New Fire Strategies in the Wake of Umoe Ventus

Annex E – Failure Mode and Effect Analysis for fire safety as a system

DBI FIRE AND SECURITY

OSK-ShipTech A/S

Content

1 Introduction

1.1 Scope

In the IMO HSC Code, the Annex 4 Procedure for failure mode and effect analysis is required to be followed to assess the way systems can fail, analyse the effect of their failure, and identify whether sufficient redundancy is embedded to face these failures and maintain operation. The FMEAs are carried out for technical systems such as steering, propulsion, fuel delivery, or even firefighting installations such as water mist systems.

It is suggested herein to follow a holistic approach for fire safety, and consider all aspects of fire safety as parts of a system, with its inputs and outputs, its sub-systems and constituent elements, and its failure modes.
This analysis aims at using the instruments provided by IMO in the HSC Code for assessing the level of safety on board high-speed crafts built with composite materials. This is proposed as an alternative to carrying out an alternative design procedure following MSC.1/Circ. 1455 as may be suggested by IMO and DMA for high-speed crafts, following the publication of MSC.1/Circ. 1574. The approach is presented in general terms to be applicable generally to any ship following the HSC Code and built using composite materials (the method is also applicable to SOLAS ships). Subsequently, a more detailed analysis using these general terms will be carried out specifically for Umoe Ventus.

1.2 Specificities of considering fire safety as a system

Providing safety on board a ship in case of a fire event is not only done using technical systems. There is obviously the part involving a range of systems in the traditional sense (e.g. alarm, detectors, water mist, CO_2 etc.), but there are additional aspects of a human nature, for instance reacting upon hearing the fire alarm, or taking the decision to evacuate the ship. Some aspects involve both technical and social aspects, such as confirming the detection of a fire or manual firefighting. Because it encompasses these different aspects, fire safety is an untraditional system, but its constituent elements can fail nevertheless which means redundancy should be provided.
Fire safety is not only present in the operational life of the ship; it is also devised during the design phase, and represents an area of particular focus when a ship is built with composite materials. Therefore some of the aspects of the analysis refer to the design phase, and the redundancy proposed as a result concerns making a safer design.

Fire safety evolves with available technologies and knowledge growth, which means that regulatory provisions are not always in line with the reality of, for instance, construction materials. The analysis can also help highlighting knowledge gaps and areas of improvement for regulatory codes.

Due to these three different aspects (assessment of fire safety on board ships in general, operational phase, and design phase), the FMEA analysis proposed in this document is performed at different levels. A general analysis will address the knowledge and regulatory aspects, and lays down the foundation to work on specific projects. A case study is then proposed to present the effect of a targeted analysis.

1.3 Principles of FMEA

As stated in the HSC Code, Annex 4, "FMEA for high-speed craft is based on a single-failure concept under which each system at various levels of a system's functional hierarchy is assumed to fail by one probable cause at a time. The effects of the postulated failure are analysed and classified according to their severity. […] Any failure mode which may cause a catastrophic effect to the craft shall be guarded against by system or equipment redundancy unless the probability of failure is extremely improbable."

An FMEA proceeds following these steps:

- Definition of the system;
- Illustrate interrelationships of the sub-systems and their constitutive elements using block diagrams;
- Identify all failure modes and their causes;
- Evaluated the effects on the system of each failure mode;
- Identify methods of failure detection;
- Propose corrective actions for the failure modes;
- Assess the probability of failures causing hazardous or catastrophic effects.

This methodology will be closely followed in the proposed approach. The first two points are described in the following sections. FMEA worksheets will be used to document the last 5 points of the above list.

2 System definition

The present document proposes a definition of the system "fire safety" following the procedure of IMO HSC Code Annex 4 – 7 System definition.
It must be noted that the system "fire safety" as considered herein requires the presence of a fire on board, or the assumption that there is a fire on board if the method is used for fire drills. The focus is not on preventing a fire from occurring.

2.1 Description of the system "fire safety"

2.1.1 Operation of the system "fire safety"

What the system does: in case of a fire on board, the system provides safety to crew and passengers, fulfilling the fire safety objectives.
How the system does it: the system brings together sub-systems and their constituent elements covering human and technical aspects of managing a fire situation on board a ship.
System inputs: what triggers the use of the system: fire somewhere on board the ship.
System outputs: what happens if the system works properly: there are three possible outputs according to the level of efficiency of the action of the system:

- Fire is put out
- Fire is contained
- Evacuation of crew and passengers is successful

2.1.2 Structure of the system "fire safety"

Between the input "fire on board" and either one of the three outputs, three sub-systems are found. These sub-systems are **DETECTION**, **FIREFIGHTING**, and **EVACUATION**.
The sub-systems are made of constituent elements belonging to three different categories, namely technical, human, or socio-technical.
The various sub-systems and constituent elements can be found at several stages of the ship's life. This means that some corrective actions belong to the design phase, others to the operational phase. The analysis will hence ensure robustness of the design methodology as well as robustness of the technical solutions.

2.2 Functional relationship among system elements

The three sub-systems within the "fire safety" system are linked as illustrated in Figure 1. More details with the implementation of the constituent elements of the sub-systems will be provided in the block diagram.

The constituent elements of the three sub-systems are listed below. In **blue** are the technical elements, in **green** the human elements, and in **red** the elements combining technical and human aspects into a socio-technical element. In terms of failure, this means that the source could come from both a technical and a human aspect as both are involved in the workings of the element.

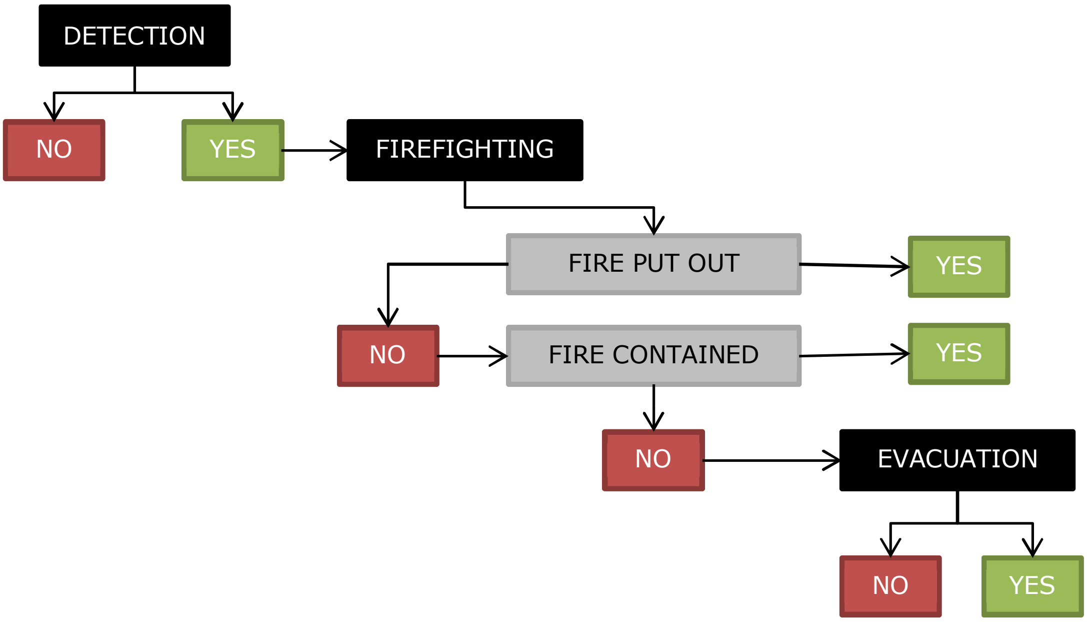

Fig.1 – Functional relationship among the 3 sub-systems within the "fire safety" system

DETECTION sub-system

- **Classification of spaces**
- **Choice of detector**
- **Detector placement**
- **Detectors** (as technical items)
- **Signal treatment**
- **Alarm system**
- **Human detection (visual, noise, smell)**
- **Layout of control panel**
- **Reaction on alarm**
- **Detection confirmation**

FIREFIGHTING sub-system

- **Classification of spaces**
- **Firefighting strategy**
- **Choice of active systems**
- **Decision to start manual firefighting**
- **Adapted PPE**
- **Manual firefighting equipment** (as technical items)
- **Creativity/adaptability**
- **Layout of control panel**
- **Activation of active systems**
- **Active systems** (as technical items)
- **Manual firefighting**
- **Passive protection**
- **External help**
- **Situation assessment by master**

EVACUATION sub-system

- **Decision to evacuate**
- **Communication of the evacuation decision**
- **Evacuation procedure**

- **Safe haven**
- **Lifeboats**
- **External help**

In the **FIREFIGHTING** sub-system, the ***Active systems*** element refers to all active fire safety systems on board, to keep the analysis general. In this category can be found:
- Sprinkler system
- Water mist system
- CO2 system
- Foam extinguishing system
- Fire dampers
- Fire doors
- Ventilation shut off

Fire pumps are considered as part of the sprinkler/water mist system. Emergency generators are considered as part of the various active systems and should appear in their respective FMEA. The choice of systems to be investigated will depend on the solutions chosen in the design of the ship, and the block diagram can be detailed further to include them. Each active system can then make the object of its own FMEA.

2.3 Acceptable functional performance limit of the "fire safety" system and its elements

The only operational mode under investigation is "normal seagoing conditions at full speed". It is under this mode that Umoe Ventus burnt.
The idea of "limit" is interpreted herein as the minimum objective the system/sub-system/constituent element should reach. Nothing below this limit is acceptable, and anything above this limit is considered a positive outcome. The acceptable functional performance limits of the sub-systems and their constituent elements are presented in Table 1.

Table 1 – Acceptable functional performance limits of the sub-systems and their constituent elements

System part	Acceptable functional performance limit
Full system	**All lives safe, loss of ship**
DETECTION	**Detection and confirmation within 15 min from the first signs of fire**
Classification of spaces	Accounting for construction material, all risky spaces are categorised as such
Choice of detector	Adapted to the type of fire to detect
Detector placement	Close to foreseen fire source
Detectors	Detects fire
Alarm system	Triggers upon signal from detectors
Layout of control panel	User-friendly in highly stressful situations
Reaction on alarm	Start firefighting operations, even if preventive (e.g. false alarm); keep calm
Detection confirmation	Within two minutes of fire detection, for FRP ships
FIREFIGHTING	**Protection to ship occupant for 30 min, time to evacuate the ship**
Classification of spaces	Accounting for construction material, all risky spaces are categorised as such
Firefighting strategy	At least adapted to the identified fire risk scenarios

System part	Acceptable functional performance limit
Choice of active systems	Adapted to the type of fire to fight, to the configuration of the ship, and to crew response under stress
Decision – manual firefighting starts	Starts upon alarm, before detection confirmation
Adapted PPE[1]	Can be reached and put on within 2 min after decision to start manual firefighting
Manual firefighting equipment	Can be deployed within 2 min after decision to start manual firefighting
Creativity/adaptability of crew	Must face the decision of evacuation timely and conduct the procedure safely
Layout of control panel	User-friendly in highly stressful situations
Active system activation	Within 2 min of detection confirmation
Active systems	Able to extinguish fire when triggered timely; able to contain fire when triggered late
Manual firefighting	Delays fire spread to ensure safe evacuation; crew engaged in manual firefighting remains unharmed
Passive protection	Fulfils FTP Code requirements, and stays in place
External help	If part of strategy, ship able to maintain itself until help arrives
Situation assessment by master	Leads to the minimum safe decision - evacuation
EVACUATION	**All lives safe, ship abandoned**
Decision to evacuate	Taken latest at (max fire resistance time from FTP Code)-(time elapsed since detection)
Communication of decision to evacuate	Technically feasible at all time; must not trigger panic
Evacuation procedure	Crew and passengers are safe in the life rafts
Safe haven	Provides protection until evacuation is completed
Lifeboats	Must not ever burn
External help	If part of strategy, ship and life rafts able to maintain themselves until help arrives

2.4 Constraints of the system "fire safety"

The "fire safety" system comes with its own constraints.

- Large portions of the system, sub-systems, and constituent elements are dependent on human action
- The system is designed based on foreseen risk scenarios. These scenarios guide the choice of constituent elements as "systems" in the traditional sense of the term (e.g. alarm system, detectors, CCTV, water mist system). Fires following unforeseen scenarios rely heavily on human constituent elements
- The analysis is deemed valid for all 3 operational modes[2] described in HSC Code Annex 4. Since external help is deemed quickly available in the 2nd and 3rd operational modes, the analysis is explicitly carried out for the first operational mode, considered as worst case scenario. This approach limits the extent and weight of the work.

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[1] PPE: Personal Protection Equipment

[2] These three modes are: normal seagoing conditions at full speed, maximum permitted operating speed in congested waters, and manoeuvring alongside

3 System block diagram

The system block diagram is a graph placing the various sub-systems and their constitutive elements in relation with each other. As previously stated, the only operational mode considered for now is "normal seagoing conditions at full speed".
The block diagram is presented at the end of the document. For each constitutive element of a sub-system, a label is given for reference in the subsequent analysis. The same colour code as used in the sections above indicates the nature of the constitutive elements (technical, human, or socio-technical). Black arrows place the constitutive elements in relation to each other, indicating the main flow. Thick green arrows represent redundancies and embedded fail-safe measures.

The presented system block diagram represents a first iteration of the design of the system "fire safety". In this iteration, the constitutive elements are the ones coming naturally to mind when thinking of "fire safety". This means that at this stage, redundancies are not all available since they may not be part of the design yet. The subsequent analysis of failures will lead to refinements of the system, and creation of the necessary redundancies. In turn this will lead to a new system block diagram for an updated system including redundancies. The updated system block diagram will be presented further on in the document.
Presenting the system block diagrams this way may show the process of the analysis, and the benefits of carrying it out. It also highlights that an FMEA applied to the system "fire safety" can be used at several stages.
As mentioned in Section 1, it can be used as a general analysis (not applied to a specific ship) to highlight common failures of the system which apply to all ships. A general procedure can then be put forward with suggestion of main aspects to look into when analysing an actual ship project. The idea is to propose a base document laying the procedure to design fire safety.
This leads to the specific use of FMEA, which applies to a given ship design. An example of specific analysis will be shown for the case of Umoe Ventus, to illustrate that the failures of the system could actually be highlighted by the analysis.

4 System analysis

The objective of this section is to look at the failure of the various constitutive elements of the sub-systems. The methodology is to look first at the constitutive elements described in the block diagram to provide insight at a general level. The next step is to perform the FMEA once more at the level of a constitutive element, then considered itself as a system, to provide fail-safe measures at its own level. Only the first level will be documented herein.

This part of the analysis considers the points highlighted in Section 1.3. An FMEA worksheet is then created to account for: failure modes and their causes, local and end effects of the failure, failure detection methods, corrective measures, probability of causing hazardous or catastrophic effects. A template for the FMEA worksheet is shown at the end of the document.

The analysis is carried out with full considerations of the findings of the current project. This specifically accounts for the suggestions formulated in terms of classification of spaces, treatment of void spaces and open spaces, consideration of hot surfaces, exhaust routing, consideration of the actual performance of FRP materials when exposed to elevated temperatures, human factors, relevance of maintenance operations, role of the design code, etc.

This section does not aim at covering all the constitutive elements of the system "fire safety". A general illustration of its use will be shown, followed in a second stage by an application to the case of Umoe Ventus.

4.1 FMEA for the system "fire safety" – general use

The stage of general use of FMEA for the system "fire safety" aims at highlighting areas where fire safety design could be improved, and at providing first guidelines on how to perform the analysis. Given the scope and time frame of the project, the content of the present section is limited to an illustrative purpose, focusing mostly on recommendations.
The proposed FMEA worksheet is well-suited for implementation in software (e.g. Microsoft Excel) but is not very readable in a report format. The cases presented herein will therefore follow the same headings but presented in a way more suited to the purpose.
The use of the FMEA worksheet at general use considers only the constitutive element as a general idea. When using the method for a specific design, the analysis can be carried out on room-per-room basis. In the case of detectors for instance, it would mean considering the failure of the detector present in the considered room. If several detectors are present in the same room, several failure modes can be considered (e.g. all detectors are down, only one is down, etc).

Three main elements will be presented, all belonging to the **DETECTION** sub-system. Attention will be given to the constitutive elements "***classification of spaces***" (Table 2), "***Detectors***" (Table 3), and "***Alarm system***" (Table 4). An overview of their respective failure modes will be proposed, but only one will be developed (again for clarity purposes). The failure mode developed in more details in highlighted in bold in the list below.

Classification of spaces - overview of failure modes:
- Low-risk area classified as a high-risk area
- **High-risk area classified as a low-risk area**

Detectors – overview of failure modes:
- Fails to start (broken)
- **Fails to start (clogged)**

- Fails to start (loss of power)
- Fails to start (wrong sensitivity)
- Triggers when no fire (power supply issue or short circuit)
- Triggers when no fire (wrong sensitivity)
- Triggers at the wrong location (draft)

Alarm system – overview of failure modes:
- **Fails to start**
- Loss of input from detectors
- False alarm

Table 2 – FMEA table for ***Classification of spaces***

Sub-system	Detection
Type	Socio-technical
Phase	Design
Function	Identify high risk spaces to provide increased protection at the right places
ID #	D1
Failure mode	High-risk area classified as low-risk area
Failure cause	Design error; non-adapted regulations; Lack of knowledge on composite materials
Local effect	High-risk area will not be fitted with necessary fire detection and firefighting means, and will be left out of the design of the fire safety strategy
End effect	Overlooking fire start; long delay in taking major safety decisions; dangerous evacuation; loss of ship; loss of life
Failure detection	Survey of past accidents; assess adaptability of current codes to new industry practice Review of classification of spaces by fire experts and class
Corrective action	Update the regulations, increase formal knowledge level about material behaviour and knowledge level in the industry about composites Make new classification of spaces for the given project and involve fire experts from early design stages
Severity of failure effect	Very high
Probability of failure	Medium
Remarks	This addresses general concerns in the industry It also gives guidance for specific ship projects

Table 3 – FMEA table for ***Detectors***

Sub-system	Detection
Type	Technical
Phase	Operation
Function	Detects fire and sends signal to alarm system
ID #	D4
Failure mode	Fails to start
Failure cause	Clogged
Local effect	No detection from detector; no signal sent to alarm system
End effect	Delayed decisions and firefighting; loss of ship; loss of life

Failure detection	Inspection and drills; alternative detection system
Corrective action	Install several detectors to provide redundancy; Perform inspection and maintenance of detectors every week; Install CCTV with potential image/light intensity recognition
Severity of failure effect	Very high
Probability of failure	Moderate
Remarks	Fast detection is a high priority in the HSC Code safety philosophy. The nature of composite materials makes it even more critical. CCTV coupled with image/light intensity recognition could also be part of an automated system linking detection to firefighting

Table 4 – FMEA table for ***Alarm system***

Sub-system	Detection
Type	Technical
Phase	Operation
Function	Notifies the crew that a fire has been detected in a given area
ID #	D5
Failure mode	Fails to start
Failure cause	Broken; power supply failure
Local effect	No information flow from detector to crew
End effect	Delayed awareness of fire on board; delayed decision; potential loss of ship and loss of life
Failure detection	Inspection and drills; Alternative notification system
Corrective action	Install both sound-based and visual notification systems; Regular inspection/trials of alarm system
Severity of failure effect	Very high
Probability of failure	Low
Remarks	-

Recommendations based on the output of the FMEA for the system "fire safety" at a general level:
- Include fire safety considerations at an early stage in the design of vessels using composite materials
- Update regulations to account for the properties of composite materials
- Increase knowledge level about composite materials
- Redundancy can be provided for constitutive elements belonging to different category types

4.2 FMEA for the system "fire safety" – the case of Umoe Ventus

In this section, the methodology will be applied to the case of Umoe Ventus. New knowledge gathered during this project is implemented in the analysis. Not all aspects can be covered due to limited resources, but selected constitutive elements of the system "fire safety" are detailed. Special focus is given to ***Classification of spaces*** belonging to the sub-system **DETECTION** and ***Passive protection*** belonging to the sub-system **FIREFIGHTING**.

The analysis of the ***Classification of spaces*** involves looking at every room present on board. In the case of Umoe Ventus, the following rooms are present: main engine room, auxiliary engine room, lift fan engine, lift fan room, pump room, bridge, passenger lounge, pantry, wardrobe, cabin 1, cabin 2, WC. Only the lift fan room will be presented herein, which incidentally corresponds to the room where the fire started. The analysis is provided in Table 5.

In the Umoe Ventus design, the lift fan room is an open space (open to one side). On this account, the HSC Code classifies it as an area of low fire risk. However, elements of machinery were located in this room, which could make it an area of moderate fire risk, similarly to auxiliary machinery spaces. Nonetheless, it would not have been considered as an area of high fire risk in the current state of regulations.
The technical analysis presented in Appendix D proposes to classify all areas with hot systems as areas of high fire risk when the vessel is built with composite materials. This hypothesis is followed in the analysis presented in Table 5.

Table 5 – FMEA table for ***Classification of spaces*** applied to the lift fan room

Constituent element	Lift fan room
Sub-system	Detection
Type	Socio-technical
Phase	Design
Function	Ensure that this high-risk space is classified as such
ID #	D1.4
Failure mode	This is a high-risk space. Failure if it is identified as less risky.
Failure cause	Design error; non-adapted regulations; Lack of knowledge on composite materials
Local effect	This high-risk area will not be fitted with necessary fire detection and firefighting means
End effect	Overlooking fire start; long delay in taking major safety decisions; dangerous evacuation; loss of ship; loss of life
Failure detection	Design review with use of FMEA; involvement of fire safety engineers; review of classification of spaces by fire experts and class
Corrective action	Classify as high risk; Update regulations
Severity of failure effect	Very high
Probability of failure	High
Remarks	In traditional steel designs, this type of room would be considered as representing a moderate risk. It is classified here as high risk, based on findings from the technical analysis presented in Appendix D. The probability of failure is considered as high since the classification of this type of room as high risk is not the practice in traditional ship design.

This analysis shows that a systematic FMEA would have highlighted the issue of the classification of spaces at the origin of the fire of Umoe Ventus. Would the classification of space have been different, a detector would have been fitted in the room, and other measures would also have been taken. It is expected that the analysis would also have highlighted hazardous systems (e.g. routing of exhaust system) and the issue of exposed hot surfaces close to exposed elements made of composite materials.

The constitutive element ***Passive protection*** will be analysed next. The same room-by-room method is used here, to keep the philosophy of the HSC Code to provide protection where necessary in order to limit weight. In this case the FMEA is applied to the auxiliary engine room (Table 6).

Table 6 – FMEA table for ***Passive protection*** applied to the auxiliary engine room

Constituent element	Auxiliary engine room
Sub-system	Firefighting
Type	Technical
Phase	Design/construction/delivery
Function	First barrier provided to composite materials against fire
ID #	F8.2
Failure mode	Protection is not FRD60[3]
Failure cause	Design error; Inadapted regulations; Lack of knowledge on composite materials
Local effect	If not protection at all, composite materials will be very quickly involved in fire, fuelling it and accelerating fire spread.
End effect	Dramatic reduction of available time for firefighting and evacuation; dangerous evacuation; loss of ship; loss of life
Failure detection	Design review with use of FMEA; involvement of fire safety engineers; review of classification of spaces by fire experts and class Use FMEA table as a review tool/test tool
Corrective action	Allocate a FRD60 requirement
Severity of failure effect	Very high
Probability of failure	Moderate
Remarks	Based on the HSC Code, the passive protection provided should live up to the FRD30 requirements. The classification for high-risk area suggested in the study from Appendix D calls for FRD60.

Comparing the output of the FMEA table to the real design, it can be seen that the auxiliary engine room has not been fitted with passive protection at all.

[3] FRD60 or other protection levels decided upon following time needed for evacuation and other aspects of holistic design such as mechanical contribution of adjacent structures.

5 Conclusions and recommendations

5.1 General observations

Using FMEA on the Umoe Ventus case could highlight two failures. The first one concerns the wrong classification of space for the lift fan room. This failure was actually involved in the accident; therefore one could say that it was looked after in the analysis. The second failure concerns the passive protection provided to the auxiliary engine room, which was not involved in the accident. The FMEA approach could then highlight important failures with actual consequences on the safety level of the ship. Moreover, the highlighted failures belong to different phases of the design and construction process. In the case of the passive protection, the failure could have occurred at the design phase, or the construction phase, and could have been highlighted during the delivery of the vessel. The objective is not to point out responsibilities or blame design team, yard, authorities or class, since all followed established regulations.

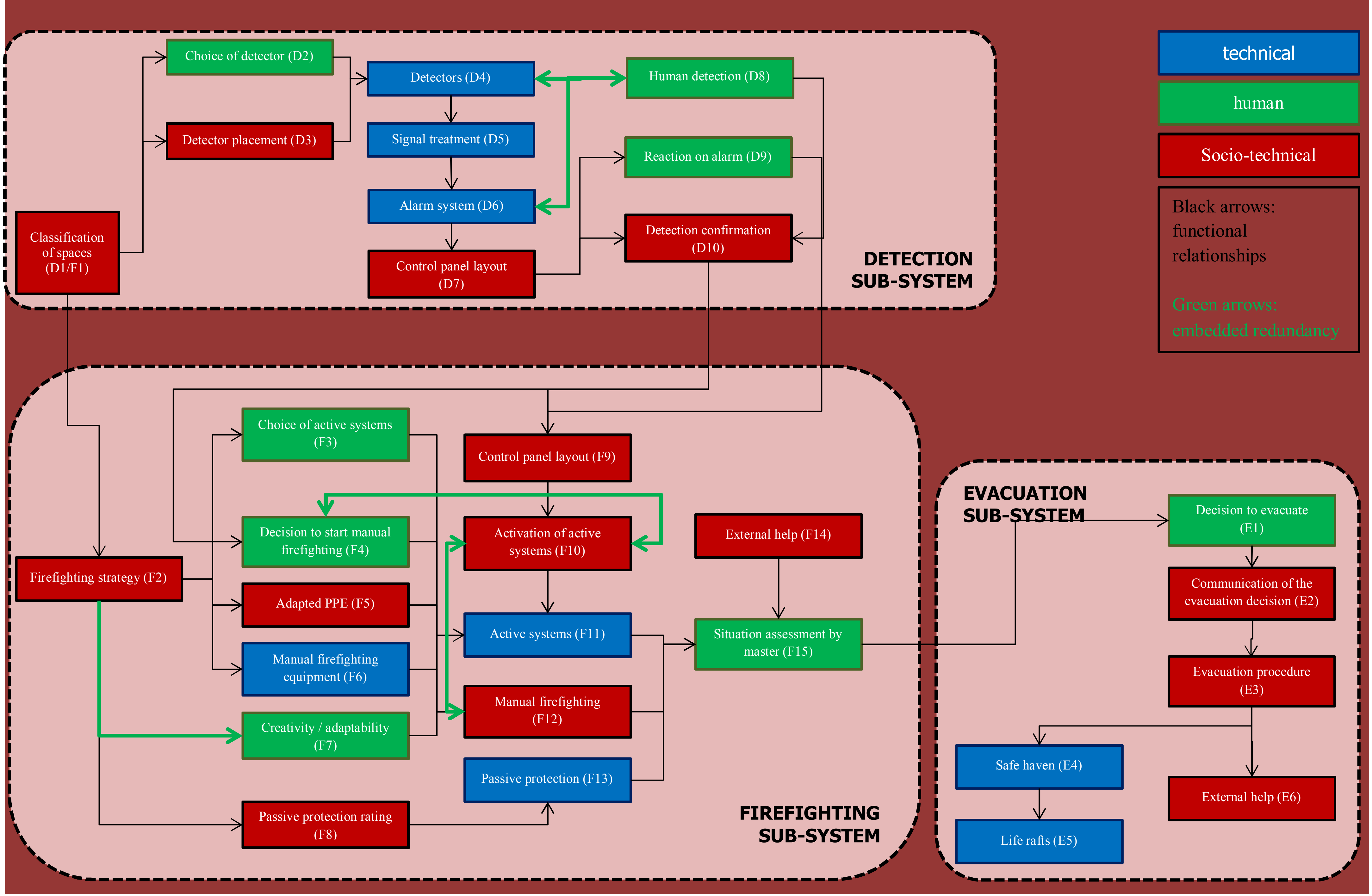
The use of FMEA applied to the system "fire safety" therefore appears as a promising design tool. It has the advantage to limit the extent of a risk analysis, to be usable at all phases of the construction process, and to integrate fire safety early in the design phase, thus limiting costs. The tool could also prove interesting for approving authorities to e.g. reject doubtful area classification, thus providing a document following the ship through its early life.

5.2 Recommendations

Some recommendations can be formulated based on the presented work:

- When designing with composite materials, their own properties should be considered, not the ones of steel
- This leads to the need of updates in the regulations in this direction
- It should be acknowledged that fire is the design situation for composite ships
- Fire safety should be integrated in early design phases
- The level of knowledge about composite materials should be raised in the industry.
- Using the FMEA methodology could provide ways to address several of the above points
- Fire safety can be considered as a "system" in an untraditional way. As a consequence, fire safety could benefit from all the advantages of reliability engineering.

BLOCK DIAGRAM – FIRE SAFETY SYSTEM



FMEA worksheet as used in this project

Name of system	
Mode of operation	
Sheet No.	
Date	
References	
System block diagram	

								Failure effect						
Constitutive elements	Sub-system	Type	Phase	Function	ID#	Failure mode	Failure cause	Local effect	End effect	Failure detection	Corrective action	Severity of failure effect	Probability of failure	Remarks