options. Techno-economic cost models for this reason have been proposed.

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