



Evaluation of FISPAT Fire Spread Analysis Tool

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Abstract

In 2002 an amendment was added to the International Convention for the Safety of Life at Sea (SOLAS)[1] which opened up for shipbuilders to replace steel with lightweight materials in the superstructures. However, SOLAS requires equal fire safety capability compared to ships with steel superstructures.

LASS-c is a cross-organizational project with the aim to find a method to build cruise ships with part of the superstructure made in lightweight materials. The purpose of this LASS-c sub-project has been to develop a software tool in Java (FISPAT) that helps identifying fire sensitive areas in cruise vessels structures.

In FISPAT the user can make a model of the vessel structure containing rooms, networks and devices. FISPAT then performs exhaustive simulation of fire spread and fault injections in the model and presents it to the user. The user then analyzes the results to find fire and fault sensitive parts. By introducing additional networks and devices or altering the ones already existing, iterative simulations lead to a better cruise vessel design.

FISPAT could be extended in different ways. Providing use of existing CAD models would speed up the analyses of different cruise vessels. As of now, the user need to manually translate the drawings into FISPAT format which takes time. Other extensions could be to allow for more complex room structures than cuboids. With a few tweaks FISPAT could be used for analyses in other related areas such as buildings but also in analyses of other types of harm than fire, e.g. virus spread in computer networks. The same simulation engine could be used for these types while some extensions could be needed for e.g. graphical representation.

Keywords: Fire spread, analysis, exhaustive, simulations, fault injection, network, sectioning device.

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Preface

This paper is a part of the LASS project (see <http://www.lass.nu/>) which is partly financed by Vinnova, the Swedish Governmental Agency for Innovation Systems. The LASS project focuses on how to build ship structures with lightweight materials and what changes need to be implemented in order for these ships to obtain the same safety as steel constructions. This report is part of the LASS-c sub-project which focuses on lightweight materials in cruise vessels.

The purpose of this work is to explain how simulations can be undertaken to show that composite material can be used instead of steel for the upper decks in cruise vessels. For more information on how to use FISPAT see [2].

The report has the following chapters:

- 1 – Introduction: Background and motivation.
- 2 – Terminology: Abbreviations used in the report.
- 3 – Scope: What's in the report and what's not.
- 4 – FISPAT model: The model used to represent the cruise vessel and perform simulations.
- 5 – Simulation: Principles and parameters for simulations.
- 6 – Exhaustive Simulation Example: FISPAT used on a small example vessel.
- 7 – Generalization: What other areas FISPAT can be used for.
- 8 – Conclusions: Wrap-up of the report.
- 9 – References: Sources used.

1 Introduction

This work relates to the construction of cruise vessel superstructures using composite material instead of steel. An amendment to SOLAS section 17 [1] in 2002 specifies that alternative materials than steel can be used if considered equivalent with respect to fire safety. The ship becomes lighter or, alternatively, additional cargo and/or passengers can be included. For a lighter ship the centre of gravity is lowered thus increasing stability. The drawback is that composite material can burn and this has to be compensated by dependable firefighting equipment.

A comparison between composite material and steel can be summarized as:

- composite material has lower density
- composite material can burn
- composite material has less mechanical strength
- composite material contains glue that becomes weak at temperatures above 100° C resulting in permanent loss of mechanical strength
- composite material is an insulator, steel is conductor

The composite material is to be used for the upper decks of cruise vessels because the stability will not be reduced as much as if the lower decks were to be built in composite materials. To prove that the safety on board will not be reduced by the introduction of composite materials a computer program has been developed and is explained in this report. The program is called FISPAT which is an acronym for Fire Spread Analysis Tool. The structure of the cruise vessel is introduced into the program where simulations of fire spread is made and the result analyzed by the user. These simulations can help increase the safety of new composite constructions.

Both fire spread and fault injections can be analyzed in the application where a given initial state is simulated and the resulting state is presented to the user. Everything in between is hidden from the user who only needs to analyze the final state once simulations are done.

The approach of this work is to start off with a vessel design including fire fighting systems and perform simulations on it. Once simulations are done and analyzed, features can be added to the vessel model and new simulations can be done. In this way the best design of the fire fighting system can be found through iterative simulations and analyses. Fire fighting systems will normally be computer controlled but also manual fire fighting has to be included if available. In the former case technical aspects are in focus such as computer networks, redundant equipment etc while in the latter case human aspects are important e.g. if the crew speaks the same language, has gotten enough training etc. For both cases it is crucial to specify the structure of cabins and other spaces that are considered in the superstructure. For example, it is more dangerous if the fire starts in a room where the computer is placed that controls fire fighting. The structure of cabins and other spaces is also necessary for analyzing how the fire could spread.

The upper decks of the vessel are candidates for composite material and thus are the foci of this work.

In this report system evaluation is made from a logical point of view i.e.

- Physical measures are not included.
- Timing, temperature and material strength issues are not considered.
- Hardware and software design, development and implementation aspects are not included.

As a consequence this evaluation should be seen as handling a worst case scope which has to be complemented with probability and consequence analyses for getting realistic cases.

Included aspects in this report are e.g.

- How different cabins and other rooms are related to each other.
- How networks, e.g. water supply pipes, are related to other networks, cabins and other spaces.
- How faults affect the system.
- Redundancy and how it affects resulting state of simulation.

In case of not known or if too complex handling is needed a conservative (i.e. pessimistic) approach is taken.

The results of this work are

- the applicability of the chosen methodology.
- the specification and results of the chosen methodology.
- suggestions for improvements.

2 Terminology

Apparatus	Sub-group of Device. An apparatus maps dependencies between two or more networks of different kinds and is one of Pump, Electric Control Unit or Other. If a network depends on an apparatus and the apparatus gets non-functioning, so will the network (if there are no redundant apparatus of the same kind).
Control options	Options chosen by the user in each simulation that defines how fire and faults are spread. There are three control options (each explained in this Terminology): <i>Spread fire if no sprinkler</i> , <i>Water network non-functioning by fire</i> and <i>Ventilation spreads fire</i> .
Dependence	Defines how the functionality of networks and devices are affected by each other. Can be one-way (e.g. a water network depending on the electric network via a pump) or two-way (e.g. a computer depending on an electric network but also controls this).
Device	Maps dependence between two or more networks and need to depend on networks to function. For example a water pump that depends on an electrical network or a control device that controls a network while it depends on an electrical network. Device have two sub-groups; sectioning device and apparatus.
Exhaustive Simulation	All possible initial states of the Vessel Model are simulated without the need for the user to change setup manually. Before the exhaustive simulation is started the user sets the initial parameters: <ul style="list-style-type: none"> • How many rooms that are initially on fire • How many networks that are initially non-functioning • How many devices that are initially non-functioning

FISPAT then simulates all possible initial states that fulfill the requirements above.

FISPAT	Fire Spread Analysis Tool
GUI	Graphical User Interface
LASS	Lightweight Construction Applications at Sea
LASS-c	Sub-project to LASS focusing on cruise vessels
Prescriptive	According to SOLAS (normative)
Redundancy	Dependence on more than one single resource. Networks can depend on redundant devices in which case one of the redundant devices can be non-functioning without affecting the functionality of the network. Devices can also depend on redundant networks in which case one of the redundant networks can be non-functioning without affecting the functionality of the device.
Risk	A function (in many cases can be thought of a product) of probability of occurrence and severity. Occurrence could be further specified by considering the possibility of detection and possibility of avoidance and control.
Sectioning device	Sub-group of Device that is used to prevent faults to spread between networks of the same kind. As long as the sectioning device is functioning a fault in one network will not spread to the other. If the sectioning device is non-functioning the fault will spread.
Sink	Where a network dumps content not needed.
SOLAS	International Convention for the Safety of Life at Sea.
SP	Technical Research Institute of Sweden
Spread fire if no sprinkler	Control option that can either be true or false. If true, fire is spread between rooms that lack functioning water network. Both rooms need to lack functioning water network for the fire to be spread. If false, fire is only spread between sub-rooms and fire spreading neighbors defined by the user.
Tank	Feeds network with necessary resources.
Ventilation spreads fire	Control option that can either be true or false. If true, fire is spread through ventilation and all rooms where the ventilation network is present will be set on fire. If false, fire will not be spread by ventilation.
Water network non-functioning by fire	Control option that can either be true or false. If true, water networks turns non-functioning if present in a burning room. If false, their functionality are not affected by fire.

3 Scope

3.1 Task

This project focuses on how to model a cruise vessel in order to simulate fire spread and fault injections. The model should be general so it can be used for other types of ships and buildings too. Once the model is specified a small example is used to show how simulations are done and that it can be scaled to larger models.

The work described in this report can be summarized as to

- transform vessel drawings to FISPAT Vessel Model.
- introduce fire and faults and model their propagation.
- identify unwanted events.
- apply analysis methods for identifying under what circumstances unwanted events can appear.
- show how safety measures for reducing dangerous consequences can be found and introduced into the model.
- evaluate the work and discuss its generality and point out interfaces to other assessment work.

3.2 General prerequisites

A number of prerequisites have to be defined:

- The ship is considered in isolation e.g. a fire is not started due to external reasons and a possible spread of fire external to the ship is not included.
- There are no special environmental factors to consider e.g. effects from temperature, wind, waves are not included.
- The ship is fully functioning and maintained as far as can be judged.
- Timing aspects are only included to a limited amount; use of “before”, “after”, “at the same time”, “in parallel” but not timing aspects expressed in seconds.

The following aspects are outside scope:

- Probabilities for events and sequences of events.
- How fire spread is made within a room/space.
- Evaluation of damage afterwards, e.g. persons killed.
- The consequences from fire (apart from those affecting fire fighting capability).
- External help.
- Officers and crew behavior and the decision processes.
- The reason for a fire and its probability. Generally, a fire could be caused e.g. by technical reasons, human mistakes, environmental conditions (e.g. lightning) or sabotage.
- The internal properties of rooms and spaces such as the amount of combustible material and its burning properties.

The detailed identification of candidates for composite material is made outside and independent of this work.

4 FISPAT model

FISPAT uses a model representation of a vessel (Vessel Model) to perform simulations of the fire spread. The Vessel Model contains rooms, networks and devices. Firewalls are also part of the Vessel Model but have no relevance to the fire spread, they are merely a graphical component to simplify the interpretation after simulations are done. By changing simulation setups for the defined rooms, networks and devices, it is possible to find the most critical combinations that cause severe damage of the vessel. The initial state of a simulation is defined by the user in the simulation setup in the GUI. The Vessel Model is discussed in section 4.1 and the fire and smoke spreading models are discussed in section 4.2 and 4.3.

4.1 Vessel Model

The FISPAT tool uses a model of the vessel called the Vessel Model to perform simulations. This Vessel Model is made up by three different parts; rooms, networks and devices.

4.1.1 Rooms

All rooms are modeled as cubicles and each cubicle belongs to a deck. The corners of a cubicle are represented by positive integers in a three dimensional space (x, y, z). The walls, ceiling and floor of a room need to be parallel to one axis of the coordinate system. This means that two adjacent corners only will have one coordinate that differs. The lowest z -coordinate indicates on which deck the room is present; hence this coordinate differs by one between two adjacent decks. The floor of one deck is the ceiling of the deck below and vice versa and a room can only be located on one deck. If a room stretches over several floors the room needs to be divided into several sub-rooms where each sub-room is located on one floor only. The x and y coordinates are also integers and their corresponding units can be chosen freely (but the same for all rooms).

Any other room shape than cubical is constructed by linking several cubicles (sub-rooms) together. This allows for a room to have a more complex structure. A room, or sub-room, cannot comprise another room, i.e. rooms cannot overlap another.

Neighboring rooms are identified by FISPAT. For two rooms to be neighbors they need to be either on the same deck or on adjacent decks. If on the same deck, one wall of each room needs to overlap one wall of the other (see Figure 1, object 1 and 2). If two rooms only have corners in common they are not considered neighbors (see Figure 1, object 1 and 3). If the rooms are located on adjacent decks, one room needs to have a corner within the other room as seen from above to be a neighbor (see Figure 1, object 1 and 4). It is not enough for the rooms to just have edges in common (see Figure 1, object 1 and 5).

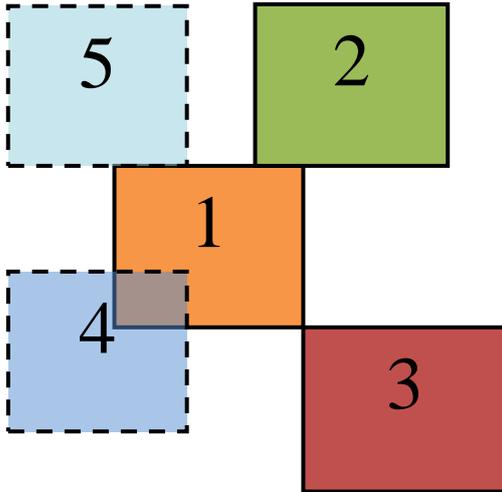


Figure 1: 1, 2 and 3 are on the same deck while 4 and 5 are on an adjacent deck. 1 is neighbor to 2 and 4. 1 is not a neighbor to 3 and 5 since they have no overlapping surfaces.

Each room has a unique ID which can be a string or a number, however all linked rooms have the same main ID and are separated by “-“ in the form “room ID-subroom ID”. These sub-rooms will automatically have the same fire and smoke status unless the user specifically sets them to be non-spreading neighbors. This is applicable when there are fire doors between rooms.

A room can be of the type corridor which is defined in the text file when setting up the room structure. The corridor type is just a graphical distinguishing to make it easier to visualize the Vessel Model for the FISPAT user.

The status of a room is one of

- Fire (indicating that smoke is also present)
- Smoke
- No fire and no smoke

The valid transitions between states are shown in Figure 2. Note that once fire or smoke is present there is no transition back to no fire and no smoke.

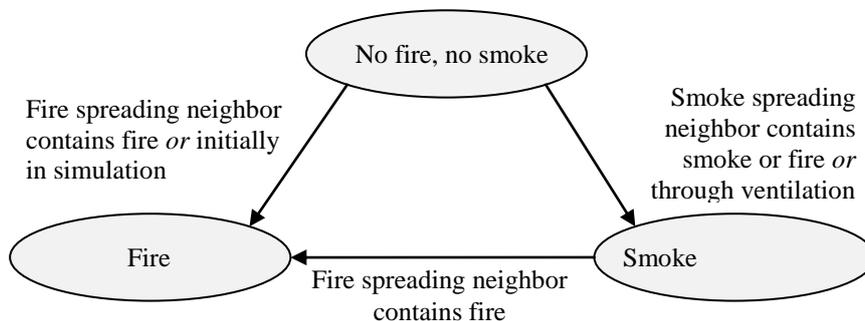


Figure 2. The status of a room can be one of *No fire, no smoke*, *Smoke* and *Fire*. The transitions between states are shown.

Apart from this the neighbors whom the room spreads fire to and whom it spreads smoke to can be defined in each simulation setup. The spreading neighbors are chosen by the user from the list of identified neighbors in the GUI. Note that fire can be spread between

rooms that are not explicitly set to be fire spreading neighbors if none of them have a functioning water network present and the control option *Fire is spread if no sprinkler* is chosen.

To summarize, a room is defined by its

- ID
- Corners
- Type
 - Room
 - Corridor
- Fire spreading neighbors
- Smoke spreading neighbors
- Status
 - No fire, no smoke
 - Smoke
 - Fire

4.1.2 Networks

There are six types of networks represented in FISPAT:

- electric power
- water
- ventilation
- hydraulic
- pneumatic
- control (computerized or not)

All networks are defined by their type and their 3-d paths and are physically present in a set of rooms. The path of a network can only change in one direction at a time, meaning that the path is either in the x-, y- or z-direction. The placement of a network, *with respect to rooms*, is the same as in reality; however, the actual placement of networks within rooms does not need to be the same as in reality.

All networks can depend on apparatuses (see section 4.1.3) to function or considered to be independent. The dependencies are specified in the apparatus except how many redundant apparatus the network needs to function which is specified in the network. If fewer than the defined redundant apparatus are functioning the network will also be non-functioning in the simulation. A network can be set to depend on two apparatus and have three redundant apparatus as input. In this case one of the apparatuses can become non-functioning and the network will still function. If more than one apparatus is non-functioning the network will however also be non-functioning. If a network depends on two different kinds of apparatus at least one of each type need to function for the network to function. See Figure 3 for a graphical example.

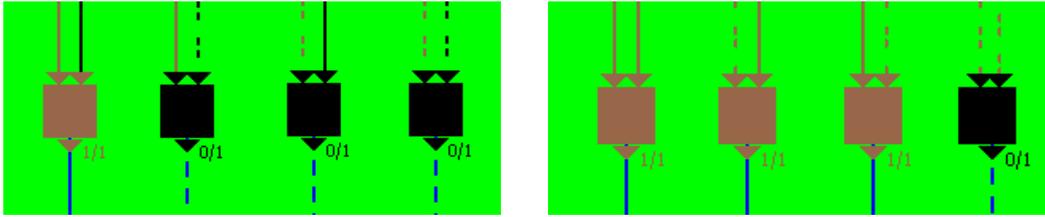


Figure 3. The brown boxes are functioning apparatus and the black boxes are non-functioning apparatus. The lines are functioning networks and the dotted lines are non-functioning networks. *Left:* Apparatus depends on different kinds of networks (arrows towards apparatus). Once one network is non-functioning so is the apparatus. *Right:* Apparatus depends on same kind of network and both networks need to be non-functioning for the apparatus to become non-functioning.

The status of a network is either functioning or non-functioning. A non-functioning network can never, during the simulation, be set as functioning again. There are three ways for a functioning network to become non-functioning:

- One of the rooms in which the network is present is set on fire (for water networks the control option *Water networks non-functioning by fire* needs to be chosen).
- Fewer than the required apparatuses on which it depends are functioning.
- The user sets the network to be non-functioning initially in a simulation.

Note that even though the network is present in a burning room it can be set functioning by the user at setup. This might be useful when testing the outcome of another type of network and/or material.

A ventilation network is set to have both an inlet and an outlet in all rooms it goes through as a consequence of the worst case scenario that is used throughout the simulation. In this way, all rooms where the ventilation network is present will be burning and/or contain smoke when the ventilation does. Individual rooms can however be excluded from spreading fire and smoke if specified by the user. The direction of air flow in a ventilation network is ignored i.e. the worst case scenario is used where fire and smoke is spread in both directions. Once fire or smoke is present in a room with a ventilation network, fire or smoke will spread (depending on Control Options) to all rooms where the ventilation network is present (unless a room is explicitly chosen not to spread).

Sinks and tanks are not part of the Vessel Model. If a water network relies on a water tank to function, the tank is omitted in the Vessel Model.

4.1.3 Devices

Devices are split up in two main categories: Apparatus and Sectioning devices. The status of a device is either functioning or non-functioning. A non-functioning device can never, during the simulation, be set as functioning again. If the device depends on several networks of the same kind, these are interpreted as being redundant and the device will function as long as one of the input networks of each type is functioning.

If a device depends on different kinds of networks, these network types are all interpreted as being needed for the functionality of the device. As long as one of the networks of each type is functioning, so is the device. This is to model redundant input networks. Any type of device can be set to depend or affect any type of network; there is no in-program check for the dependencies with respect to type of device and type of network.

There are three ways for a device to be non-functioning:

- The room in which the device is present is set on fire.
- One of the networks on which it depends is set non-functioning. This is not enough if there are redundant networks of the same type, in which case all of the redundant networks of one type need to be non-functioning.
- The user sets the device to be non-functioning initially in a simulation.

Devices are built graphically in FISPAT or can be specified by the user in a text-file. The networks on which the device depends or affects need to be built before the device can be built. This is because a device needs to depend and affect at least one network.

The positions of devices and networks in a room are not significant for the results of simulations in FISPAT. However in the Graphical Representation of the Vessel Model the user is forced to put networks that affect or depend on a device in contact¹ with the device. If a device has contact with all networks that it affects or depends on, it is properly connected. If not, it will get an error marking (yellow) in the GUI.

Devices are used to model dependencies between networks and can hence both affect and depend on networks. A device can depend on or affect the following types of networks (note that there is no in-program check for this):

Network	Device can depend on network	Device can affect network
Electricity	Yes	Yes
Water	No	Yes
Ventilation	No	Yes, but only via Sectioning device
Hydraulic	Yes	Yes
Pneumatic	Yes	Yes
Control	Yes	Yes

As mentioned above, there are two categories of devices; Apparatus and Sectioning devices.

Apparatus:

The type of the apparatus is defined by the user and can be one of:

- Pump
- Electric Control Unit
- Other

An apparatus is used to model a dependency between different networks. E.g. a water network can be dependent on an electrical network via an electric pump.

Sectioning devices:

Sectioning devices are used for making it possible to isolate two or more networks from each other. A functioning sectioning device prevents a fault in one network to spread to the other network. An example of a sectioning device is a valve on a water network which can prevent a wide spread loss of water pressure in case of a leak. The networks handled by the sectioning device must be of the same type.

¹ Contact is defined as $D_{\text{Chebyshev}}(D, N_e) \leq L$ which is the area that's covered by the device symbol in the graphical representation.

$$L = \sqrt{\text{Average area of a room on the deck with highest amount of rooms}} / 14$$

D = Device position.

N_e = Closest network endpoint

A sectioning device used in ventilation networks works in a slightly different way. A functioning sectioning device between two ventilation networks will prevent smoke (and fire if the user has set ventilation networks to spread fire using the control options) from spreading past the sectioning device including to the room where the sectioning device is present.

A sectioning device can itself be dependent on one or more input networks as in the case of a remotely controlled, electrical valve which is dependent on electricity and control networks. If electricity or control network connected to the sectioning device is faulty the sectioning device becomes faulty i.e. it cannot function as a sectioning device anymore; it becomes transparent. The effect of this will only be visible when one of the connected networks becomes non-functioning. In that case the other will be set as non-functioning as well. If the sectioning device depends on one of the networks that it sections, the other of the sectioned networks will depend on the first. Once the network that the sectioning device depends on is set non-functioning the other network will also be non-functioning.

4.1.4 Redundancy

Redundant networks and apparatus can be modeled in FISPAT. To model redundant networks, two or more networks need to be created. If a network has redundant inputs that it depends on, e.g. a water network that has two pumps, these pumps are created as two separate pumps that both affect the water network. Dependencies where a network needs more than one apparatus to function can also be modeled. In this case the network might need two functioning pumps to function and once there is less than two the network will also become non-functioning. There is no upper limit on how many redundant apparatus a network can depend on.

If a device depends on several networks of the same type, these networks are all redundant inputs to the device. As long as one of the redundant networks is functioning, so is the device. However, if all the redundant inputs are non-functioning, the device will be non-functioning. There is no upper limit on how many redundant networks a device can depend on.

4.2 Fire Spread Modeling

In general a conservative approach is taken in the simulations. A worst-case scenario is implemented where the following modeling aspects apply for rooms:

- A fire could start as a single fire centre or as multiple fire centers.
- A fire can exist simultaneously as faults.
- A fire does not affect mechanical strength of walls, floor and ceiling.
- A fire does not result in an explosion.
- Fire spread can occur horizontally, vertically (e.g. a fire in the funnel) or both at the same time.
- Fire can spread between rooms:
 - via Ventilation network.
 - if neighboring rooms lack functioning water networks.
 - if they are specified as fire-spreading neighbors.
 - via open doors (modeled as fire spreading neighbors).
- Once fire is present in a room, it will not be put out during the simulation.
- When fire is present, so is smoke. There cannot be fire without smoke; however smoke can be present in a room without fire.
- There can be multiple fire origins.

- Fire door is modeled by setting the rooms on both sides to be fire spreading neighbors (an open fire door) or by setting the rooms not to be fire spreading neighbors (a closed fire door).
- A conservative approach is used; if a room is burning the result is that all networks and devices present in that room will be non-functioning. However, water networks can be set as fire resistant by the user (the network will not be set as non-functioning because it is present in a room containing fire). The setting will apply to all water networks in the model, they cannot be individually set as fire resistant.
- A contained fire can be modeled by setting the room to not be able to spread fire to its neighbors.
- To analyze parts of a room, these parts can be modeled as virtual sub-rooms by dividing one room into several. Note that one room cannot comprise another room, i.e. rooms cannot overlap.
- If a fire can spread outside rooms e.g. at the outside of a vessel it can be modeled by adding an extra room representing the exterior of the vessel.

Networks and devices

- A fire makes networks non-functioning. However water networks only get non-functioning if the control option *Water networks non-functioning by fire* is chosen.
- For water the only networks considered are those that are used for handling fire. For example, water networks for washing are not included.
- Fire and smoke are not spread via networks except ventilation.
- For ventilation networks, all rooms in which they are present are, by default, assumed to have both air inlet and outlet. This implies that once smoke is present in the ventilation network, all rooms will contain smoke (if not stopped by a functioning sectioning device). In the same way if ventilation networks are set to spread fire then once fire is present in a room with a ventilation network fire will spread to all rooms containing that network (if not stopped by a functioning sectioning device).
- Modeling of a room without air in-/outlet is done by excluding the room from the ventilation network. This only affects the selected room and allows the other rooms where the network is present to spread smoke/fire.
- For ventilation networks, the direction of air flow is ignored allowing fire and smoke to spread in both directions.
- A functioning sectioning device on a ventilation network will prevent smoke (and fire if the user has set ventilation networks to spread fire) from spreading past the sectioning device including to the room where the sectioning device is present.
- Manual control of devices is not modeled in FISPAT.
- For a network to exist it must be present in at least two rooms (a network completely located in a single room is not significant).

4.3 Smoke Spread Modeling

The following holds for the smoke spreading model:

- Smoke can spread between rooms:
 - Via ventilation networks.
 - Between neighboring rooms if they are
 - Fire spreading neighbors (spreads fire too) *or*
 - Smoke spreading neighbors (spreads only smoke)
- Smoke can spread horizontally, vertically or both at the same time.

- Smoke is not a fault i.e. there could be a technical fault or a human error as well when smoke is present.
- Smoke may come from different places even if there is only one fire centre e.g. from different ventilation channels. Thus there is a very weak mapping between smoke location and location of fire centre.
- Since smoke is a secondary effect (from fire) it cannot be eliminated on its own.
- Smoke and toxic gases are assumed not to affect equipment such as networks and devices.

4.4 Limitations

The following aspects are not considered in simulations:

- Notion of time, only a *start* and an *end* state are relevant.
- The pace of the fire spread.
- Internal content of a room, i.e. all rooms will instantly be considered fully on fire once in contact with fire in accordance with the worst-case scenario approach.
- Probabilities of events.
- Recovery. Once an event has occurred it cannot be reversed.
- Resources to feed networks such as water, air pressure etc.
- Human interaction.
- Number of casualties.

The networks and devices in a room can be set functioning by the user even though the room is on fire. This might be useful to examine what would happen if a certain network wasn't affected by fire.

4.5 Fault Injection

Apart from simulating fire spread, FISPAT can be used to perform fault injection in the Vessel Model. In that case no room is set on fire; instead fault injection is done by setting one or several networks and/or devices as non-functioning. When the initial state is simulated, the spread of the fault can be analyzed in the resulting state. By performing exhaustive simulations with this kind of fault injection one can determine which networks and/or devices that are most critical. Redundant networks and devices can then be added to the Vessel Model to see if the construction can be made more robust and tolerable to faults.

4.6 Interfaces to other investigations

Room size and interior composition are not considered in the simulations which calls for other investigations on how these parameters affect the fire spread. In FISPAT once fire is present in a room, the whole room is set on fire which is a simplification. For more knowledge on how the fire actually behaves, experiments may need to be undertaken. The simulations in FISPAT can serve as a starting point in choosing initial conditions for these experiment. The most critical rooms for fire spread can be found by simulations and experiments can then be performed on these.

Consequences and probabilities are not considered which opens up for separate analyses of number of people killed or injured in case of fire. This is not discussed in this report but FISPAT can be a good starting point for these analyses. By simulating different initial states and analyze which rooms will be on fire in the resulting state, the further consequences can be analyzed outside the program.

Spread speed (fire, smoke) is not considered and is also suitable for experiments. Once fire is present in the Vessel Model it will spread instantly to the rooms that meet the requirements for fire spreading. However in reality this can be analyzed in fire laboratories and more complex scenarios can be found and used for the overall consequence examination.

Performing iterative simulations in FISPAT with slightly different Vessel Models is a very efficient way to evaluate possible vessel drawings before a vessel is being built. Altering a network path to find the consequences of the overall fire spread is very easy. Once the worst outcome of an initial fire is found through simulations, means can be applied in order to reduce the consequences. Introducing redundant networks and devices can be efficient ways to reduce the effects of a fire.

5 Simulation

5.1 Principles

The simulations in FISPAT are deterministic and go on until the status of all rooms, networks and devices do not change. Once fire is present in a room, it destroys all devices and networks except water which depends on the Control Options. Fire is also spread to all fire spreading neighbors and, if the room has no functioning water network, to all adjacent rooms that lack functioning water network. Smoke is also spread to the smoke spreading neighbors. This process then goes on until no more rooms are set on fire and no more networks and devices are set as non-functioning.

The two kinds of simulations, exhaustive and non-exhaustive, are handled separately. The non-exhaustive simulations are not optimized; the non-exhaustive class is instead programmed to be informative to the user and saves text information that is displayed.

In the exhaustive simulations class, optimized code is vital. In FISPAT the optimization is done by:

- Reducing the number of simulations – By identifying initial setups that produce the same outcome the amount of simulations can be reduced. This is done by identifying rooms in the Vessel Model that will produce the same results if it is initially burning and reducing all but one of those initial setups from the simulations. This means that it is enough to set one room burning of fire spreading neighbors as well as for neighboring rooms that have non-functioning water network since these will spread fire between each other.
- Using localization – By reusing rather than cloning the objects used in the simulations the degree of localization is increased. This is done by the use of parameter sets that determines initial setup and applying it on the same Vessel Model throughout the exhaustive simulation instead of producing a new Vessel Model for each simulation. The initial parameters are then saved instead of the complete resulting Vessel Model.
- Use of parallel threads – FISPAT creates as many simulating threads as there are available processors. To prevent the different threads from simulating the same parameter setup a synchronized method is used to feed the different threads with unique setups.
- Store as little information as possible – Only the parameter setup and the resulting number of rooms burning, containing smoke and non-functioning networks/devices are stored to make storing as effective as possible. If the user wants to have a graphical look at the resulting Vessel Model, FISPAT simulates

the initial state again and presents it. This forces the processor to work each time a resulting state is to be shown but it decreases the stored data which is desirable when thousands of simulations are performed.

5.2 Simulation Setup Parameters

Whether a single simulation or exhaustive simulation is performed a number of parameters need to be set before the simulation is performed.

Non-Exhaustive Setup

For a non-exhaustive setup, the following parameters can be set:

Room Parameters (per room)

- Fire status
- Smoke status
- Fire spreading neighbors
- Smoke spreading neighbors

Network Parameters (per contained network)

- Functioning/Non-functioning

Device Parameters (per contained device)

- Functioning/Non-functioning

Control Options (global)

- If water networks are damaged by fire
- If ventilation networks spreads fire or only smoke
- If fire is spread between rooms that lack functioning water networks

Exhaustive Setup

To do exhaustive simulations a number of parameters can be specified in addition to those specified in a non-exhaustive simulation. The extra setup parameters that can be specified are:

- Number of rooms initially burning.
- Number of networks initially non-functioning.
- Number of devices initially non-functioning.

If the status of a Vessel Model constituent is manually set in the setup, this constituent will be the same for all simulations. When the initial parameters are chosen, FISPAT performs the required simulations whose results then can be analyzed to find the most critical setups.

The criteria for storing results are given by the user and all need to be met for a simulation to be saved. The criteria are:

- Number of rooms burning.
- Number of rooms containing smoke but no fire.
- Number of non-functioning networks.
- Number of non-functioning devices *or*
 - Number of non-functioning apparatus *and*
 - Number of non-functioning sectioning devices.

These criteria are set to limit the results that need to be analyzed. The user might only be interested in results where at least 10 rooms are burning and at least 4 networks are non-functioning. The *Number of rooms burning* criterion is then set to 10 and the *Number of non-functioning networks* criterion is set to 4. All simulations where these criteria are met or exceeded are saved.

The maximum number of outputs is also chosen to limit the amount of data that is stored. If the user wants a maximum of 1000 results the *Set maximum number of outputs* is set to 1000. Once this number is reached, the exhaustive simulation stops and a message *Output exceeded* is displayed. Now the user can look at the results from the 1000 simulations that were saved and sort them by the criterion that is most interesting. Then the save criterion and/or the *Set maximum number of outputs* can be increased until all simulations can be performed.

To save computation time a reduction of simulations is done before the exhaustive simulations. Initial setups that produce the same results are eliminated. Because of the strict deterministic nature of the simulations, these eliminated initial setups are easily reconstructed.

5.3 Analyzing Exhaustive Simulation Results

Once all simulations are done the user can examine the results. First the results can be sorted on parameters

- Simulation ID
- Number of rooms burning
- Number of rooms with smoke
- Non-functioning networks
- Non-functioning devices *or* non-functioning sectioning devices and apparatus

The user can now look at the initial and resulting state of a simulation and also open many windows from different simulations for results comparison. With this information it is possible to introduce new networks or devices into the Vessel Model and perform new exhaustive simulations to see the difference in outcome. The resulting states can also be saved for later use.

When performing exhaustive simulations, FISPAT omits the simulations that would produce the same results. This is done for two reasons; reduce total simulation time and reduce the number of results that need to be analyzed by the user.

When viewing the exhaustive simulation results the user is potentially viewing the results of several different initial setups. Because fire spread between initially fire spreading neighbors are commutative and deterministic it doesn't matter in which room, of the initially fire spreading neighbors, the fire started. Thus only one of these simulations are performed. The same holds for multiple initial fire origins in which case only one of the initially fire spreading neighbors is set on fire initially in each group of fire spreading rooms. It is important that the user realizes that even though only one specific room is initially set on fire the result could have been the same for other rooms being set on fire. A lot of simulations with the same outcome are reduced by this approach hence facilitating the simulation results analyses.

- 1 sectioning device (SD1) in R5

The control options used are

- Spread fire if no sprinkler – true
- Water network non-functioning by fire – false
- Ventilation spreads fire – false

6.1 Setups

Three test setups are shown in the example. In the first one room is set on fire, in the second one network is set non-functioning and in the third one device is set non-functioning.

6.1.1 Test 1 – One room initially on fire

One room initially on fire and all networks and devices functioning. This evaluation is made to show the complexity that is involved even with only one room initially on fire. Since fire is spread between two adjacent rooms if both lack functioning water networks (Control option *Spread fire if no sprinkler* set as true) the outcome of the simulation is interesting.

Expected Outcome

Room set on fire	Rooms burning	Rooms containing smoke	Non-Functioning Networks	Non-Functioning Devices
R1	R1	R2	h1	-
R2 or R3 or R7	R2, R3 & R7	R1	c1, e1, h1	cu1, other1
R4-1 or R4-2	All	-	All	All
R5	R5	-	c2	SD1
R6	All	-	All	All

Table 1. Expected outcome of test 1.

6.1.2 Test 2 – One Network Initially Non-Functioning

One network is set non-functioning initially in the exhaustive simulation. This evaluation is to show how network faults propagate through the Vessel Model and turns devices non-functioning.

Expected Outcome

No rooms are expected to be on fire or containing smoke in this simulation.

Network initially non-functioning	Non-Functioning Networks	Non-Functioning Devices
c1	c1, e1, h1	cu1, other1
c2	c2	SD1
e1	e1, h1	other1
e2	e2	-
e3	e3, w1, w2	Pump2, SD1
h1	h1	-
w1	w1, w2	SD1
w2	w2	-

Table 2. Expected outcome of test 2 where one network is set non-functioning initially.

6.1.3 Test 3 – One Device Initially Non-Functioning

One device is set non-functioning initially in the exhaustive simulation. This evaluation is to show how device faults propagate through the Vessel Model and that networks get non-functioning.

Expected Outcome

No rooms are expected to be on fire or containing smoke in this simulation.

Device initially non-functioning	Non-Functioning Networks	Non-Functioning Devices
pump1	w1, w2	pump1, SD1
pump2	w1, w2	Pump2, SD1
cu1	e1, h1	cu1, other1
other1	h1	other1
SD1	-	SD1

Table 3. Expected outcome of test 3 where one device is set non-functioning initially.

6.2 Results

6.2.1 Test 1 – One Room Initially On Fire

The outcome of test 1 is presented in Table 4. The outcome of R2 set on fire is presented in Figure 5.

Room set on fire	Rooms burning	Rooms containing smoke	Non-Functioning Networks	Non-Functioning Devices
R1	R1	R2	h1	-
R2	R2, R3 & R7	R1	c1, e1, h1	cu1, other1
R4-1	All	-	All	All
R5	R5	-	c2	SD1
R6	All	-	All	All

Table 4. The result from test 1 where one room was set on fire initially.

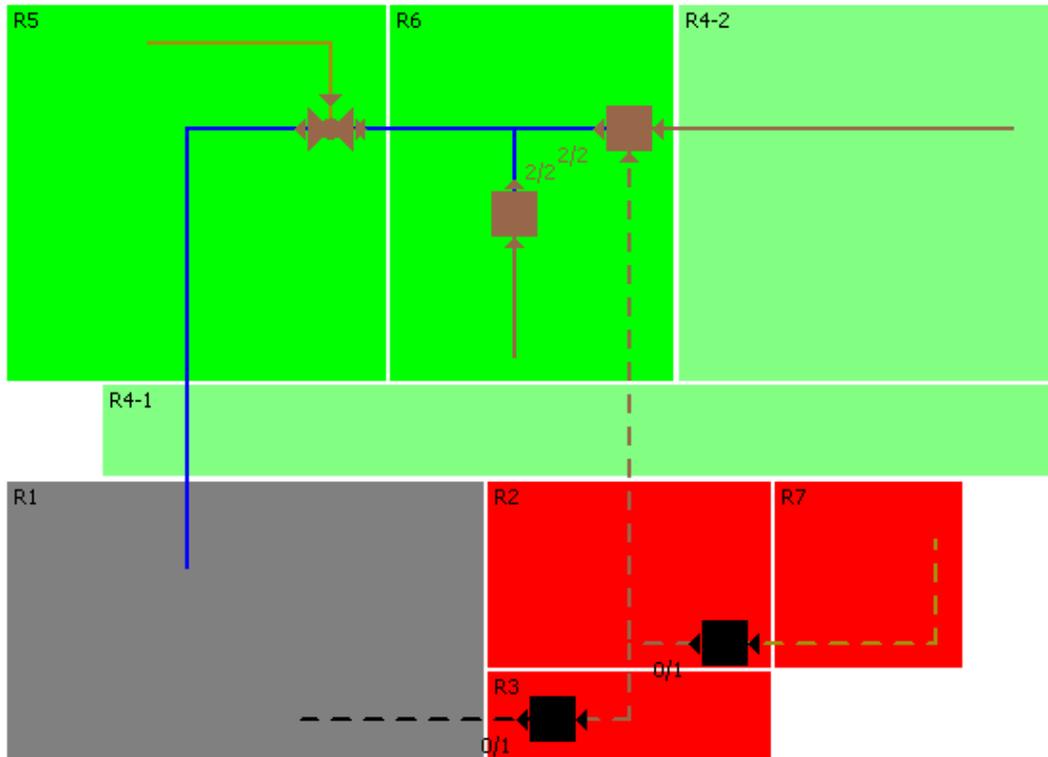


Figure 5. Initial fire in room R2 which is spread to R3 and R7 as a consequence of no functioning water network. Network c1, e1 and h1 are non-functioning as consequence of fire as well as devices CU1 and other1.

6.2.2 Test 2 – One Network Initially Non-Functioning

No rooms were on fire or contained smoke after the simulations.

Network initially non-functioning	Non-Functioning Networks	Non-Functioning Devices
c1	c1, e1, h1	cu1, other1
c2	c2	SD1
e1	e1, h1	other1
e2	e2	-
e3	e3, w1, w2	pump2, SD1
h1	h1	-
w1	w1, w2	SD1
w2	w2	-

Table 5. Results from test 2 where one network was set non-functioning initially.

6.2.3 Test 3 – One Device Initially Non-Functioning

No rooms were on fire or contained smoke after the simulations.

Device initially non-functioning	Non-Functioning Networks	Non-Functioning Devices
pump1	w1, w2	pump1, SD1
pump2	w1, w2	pump2, SD1
cu1	e1, h1	cu1, other1
other1	h1	other1
SD1	-	SD1

Table 6. Results from test 3 where one device was set non-functioning initially.

6.3 Performance

Evaluation has been made with the Vessel Model presented in section 6 which contains 8 rooms, 8 networks and 5 devices. The same control options are used. To test the performance of FISPAT exhaustive simulations have been made with all of

- 3 rooms initially burning
- 4 networks initially non-functioning
- 2 devices initially non-functioning

The number of simulations made, if no smartness would be built in to the program, would be

$$\binom{3}{8} \binom{4}{8} \binom{2}{5} = 39200$$

However FISPAT reduces the simulations that would have the same resulting state and hence only needs to set

- One of R4-1 and R4-2 (sub-rooms) initially burning
- One of R2, R3 and R7 (no functioning water network) initially burning

Instead of setting 3 of 8 rooms as initially burning only 3 of 5 rooms need to be set. This result in

$$\binom{3}{5} \binom{4}{8} \binom{2}{5} = 7000$$

simulations. This is a 82.1% reduction of simulations that need to be performed.

The 7000 simulations takes about 100-200 milliseconds to perform on a PC with Intel Core 2 Duo processors at 2.4 GHz and 2 GB of RAM. The time for each simulation depends on how much “fire spread“ that is taken place in the simulation i.e. how many rooms that have fire spreading neighbors and how many networks and devices that are set non-functioning and in turn affects dependent networks and devices. The more fire spread and fault propagation that occur the longer time a simulation requires.

6.4 Conclusions

The examples presented in section 6.1 along with the results in sections 6.2 and 6.3 show that FISPAT performs otherwise large and quite complex simulations in a fast and efficient manner. For a human being the simulations would take much longer time and the faults involved could lead to incorrect conclusions of the analyzed Vessel Model. This Vessel Model contains 8 rooms only but serves as an illustration of the benefits of FISPAT.

It is clear that a fire starting in R4 would lead to serious consequences which might not be obvious at a first glance. The consequences of an initial fire in R6 might be more easy to spot since the room contains both networks and devices. With FISPAT the results can easily be interpreted and the user can find that these initial states lead to the same consequence; all rooms are burning and all networks and devices are turned non-functioning.

When it comes to the fault injections it is also easy to identify the networks and devices where a fault is spread to other networks and devices. If for example e3 is non-functioning initially in a simulation the consequence at the end of the simulation is that two more networks along with two devices are turned non-functioning. The networks that causes the most other networks and devices to be non-functioning is easy to spot right from the result table.

The user need to be careful when setting up the Vessel Model and choosing the Control options but after that FISPAT simulates all scenarios and presents the results. Once the Vessel Model is set up this lets the user try many different scenarios efficiently and effectively.

7 Generalization

During the development of FISPAT some possible improvements have been discussed but not implemented. These are improvements to the functionality and user friendliness of the tool.

Improvements in FISPAT could be made regarding:

- Allow more complex room structures than cuboids would lead to less manual interpretation of the vessel drawing and more accurate fire and smoke spread.
- Allow translation of CAD drawings or similar directly to FISPAT would decrease the time it takes to set up a Vessel Model for the user.
- Allow the status of rooms, networks and devices to be excluded in exhaustive simulations, i.e. the room/network/device is never set as initially burning/non-functioning when making exhaustive simulations. This would be beneficial for users that are not interested in initial fire/faults in certain rooms, networks and devices but now will get these in the results anyway.
- Not counting sub-rooms as individual rooms would simplify the interpretation of the result table. As of now each sub-rooms is presented as a room in the result table.
- Insert more categories to sort exhaustive results, e.g. rooms containing functioning water networks would allow the user to identify the results it is interested in more easy.

Apart from these functionality aspects FISPAT could be modified in order to be used in other areas than cruise vessels. Such areas could be buildings or other contexts such as firewalls in computer networks. To allow these different areas the program could be generalized so that the FISPAT simulation engine is the body of the application and different plug-ins could be used for different usage areas.

When it comes to computer networks each connection between computers, or individual networks, could be modeled by a network in FISPAT. A network firewall would be modeled by a sectioning device that prevents a fault in one network to spread to the other and vice versa. After the initial network model is built exhaustive simulations can be run in the same way as in the current Vessel Model to find weak spots. Introducing redundant firewalls and/or networks would be one way to test the robustness of the system.

Another area where FISPAT could be used is oil refineries. Even though this might be open space, virtual rooms could be introduced in the model to allow fire to be spread between different pipelines. Safety mechanisms present to reduce fire spread could be modeled as water networks to prevent fire to be spread between certain pipelines and areas.

8 Conclusions

The FISPAT tool has proven to perform fast exhaustive simulations on fire and fault spread in cruise vessel models. Once simulations are performed, the results are analyzed by the user which in turn can use these to introduce new features in the Vessel Model and continue with new simulation setups. By doing this FISPAT is very efficient in trying lots of different models of a cruise vessel and how an introduction of a certain design feature affects the overall safety of it.

The user cannot influence the simulation outcome and hence FISPAT offers an objective test of cruise vessel design. However, it is important that the user sets up the Vessel Model with great care and take on a pessimistic approach when in doubt. The control options need also be chosen with care so the results will be valuable. The simulation result can be used as one input to show that vessels built with composite super structure can have the same safety as steel structures. According to SOLAS chapter 17 cruise vessels can be built with composite super structures as long as they are as safe as steel super structures. One part in this analysis can hence be shown with FISPAT.

The example described in section 6 illustrates how efficient and effective FISPAT is and that the results are easy to interpret as opposed to manual investigations. A total of 18 simulations were performed in this small Vessel Model. A real cruise ship might have a couple of thousand rooms along with tens or hundreds of networks and devices making it hard to get an overview manually. Once exhaustive simulations are started the user doesn't need to interact until simulations are done and can then sort the results as wanted. This makes simulations results very easy to interpret and the worst case easy to identify.

One of the benefits of the program implementation is the modularity of it. Care has been taken in splitting up functions in different classes and packages so it can be reused for other purposes. The simulation methods are separated from the Vessel Model and the GUI implying that the altering of FISPAT, to suit other needs and accommodate other structures and areas, should be fairly straightforward.

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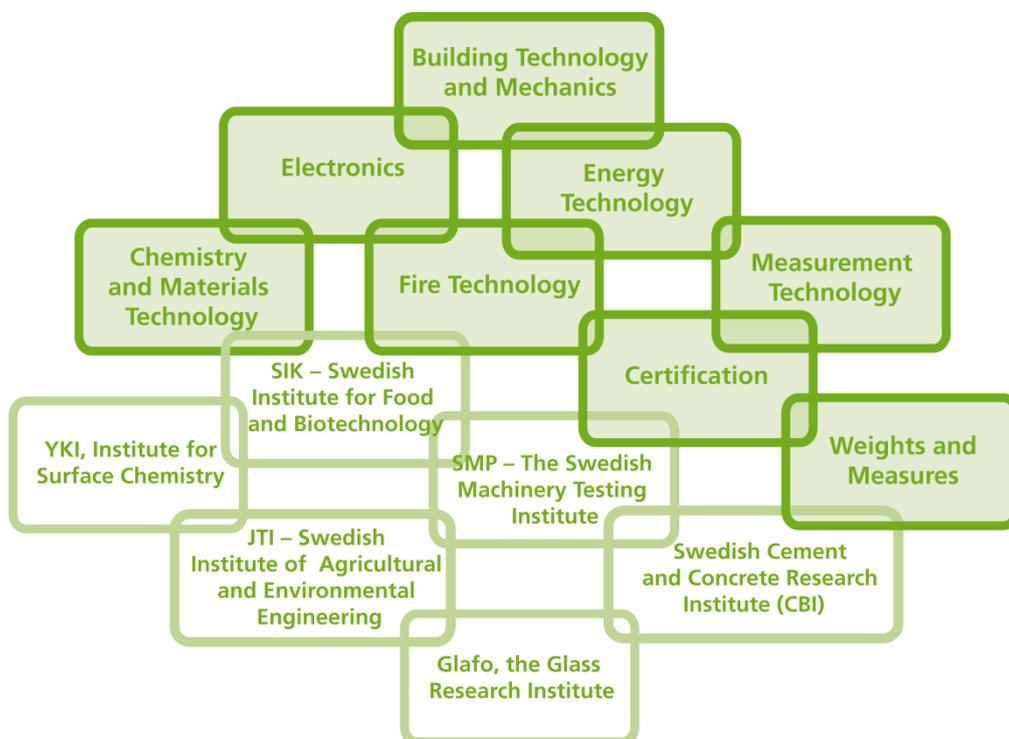
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