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A Fuzzy Decision Support System for Equipment Repair Under Battle Conditions

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Abstract

In battle scenarios, Navy Units survival is highly dependent on the speed and quality of decisions taken in the different functional areas onboard. In this context, decision support systems can play a vital role in the decision process enhancement.

Within the Portuguese Navy a fuzzy decision support system is under development for shipboard Weapon Engineering equipment repair priorities management under battle conditions. The system is currently being tested and used in the Weapon Section Base of "Vasco da Gama" Class Frigates, providing support related with faults detected in the equipments subsystems which are part of the SEWACO combat system. In this paper we present the system and discuss the fuzzy multiple attribute decision-making model adopted.

***Keywords*:** Battle conditions; Equipment repair priorities; Fuzzy decision making.

1. Introduction

The speed and quality of decisions taken in the different functional areas onboard ships are critical factors for Navy units' survival under battle conditions. These decisions are, mainly, tactical and operational under the scope of Naval Operations, and of defining repair priorities and resource assignment under the scope of technical activities for areas such as Propulsion, Energy Production and Distribution or Sensor and Weapons Engineering. For all these decisions, time is a critical factor, but the stress inherent to combat situations affects the performance of decision-makers.

In the above context, decision support systems can play a vital role in the decision process enhancement. However, there is a lack of decision support tools for the co-ordination of the

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technical activities subsequent to battle incidents. There are strong reasons for the lack of such facilities. First, any decision process, at that level, is extremely complex due to the high number of parameters under consideration. Second, one faces the problem which is how to “explain” to a machine the meaning of vague concepts usually used in situation characterization, such as the ones implicit in linguistic expressions like “severe limitations”, “very degraded”, “quickly repaired” or “very important equipment”. Another important problem is the uncertainty inherent to the information used by decision support systems, with classifications based in natural language, i.e., in current terms of human language. Even if this language appeals to some formalism, there will be the question of how to decide in face of data like "*equipment A, which is fundamental to face threat X, is degraded*" and " *equipment B, which is very important to respond to threat Y, is inoperative*". Particularly if the scenario is of multi-threat, a mix of X and Y, but where the first threat is considered "*slightly*" more important. Classical set theory and Boolean logic present serious limitations to manipulate data that has ill defined outlines.

One possible approach to handle vague concepts is Fuzzy Set Theory, formulated and developed by Zadeh [16]. Fuzzy set theory is a generalization of classical set theory that provides a way to absorb the uncertainty inherent to phenomena whose information is vague and supplies a strict mathematical framework, which allows its study with some precision and accuracy.

Recently in Portuguese Navy ships the weapons and electronics equipment repair responsibilities were centralized in the Weapons Engineering Department (WED). Until this organic change onboard, dated from the early 1990's, the repair responsibilities were distributed by the technical services, which had both operator and technical personnel. This organizational modification lead to new approaches to the maintenance problem, in battle scenarios, specially in the organization of human and material resources, in the compilation processes and information processing and in the decision making of degraded or inoperative equipment repair priorities.

Nowadays the decision support tool used is presented in tabular format and is inscribed on the boards where the faults are registered. It provides only one priority suggestion, per equipment, for each of the six priority combinations (A-F) for threat levels Red/Yellow/White (see Figure 1). However, some limitations were soon experienced with these decision aids, which are virtually insoluble based on the board type support available. One of the major disadvantages of the decision table method is the lack of dynamism, since it has no ability to answer most of the relevant operational scenario evolutions.

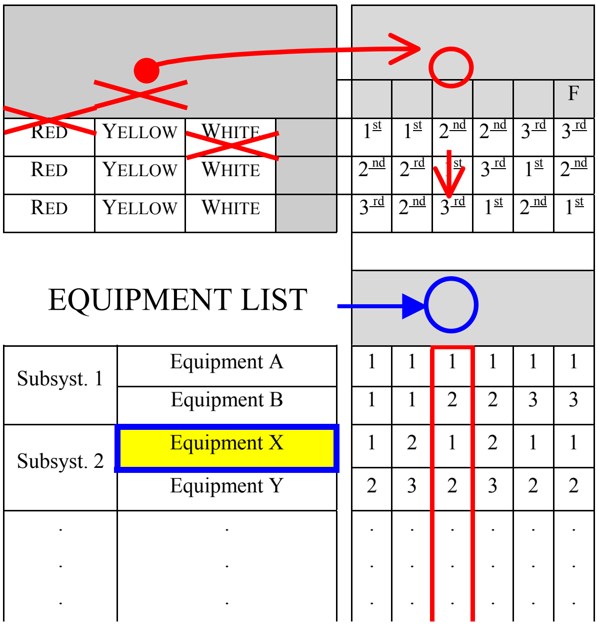


Figure 1 – Example of the actual manual process using a decision table

Within the Portuguese Navy a fuzzy decision support system (FDSS) is now under development for shipboard weapon engineering equipment repair priorities management, under battle condition. A prototype version is currently being tested and used in the Weapon Section Base of "Vasco da Gama" Class Frigates, providing support related with faults detected in the subsystems of the sensor and weapon command and control (SEWACO) system (Simões-Marques and Gameiro-Marques [11]).

The fuzzy decision support system (FDSS) will be used, primarily, in the Weapon Section Base of these multipurpose ships, in multi-threat evolutionary battle scenarios.The decision model used in FDSS, is being developed (Simões-Marques and Ribeiro [12]) and uses a Fuzzy Multiple Attribute Decision Making – FMADM approach (Chen and Hwang [3], Ribeiro [8], Zimmermann [28]). The FMADM model allows dealing with uncertainty or imprecision, with the help of tools decurrent from the Fuzzy Set Theory combined with methods from the multicriteria area.

The paper is organized as follows. First a brief overview on the theoretical foundations of the FDSS is presented. Second, we will present the structure of the model developed and discuss aspects related with the data concepts, model resolution, validation and evaluation for the management of repair priorities of equipment integrated in the SEWACO system of “Vasco da

Gama" Class frigates, of the Portuguese Navy. At the end we will present the conclusions and future extensions.

2. Theoretical foundations overview

2.1 Fuzzy sets

Fuzzy Set Theory (FST) was formulated, around 30 years ago, by Lotfi Zadeh [16]. A fuzzy set presents a boundary with a gradual contour, by contrast with classical sets, which present a discrete border. Let U be the universe of discourse and *u* a generic element of U, then U = {*u*}. A fuzzy subset Ã, defined in U, is:

$$\tilde{A} = \{\, (u, \mu_{\tilde{A}}(u)) \mid u \in U \}$$

where $\mu_{\tilde{A}}(u)$ is designated as *membership function* or *membership grade* **(**also designated as *degree of compatibility* or *degree of truth***)** of *u* in Ã. The membership function associates with each element *u*, of U, a real number $\mu_{\tilde{A}}(u)$, in the interval [0,1].

Fuzzy sets admit a set of basic operations such as union, intersection, complement, composition, Cartesian product, concentration and dilation (Zadeh [19-21]). For the model presented in this paper the main operations used are intersection and union and composition. The interest of the intersection and union operators relies on the basic definition of decision making, which is the selection of the best activities (OR operation) which simultaneously satisfy goals and constraints (AND operation) (Bellman and Zadeh [2]).

There is another important concept for the fuzzy decision support system, the concept of relation between elements of the sets. A fuzzy relation represents the degree of association between the elements of two or more sets and can be represented by membership grades. The concept of fuzzy relation is easily generalized to n-dimensions, but in this paper only binary fuzzy relations will be considered.

A fuzzy relation, between an element $x \in X$ and an element $y \in Y$, is defined in the $X \times Y$ space, designated by Cartesian product, which is the set of all the dual pairs (x,y).

Thus, a fuzzy relation Ñ, defined in $X \times Y$, is the subset of the $X \times Y$ comprehending all dual pairs, where the association is represented as:

$$\tilde{N}(x,y) = \{((x,y), \mu_{\tilde{N}}(x,y)) \mid (x,y) \in X \times Y\}$$

Considering two binary fuzzy relations $P(X,Y)$ and $Q(Y,Z)$, having the Y set in common, it is possible to perform the composition of these two relations. The result is a new relation $R(X,Z)$, iff at least one element $y \in Y$ pertains simultaneously to relations P and Q. This composition can be denoted by

$$R(X,Z) = P(X,Y) \circ Q(Y,Z)$$

There are some composition operations frequently used for binary fuzzy relations, as for example the max-min and max-product (Klir and Folger [7]). Is this paper we use max-product compositions. The details of fuzzy relations are largely documented in literature (see, for instance, Klir and Folger [7], Zadeh [16] and Zimmermann [28]).

Another important concept for the fuzzy set theory relates with linguistic variables (Zadeh [19-24]). A linguistic variable is a variable that admits as value words or sentences of a natural language, which can be represented as fuzzy sets. If, about the importance of certain equipment, one states "*The equipment is fundamental*", then the word *fundamental* can be looked as a linguistic value of the variable *importance*, i.e., is the label of the fuzzy set *fundamental*. Here we use a simplified version where the linguistic terms are autonomous discrete fuzzy sets, as for instance *utility* which has elements {irrelevent, desirable, important, almost fundamental and fundamental}.

To the interested reader, we suggest reading Ross [10], Zadeh [16-27] and Zimmermann [28] that provide a detailed overview of FST.

2.2. Fuzzy decision making

Decision making may be characterized as a process of choosing or selecting 'sufficiently good' alternative(s) or course(s) of action, from a set of alternatives, to attain a goal or goals (Ribeiro [9], Jaiswal [6]).

Bellman and Zadeh [2] proposed the first decision model where goals and constraints are treated as fuzzy sets. A fuzzy decision D can, thus, be defined as the choice that satisfies simultaneously the goals G and constraints C. This conjunction can be interpreted as a logical AND, which can be modeled as an intersection of the fuzzy sets G and C.

Formally,

$$\mu_D(x) = \mu_{G \cap C}(x) = \mu_G(x) \otimes \mu_C(x)$$

The best (optimal) alternative designated by optimal decision D^* is the greatest membership grade in D, usually achieved with the union operation.

One situation to consider is the existence of different preferences or importance degrees for goals and constraints or between attributes. These preferences or importance degrees can be considered in the model by ponderation or weighted coefficients. A common method (the one followed is this paper) for a fuzzy decision D is a weighted combination of n goals with m constrains (French [5]), such as:

$$\mu_D(x) = \sum_{i=1}^{n} u_i \mu_{G_i}(x) + \sum_{j=1}^{m} v_j \mu_{C_j}(x)$$

where u_i and v_j are the relative importance assigned, respectively, to each fuzzy goal G_i ($i \in \mathbb{N}_n$) and to each fuzzy constraint C_j ($j \in \mathbb{N}_m$). In this paper the equation only has the second element because we are dealing with multiple attributes.

Many other aggregation rules have been proposed in the literature as, for example, max-min (Yager [14, 15]), approximate extension principle (Dubois and Prade [4]) and evidential logic rule (Baldwin [1]).

In general, fuzzy multi-criteria decision problems can be classified in two categories (Chen and Hwang [3], Ribeiro [9]):

- Fuzzy Multiple Objective Decision Making (FMODM); and
- Fuzzy Multiple Attribute Decision Making (FMADM).

The first category (FMODM) consists of a set of conflicting goals that usually are difficult to achieve simultaneously. MODM deals with problems where the alternatives are not pre-defined, so the decision-maker has to select the more promising alternative facing the quantity of (limited) resources available. Resouces, objectives and coefficients can all have some form of fuzziness.

In the second category (FMADM), the alternatives are pre-determined and known. The decision-maker has to select/prioritize/rank a finite number of alternative actions. The choice of alternatives is performed based on their imprecise attributes classification. In general FMADM has to satisfy a unique goal, however, it can be of two types (Ribeiro [8]): (1) select an alternative presenting the attributes with best characteristics, or (2) classify the alternatives, based on a role model. The FMADM is a qualitative approach, due to the existence of criteria/attribute subjectivity and fuzziness. This approach requires information about the preference among the values that an attribute could assume, as well as, the preferences across the existing attributes. The proposed model in this paper follows this approach.

The FMADM method has two main phases: (1) the rating of each alternative, by aggregation of the degree of satisfaction for all criteria, per decision alternative; and (2) the ranking of the alternatives with respect to the global aggregated degree of satisfaction.

For more details about decision-making problems, decision support systems and the FMADM methodology see, for instance, Chen and Hwang [3], French [5], Ribeiro [9], Turban and Watkins [13], Zadeh [18] and Zimmermann [28].

3. Fuzzy Decision Support Model

The main concepts described in this paper are the result of studying and observing the operational procedures related with typical decision making processes in repair priorities management, in order to identify the ones that optimize the process.

To develop this model a systematic process was followed, as much as possible, to analyze the alternatives, attributes and goals. The basic set of steps followed is (Jaiswal [6]): (1) formulation of the problem; (2) model development; (3) data collection and model resolution; (4) model validation; and (5) evaluation and implementation.

This section presents the development of the fuzzy decision support system for the management of equipment repair priorities, under naval battle scenarios.

3.1 Formulation of the problem

3.1.1 Main concepts

A combat ship has to satisfy some operational requirements, which depend on the ship characteristics, on the operations area and on the friendly and opposite forces.

Not all ships present identical characteristics, either nautical or fighting. Nautical characteristics affect the environmental and geographical conditions in which a ship can operate. A rowing boat is not adequate to perform oceanic travels, neither to stay long time in the sea. In the same manner a battleship or an aircraft carrier is not adequate to landing personnel or material in a beach or to sail little rivers. Fighting characteristics affect the response capability to the different threat types which a ship can be faced with. Not all combat ships are equipped, in equal manner, to answer different types of threat, some can be specialized in a unique warfare type, having no means to face other situations.

The ship areas of operations affect pre-warning and reaction times, the choice of weapons to employ and the ship's maneuver capability. It's easy to understand that a ship sailing near or surrounded by land is exposed to attacks of different characteristics then the ones in open sea. In this situation short reaction times are required, and maneuvering freedom is very limited. For instance, a ship sailing in a very steep fiord cannot account for most of their sensors, especially the long range ones. The effectiveness of some weapons will also be affected, due to target closeness and permanent land interference, that impairs the guidance systems normally used. Finally, any tactical maneuver planned to be performed in conjunction with weapons employment, e.g. alter speed and course, must be carefully weighted face to the eminent risk of running ashore or colliding.

The presence of friendly forces permits specialization of each element in some warfare components, i. e. the ones that are more able to perform. Not less important is the knowledge on opponents' characteristics, which permits determining and planning advisable type of actions in order to win the necessary advantage over them, according to the different threat types present.

In a combat ship equipment's repair priorities management must be dynamic and consider multiple factors. In this process, the decision-maker must evaluate internal “clients” real necessities, i.e. the needs related with the system whose maintenance he is responsible for. However, the maintenance services can also be “client” of other services. When a technician turns on and tests a subsystem, in order to deliver it to the operating personnel, he will only succeeds if energy and other system requirements are satisfied, for which this technician, eventually, is not responsible for.

An equipment repair priority system must consider the impact that faulty equipment has to the ship considering its specific purposes. It is useless to know that an equipment is degraded, and not inoperative, if one has no measure of that degradation. The priority and resources assigned to a repair will be dependent on the impact of the equipment degradation on the system's overall operationality. Consider, for instance, the importance of a degradation caused by faulty lamps or meters, compared with other so limiting that it's only advisable to use the equipment in extreme situations, with the risk of becoming definitively destroyed. For example, an engine structurally damaged or an electronic equipment operating in “battle short” mode (i.e., short-circuiting protections).

Lessons from recent conflicts indicate that a combat ship involved in battle incidents, under complex scenarios and subject to some threat and command priorities dynamics, quickly push technical decision-makers to situations where they have to handle and rank some dozens of fault reports almost simultaneously. Time spend in fault identification, together with normal delays in information flow, adding to the vagueness of many reports, concurring with absence of information related with problems weakly characterized, place the decision-maker in a situation which can easily lead to omission of data and goals which are very important, such as, the ones affecting Command goals and needs. Usually there are also other factors introducing psychological and physical stress such as extended periods of tension, many hours without sleep, wearing uncomfortable equipment and the existence of high temperatures or smoke from fires or from ventilation restrictions.

Thus, the need for automatic reliable means of decision support which react immediately to scenario changes and to new data are obvious. In this context the requirements for the model development are:

a) a set of degraded or inoperative equipments is to be ranked, in accordance with repair priorities;
b) it must be applicable to ships with multi-threat capabilities;
c) it must be possible to scale the model in accordance with the complexity of the system under consideration.

Table 1 depicts the main factors for equipment repair priorities.

Table 1

Factors to consider in priorities evaluation		
Operational	1.	general scenario in which the ship is to operate, considering geographical factors and available intelligence about hostile platforms and weapons;
	2.	ship specific mission;
	3.	threats degree of presence and importance, established in accordance with command priorities;
Technical	4.	system's architecture, considering different functional areas and subsystem/ equipment interconnections, importance and existing redundancies;
	5.	logistic or technical limitations, endogenous or exogenous, which affect equipment employment or repair capability;
	6.	faulty equipment degradation level.

As the table indicates, the priorities evaluation factors can be grouped in two areas, operational and technical, where:

- operational factors (items 1 to 3) are associated with system exploration requirements;
- technical factors (items 4 to 6) are the ones related with system architecture and functioning.

The main concepts of this model are:

System – a set of equipments, which allow the satisfaction of general functions/objectives. Examples: "propulsion system", "energy production and distribution system" or "combat system".

Subsystem – a set of equipment necessary to ensure certain discrete functions, at a macroscopic level (designated as macro-functions). In general it is a natural division, corresponding to the equipment set of one supplier. Examples: "diesel engine subsystem", "gyroscopic subsystem", "early warning radar subsystem" or "weapon control subsystem".

Equipment – an entity, pertaining to a subsystem, intended to perform a discrete high level function. The decomposition of a subsystem into equipments usually coincides with a physical division of a complex subsystem of modular architecture. Examples: "transmitter", "antenna", "receiver", "processing unit" or "operators console".

Function line – the set of macro-functions necessary to perform a final objective of a system. For instance, to employ a weapon is necessary the confluence of a set of individual functions and events related with the detection, localization and identification of a target; target acquisition by a weapon director; weapon assignment, as well as some auxiliaries functions related with referential data processing or with data transfer between subsystems.

The attributes used in the FDSS are:

FLTH is a fuzzy relation between function lines (*FL*) and threats (*TH*) that represents the preference or importance of using a particular function line (*fl*) to face a certain threat (*th*). This fuzzy relation is defined as:

$$FLTH(fl,th) = \{((fl,th),\ \mu(fl,th)) \mid (fl,th) \in FL\times TH\} \quad \textbf{[i]}$$

Note that the *FLTH* fuzzy relation corresponds to factor 1 of Table 1.

FLSEL is a crisp set that selects the chosen function lines, in accordance with the specific missions of the ship. The *FLSEL* crisp set is defined as:

$$FLSEL\,(fl) = \{\ \mu_{FLSEL}(fl) \in \{0,1\} \mid fl \in FL\} \quad \textbf{[ii]}$$

Where parenthesis {} refer to discrete values. The *FLSEL* set corresponds to factor 2 of Table 1.

THST is a fuzzy set that expresses the threat status by means of a weight, which represents the respective importance of the threat (*th*). The threat status fuzzy set is defined as:

$$THST\,(th) = \{\ \mu_{THST}(th) \mid th \in TH\} \quad \textbf{[iii]}$$

THPR is a fuzzy set that associates to each threat (*th*) a weight, according to the relative priority assigned by ship's Command. It is defined as:

$$THPR\,(th) = \{\ \mu_{THPR}(th) \mid th \in TH\} \quad \textbf{[iv]}$$

The *THPR* set together with the *THST* set corresponds to factor 3 of Table 1.

FLSS is a fuzzy relation between function lines (*FL*) and subsystems (*SS*) sets, corresponding to the utility of each subsystem in each function line. The utility is expressed by a degree (weight), based in linguistic values. *FLSS* is expressed by:

$$FLSS(fl,ss) = \{((fl,ss), \mu(fl,ss)) \mid (fl,ss) \in FL \times SS\} \quad \textbf{[v]}$$

SSEQ is a fuzzy relation, between the set of subsystems (*SS*) and equipments (*EQ*), representing the utility of each equipment (*eq*) to each subsystem (*ss*). This attribute is expressed as:

$$SSEQ\ (ss,eq) = \{((ss,eq),\mu(ss,eq)) \mid (ss,eq) \in SS \times EQ\} \ \textbf{[vi]}$$

The *SSEQ* relation together with the *FLSS* relation corresponds to factor 4 of Table 1.

EQSEL is a crisp set, which selects the equipments considered recoverable. It's defined as:

$$EQSEL\ (eq) = \{\ \mu_{EQSEL}(eq) \in \{0,1\} \mid eq \in EQ\} \quad \textbf{[vii]}$$

The *EQSEL* set corresponds to factor 5 of Table 1.

EQST is a fuzzy set that expresses the Equipment Status, representing the respective degradation degree. This attribute is defined as:

$$EQST\ (eq) = \{\ \mu_{EQST}(eq) \mid eq \in EQ\} \qquad \textbf{[viii]}$$

The fuzzy set *EQST* corresponds to factor 6 of Table 1.

EQEV is the output fuzzy set, corresponding to the final evaluation of the faulty equipment set which is considered recoverable, weighted by all the factors previously described. It is the final ranked equipment repair priorities. This fuzzy set is defined as:

$$EQEV\ (eq) = EQUT^{*}(\ eq) \ \otimes EQST\ (eq) \qquad \textbf{[ix]}$$

The *utility* of an element defines its relative importances/weight for the prioritization process and its elements are:

Irrelevant - the element utility to perform a function is null. For instance, the utility of a subsystem *x* to the function line *y* is null or the utility of the equipment *z* to the subsystem *w is* null.

Desirable - the element utility to perform a function is marginal.

Important - the element utility to perform a function is significant, but has alternatives.

Almost Fundamental - the element utility to perform a function is very significant. Without this element the performance of the function will be seriously affected.

Fundamental - the element utility to perform a function is vital. Without this element the function is not performed.

Threat status (*THST*) is a fuzzy set comprehending three weights, semantically defined as:

Red - a threat is present or eminent.

Yellow - the possibility of threat occurrence is very high.

White - the threat is not considered probable.

Equipment Status (*EQST*) is a fuzzy set with five weights, semantically defined as:

Operative - the equipment does not present any failure.

Almost Operative - the equipment presents minor faults, which does not affect significantly his performance.

Degraded - the equipment presents faults, which affect his performance.

Almost Inoperative - the equipment presents major faults, performing only a very reduced number of its functions.

Inoperative - the equipment cannot perform any of their functions.

3.1.2 Context and resources

The decision making process for the definition of the repair priorities of Weapons and Electronic equipment of a combat ship is considered a higher level process. In this process the employment mode of existing sensors and weapons is defined, according to several factors such as, present threat types, geographical scenario of operation, composition of the force where the ship is integrated (if there is one) and specific missions assigned.

Modern ships count with a large equipment set that, off-line or integrated in a more complex system, ensure the fighting capability of the ship. Weapons Engineering Department (WED) mission is to perform the maintenance, at electrical, electronic and electromechanical level, on the different subsystems that contribute to the fighting capability, in order to assure high readiness standards by means of high availability of the combat system. At a macroscopic level combat systems can be considered as the conjunction of resources of the type:

- sensor and communications;
- command and control;
- weapon controls;
- weapons;
- reference;
- support.

Sensor and Communications type resources are the set of subsystems that provide detection, identification and information extraction capabilities relative to other platforms, present in the Unit coverage radius. These platforms can be air, surface (terrestrial or maritime) or subsurface type. In this group the means to ensure the coordination between friendly forces are also included.

A platform is, generically, any vehicle or weapon that travels or stands in certain area of interest as, for example, airplanes, helicopters, missiles, ships, amphibious vehicles, terrestrial vehicles, coastal artillery or missile batteries, submarines, torpedoes and mines.

Command and Control type resources are subsystems for automatic data processing, which integrate information received from sensors. These subsystems are the support measure for decision making at tactical and operational level, supplying not only the means for visualizing the information compiled, but also recommendations about actions to take in order to react to the operational scenario.

Weapon Control type resources are the set of subsystems that receive target position data, to control the launchers positioning and the events sequence previous to the firing of a weapon.

Weapon type resources are the subsystems used to achieve an active interaction with a target platform, in general, aiming at its destruction or neutralization.

Reference type resources are a set of subsystems that supply the geographical, positional, and environmental data necessary to the solution of problems related with the accurate knowledge of the ship's dynamic situation. For instance, about the ship geographical position, heading, course, attitude, and speed are processed. These data are critical to the correlation of information received from different sensors and, also, to the weapon subsystems fire problem resolution.

Support type resources are the means that support the interconnection between different subsystems, e.g., Local Area Networks (LAN) for digital data transfer.

The resources described are, normally, integrated in chains, designated as function lines, with or without redundancy at different levels, as for instance, ***sensor - command and control - weapon control – weapon***, in parallel with ***reference and support***. See Figure 2.

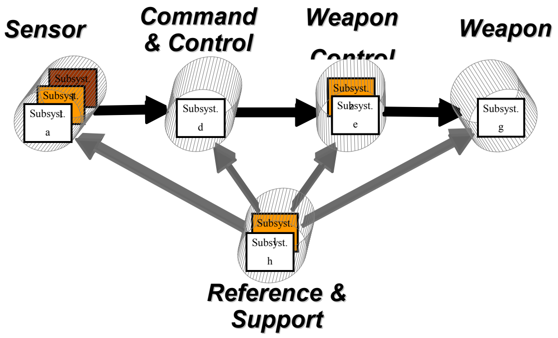


Figure 2 –Resources sequence needed to the function line of a weapon

Eventually some subsystems may not be included in function lines that end in a weapon. In such cases function lines have a different typology from the one presented.

3.2 Model Development and Resolution

The “Vasco da Gama” Class Frigates, commissioned to the Portuguese Navy since January 1991, are multipurpose ships, which have an integrated combat system, designated by SEWACO (*Sensor and Weapon Command and Control System*), which, generally, follows the described structure.

In order to identify the universe of discourse and the relations between the four existing factors (Threats, Function Lines, Subsystems and Equipments), applied to the Portuguese Navy "Vasco da Gama" Class SEWACO, a large amount of data was gathered. Since the data is classified, thus not compatible with the public scope of this paper, no real data will be presented here. The examples used are anonymous, not reflecting any real situation of the developed application.

The first step in data collection was to identify the universe of the sets, intended to be used in the FDSS, such as Threats, Subsystems and Equipment sets definition.

At Function Lines level, beyond the enumeration of the ones documented, there was the need to consider function lines in a broader sense, i. e. the ones which do not follow the logic of being subsystem chains ending in a weapon. This is due to the existence of subsystems that remain out of the classical function lines concept but have a significant role in the system. One example, is the communications subsystem, which is fundamental for tactical command and control.

The second step in data collection was the definition of the function line to subsystem (*FLSS*), subsystem to equipment (*SSEQ*) and function line to threat (*FLTH*) relations used in the FDSS. The approach adopted to the *FLSS* and *SSEQ* relations was different from the one employed in the *FLTH* because the first two can be easily described with linguistic values.

The *FLTH* relation, who represents the utility of Function Lines to different types of Threat, is rather complex because it should be processed dynamically and in real time. The *FLTH* relation represents what can be seen as the WED Battle Order, i.e., the data that, varying in accordance with enemy platform characteristics and geographical scenario, allow the technical decision-maker to evaluate the relative importance of Function Lines in different contexts. For a practical implementation we consider the use of different pre-defined *FLTH* relations. The one that best matches the characteristics of the actual situation is selected. Thus the *FLTH* relation is defined by navy experts, as best representing the function lines utility to the different threats considered.

The threat priority (*THPR*) fuzzy set contains the weights to assign to threats, in accordance with Command priority order. If equality in the Threat Status happens, the weights assigned will be slightly decreased, from maximum priority (weight 1). For instance, if the three threats have, *a priori*, the same status, the most prioritary to the Command receives the coefficient 1, the one with second priority receives the coefficient 0.95 and the less prioritary receives the coefficient 0.9. It is important that these coefficients are close to one, in order to reduce the penalizing impact in the evaluation process.

The function line selection (*FLSEL*) and equipment selection (*EQSEL*) crisp sets contain binary values, according to the function line and equipment selection as described in section 3.1.1.

The above mentioned data is included in the database and the knowledge base components of the FDSS, as depicted in Figure 3. The knowledge base comprehends the initialization values and considers a stable architecture system operating in a scenario where the geographical factors and the enemy characteristics are constant along the period of time considered. In the present application the *FLSS*, *SSEQ* and *FLTH* relations constitute the FDSS knowledge base. The database comprehends the values associated to the real world status, which progresses with high dynamics. This data can be used either as control or as input data to the FDSS. In the present application the function lines selection (*FLSEL*), the threat status (*THST*), the threat priority

(*THPR*), the equipments selection (*EQSEL*) and the equipments status (*EQST*) sets constitute the FDSS database.

Figure 3 illustrates the integration of the database and knowledge base in the FDSS Evaluation Component. Remember that the output of this component is the equipments evaluation (*EQEV*) fuzzy set, which corresponds to the final utility evaluation of the faulty equipment set to be recovered. Notice that if an equipment, at the end of the different aggregations performed, presents a membership grade of 1, it means that a totally inoperative equipment, admitted as recoverable, is vital in a subsystem. This subsystem is also fundamental to a function line vital to react to an effective threat, prioritary to the Command.

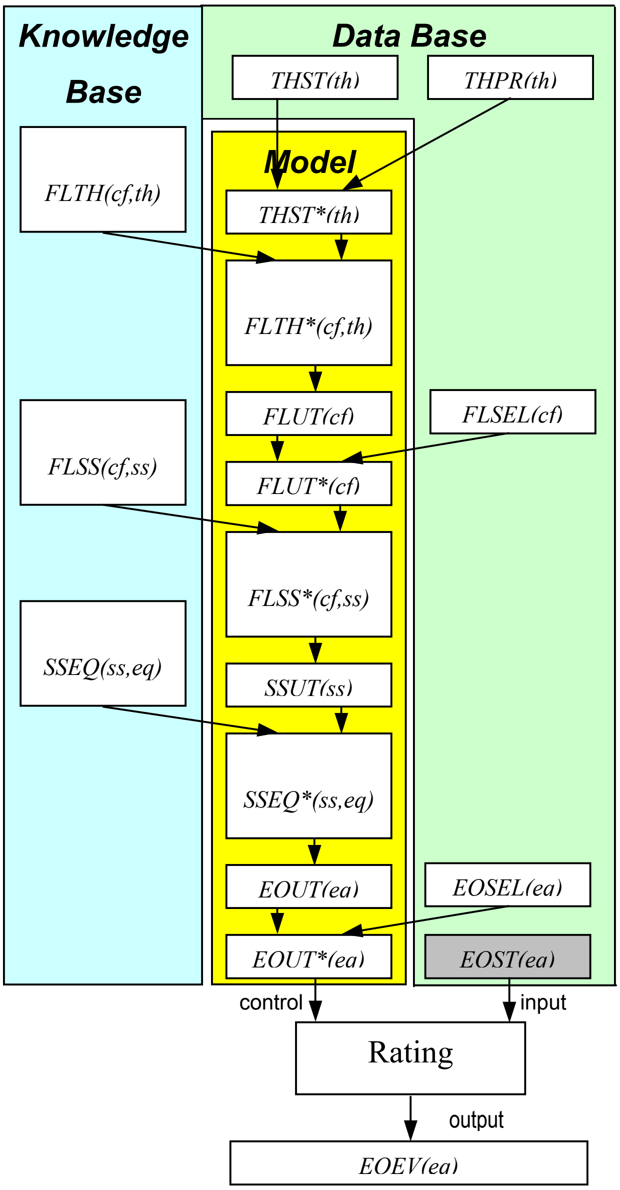


Figure 3 - The Data and Knowledge Bases of the FDSS

3.2.1 Rating Process

The FDSS decision process comprehends the rating of alternatives phase as mentioned in section 2.2. for the FMADM model. This process is based in a previous version developed by the authors (Simões-Marques and Ribeiro [12]).

In order to perform the rating we have to consider the scenario where the ship is operating. Considerations on the geographical characteristics together with data about opposite forces (which constitute the threats), allow the assignment of preference degrees to the employment of different function lines belonging to the system. For instance, consider a geographical scenario saturated of small islands, where hostile surface forces operate and there is one high possibility of short-range confrontations. Artillery guns employment will receive high priority, instead of surface-to-surface missiles, since these are prejudiced by range and target acquisition problems.

Usually, in naval context three types of threat are considered: air, surface and subsurface. The model considers these threats. However, if *a posteriori* other threats are considered relevant to the implementation, they can be included, as, for example, threats related with mines or NBC (*Nuclear, Biologic and Chemical*) warfare.

Thus a fuzzy relation (*FLTH*) [i] of membership grades representing the relation between function lines and threats is built, where the preference or importance degree of using a function line to face certain threat is defined as a weight, in the interval [0,1]. A weight 0 means that a function line is useless to the threat, while a weight 1 indicates that it is fundamental.

In reality, threats present different status, in accordance with its possibility of occurrence or eminence level. The term, which expresses the threat status, is converted into a weight representing its importance grade, assigned to the threat status fuzzy set (*THST*) [iii].

It should be noted that in the ranking phase, the occurrence of equalities in the status of different threats will reduce the discriminating power of the method. This situation is solved introducing an element (*THPR*) [iv], which represents the priority order in which the Command of the ship wants to face the different threats. Hence, threats of the same level, which are less prioritary, are affected by a coefficient that reduces its relative importance. This coefficient is kept close to one, so it doesn't affect, in a pernicious way, the evaluation process.

In accordance with the weights inscribed in the *THPR* fuzzy set, the *THST* fuzzy set is corrected originating the *THST** fuzzy set:

$$THST^{*}(th) = THST(th) \otimes THPR(th) \qquad \textbf{[x]}$$

where the symbol ⊗ represents an intersection operator. The *THST** fuzzy set corresponds to factor 3 of the table 1.

When preparing a specific mission the necessary function lines to the mission execution have to be considered. This question is especially pertinent in ships of modular construction, which are reconfigurable. Among all possible function lines the ones corresponding to a particular configuration should be selected. Even for ships with a fixed architecture, i.e., the ones not easily reconfigurable, it may be advantageous to identify the function lines, relevant to the mission to perform. Other possibility is that a function line is no longer useful due to the consumption of all resources vital to its functioning, e.g., all missiles of a certain type have been fired. This function lines pre-selection can accelerate the decision support process, since the dimension of the problem is reduced and the evaluation actions process only considers adequate resources. On other hand, since the subsystems may integrate different function lines with different utility degrees, the action of selecting useful lines prevents the contamination of the decision process by factors that, since they are not applicable, distort the evaluation. Consider, for instance, the evaluation, based in linguistic terms, of the utility of different subsystems in the *FLSS* fuzzy relation, as shown in Table 2.

Table 2 - Example of a *FLSS* relation, expressed as linguistic terms

Utility		Subsystems			
		ss_1	ss_2	ss_3	…
Function Lines	fl_1	Fund	Desir	Fund	…
	fl_2	Impt	Fund	Fund	…
	fl_3	Desir	Desir	Fund	…

Obs.: Desir = Desirable; Impt = Important; Fund = Fundamental

Suppose, firstly, that all function lines are necessary (with equal degree of importance). The overall utility evaluation of the three subsystems leads to the conclusion that all the subsystems are *fundamental* to the system, at least, for one of the function lines. Notice that this evaluation may remain unchanged or become substantially altered if some function lines are deemed as not necessary. Eliminating line fl_3 produces no change in the evaluation. If by some reason line fl_1 is no longer required the subsystem ss_1 reduces its utility to the grade *important*. If line fl_2 is rejected the subsystem ss_2 is rated just as *desirable*. Subsystem ss_3 presents always the same utility, independent of which function lines are selected.

The function line rejection/pre-selection is performed using the *FLSEL* crisp set [ii]. Assigning value 0 rejects a line and 1 selects it.

In the model, the *FLTH* relation **[i],** the *FLSEL* **[ii]** crisp set and the *THST** **[**x**]** fuzzy set characterize the operational scenario, for the repair priorities evaluation process. These data is then aggregated to generate a unique fuzzy set (*FLUT**) [xiii] that represents function lines weighted utility, considering actual threat situation, command priorities and mission.

This process is performed in three steps:

The first step, aggregates the *FLTH* fuzzy relation with the *THST** fuzzy set originating the *FLTH** fuzzy relation. This fuzzy relation incorporates actual threats status into the relation between function lines and threats and is defined as:

$$FLTH^*(fl,th) = FLTH(fl,th) \otimes THST^*(th) \quad \textbf{[xi]}$$

The second step consists of reducing the *FLTH** fuzzy relation into a *FLUT* fuzzy set, which represents the maximum utility of each function line, in accordance with the operational scenario considered. This operation is achieved by performing an "OR" operation, by rows of the *FLTH** fuzzy relation, to determine the importance of the function lines. This intermediate fuzzy set is:

$$FLUT(fl) = \bigvee_{th=1}^{n} \mu_{FLTH^*}(fl,th) \quad \text{for all } fl\,\textbf{[xii]}$$

where n represents the maximum number of threats considered and the operator $\vee$ represents the fuzzy union operation.

In the third step, the *FLUT* fuzzy set is combined with the *FLSEL* crisp set, originating the *FLUT** fuzzy set, which represents the maximum utility to the system of the selected function lines, taking into account ship's mission. This fuzzy set is defined as:

$$FLUT^*(fl) = FLUT(fl) \otimes FLSEL(fl) \qquad \textbf{[xiii]}$$

In order to proceed the rating process we have to consider now the technical factors. First the system function lines composition is analyzed to select the subsystems that will integrate them. In this selection process, the subsystems are chosen according to technical and operational criteria. Obviously, subsystems that are totally inadequate to perform required functions are rejected. For instance, it is not adequate to use radars to detect a submerged submarine; thus radar subsystems are rejected.

After subsystem selection, the next step is to analyze the measure in which subsystems satisfy the requirements of macro-functions. According to its attributes the subsystems are classified from more preferable to less preferable. For instance, a navigation radar that does not have enough accuracy, range and ideal processing capabilities, is less preferable as the main surface sensor of a combat system. In this context the navigation radar can be considered an alternative to the "sensor" resource of the function line, but its degree of preference/importance/ utility is very small.

Hence a fuzzy relation (*FLSS*) [v] is defined between function lines and subsystems sets, where a utility degree is represented by assigning importances/weights, in the interval [0,1]. A weight 0 means the subsystem was not selected to a function line. A weight 1 indicates total adequacy, maximum preference and/or indispensability.

By the aggregation of the function line maximum utility (*FLUT**) [xiii] with the fuzzy relation representing subsystems utility degree in the function lines (*FLSS*) **[**v**]**, the weighted utility degree of subsystems to function lines is obtained. This relation expresses the relative importance of the function lines considering the actual operational scenario. This fuzzy relation, named *FLSS*,* is defined as:

$$FLSS^*(fl,ss) = FLSS(fl,ss) \otimes FLUT^*(fl) \qquad \textbf{[xiv]}$$

Now it is performed the reduction of the *FLSS** fuzzy relation to obtain the *SSUT* fuzzy set, which represents the maximum utility of each subsystem considering the selected function lines and the processed operational scenario. This process is identical to the one used in the computation of the *FLUT* fuzzy set, i.e., the fuzzy OR operation is used. However, the operation that originates the *SSUT* fuzzy set is performed by columns of the *FLSS** fuzzy relation. The new fuzzy set is defined as:

$$SSUT(ss) = \bigvee_{fl=1}^{m} \mu_{FLSS^*}(fl,ss) \quad \text{for all } ss\,[\mathbf{xv}]$$

where *m* represents the maximum number of function lines existing in the system.

After determining the *SSUT* the subsystem utility evaluation is performed. We recall that our final goal is to evaluate equipment utility. This intermediate evaluation is based on the principle that the wordiness of one equipment depends on the utility of the subsystem where it is integrated. Thus, since subsystems incorporate several equipments, the dimension of the problem is reduced and the computations, with lesser data, are quicker.

In order to get to equipments level it is necessary to consider the utility degree of each equipment considered in the set of subsystems, which were identified. Naturally, there are equipments that have no utility to a certain subsystem, since they belong to another subsystem, hence its utility degree will be quantified as 0. An equipment, which is vital to perform the function of subsystem, receives a utility degree of 1. Equipment with intermediate utility degrees will be quantified in the interval [0,1]. A fuzzy relation is then defined between subsystems and equipments sets, which is designated by *SSEQ* [vi].

By aggregating this *SSEQ* relation with the *SSUT* fuzzy set a new *SSEQ** fuzzy relation is obtained that incorporates the utility degree, for the different subsystems, and is defined as:

$$SSEQ^*\,(ss,eq) = SSEQ\,(ss,eq) \otimes SSUT\,(ss) \qquad \textbf{[xvi]}$$

A reduction of the *SSEQ** fuzzy relation to an *EQUT* fuzzy set is the next step. This fuzzy set represents the maximum utility of each equipment onboard, considering the selected function lines and the operational scenario, which was processed. This process is achieved with the OR operator. The operation is performed by columns of the *SSEQ** fuzzy relation and is defined as:

$$EQUT(eq) = \bigvee_{ss=1}^{k} \mu_{SSEQ^*}(ss,eq) \quad \text{for all } eq\,[\mathbf{xvii}]$$

where *k* represents the maximum number of subsystems existent in the system.

As mentioned, the data contained in this fuzzy set represents the evaluation of the maximum utility of each equipment onboard. However, in the same way that a system may not have all the function lines available, a subsystem may also not have all the equipments available. Several occurrences can be considered in this situation. The first relates with the eventual modularity of a subsystem, which can contain different equipment configurations. The second, perhaps the most concerning in battle situations, is one where the equipment is considered irrecoverable because of some incident, either by spare shortage or due to damage extension which exceeds onboard repair capabilities. Another possible situation to account for is apparently faulty equipment, which, in reality, is being affected by an exogenous cause, e.g., non-existence of power supply.

The model supplies decision support exclusively to equipment internal faults considered recoverable, thus the decision-maker will just focus in the set of alternatives that deserve consideration.

The selection of equipment considered recoverable is performed by the *EQSEL* crisp set [vii], which assigns value 0 to equipments to reject and 1 to equipments to select.

After this a *EQUT** fuzzy set is obtained that represents the maximum utility of equipment considered recoverable, pertaining to the subsystems of selected function lines, taking into account the ship's mission, scenario characteristics, threat status and command priorities. This fuzzy set is defined as:

$$EQUT^*(eq) = EQUT(eq) \otimes EQSEL(eq) \qquad \textbf{[xviii]}$$

The last factor to consider is the actual equipment status (*EQST*) [viii]. This factor determines the quantity of equipment under appreciation and, how serious their faults are.

The equipment degradation level is represented as a weight, in the interval [0,1], which represents the respective degree of inoperativity. The value 0 means equipment operative and the value 1 equipment totally inoperative.

The aggregation of the *EQUT** and the *EQST* fuzzy sets originates a *EQEV* fuzzy set, which corresponds to the final evaluation of the faulty equipment set, which is considered recoverable, weighted by all the factors previously described.

A summary of the formalization used is listed in Table 3 and the evaluation process is depicted graphically in Figure 4.

Table 3 - Formalization summary of factors considered in the evaluation of priorities

Formalization of the factors to the evaluation of the priorities	
$FLTH(fl,th) = \{((fl,th),\mu(fl,th)) \mid (fl,th) \in FL{\times}TH\}$	**[i]**
$FLSEL\,(fl) = \{\,\mu_{FLSEL}(fl) \in \{0,1\} \mid fl \in FL\}$	**[ii]**
$THST\,(th) = \{\,\mu_{THST}(th) \mid th \in TH\}$	**[iii]**
$THPR\,(th) = \{\,\mu_{THPR}(th) \mid th \in TH\}$	**[iv]**
$FLSS\,(fl,ss) = \{((fl,ss)\,,\,\mu(fl,ss)) \mid (fl,ss) \in FL \times SS\}$	**[v]**
$SSEQ\,(ss,eq) = \{((ss,eq),\mu(ss,eq)) \mid (ss,eq) \in SS \times EQ\}$	**[vi]**
$EQSEL\,(eq) = \{\,\mu_{EQSEL}(eq) \in \{0,1\} \mid eq \in EQ\}$	**[vii]**
$EQST\,(eq) = \{\,\mu_{EQST}(eq) \mid eq \in EQ\}$	**[viii]**
$EQEV\,(eq) = EQUT^{*}(eq) \otimes EQST\,(eq)$	**[ix]**
$THST^{*}\,(th) = THST\,(th) \otimes THPR\,(th)$	**[x]**
$FLTH^{*}(fl,th) = FLTH(fl,th) \otimes THST^{*}\,(th)$	**[xi]**
$FLUT(fl) = \bigvee_{th=1}^{n} \mu_{FLTH^{*}}(fl,th) \quad \text{for all } fl$	**[xii]**
$FLUT^{*}(fl) = FLUT(fl) \otimes FLSEL\,(fl)$	**[xiii]**
$FLSS^{*}(fl,ss) = FLSS(fl,ss) \otimes FLUT^{*}\,(fl)$	**[xiv]**
$SSUT(ss) = \bigvee_{fl=1}^{m} \mu_{FLSS^{*}}(fl,ss) \quad \text{for all } ss$	**[xv]**
$SSEQ^{*}\,(ss,eq) = SSEQ\,(ss,eq) \otimes SSUT\,(ss)$	**[xvi]**
$EQUT(eq) = \bigvee_{ss=1}^{k} \mu_{SSEQ^{*}}(ss,eq) \quad \text{for all } eq$	**[xvii]**
$EQUT^{*}(eq) = EQUT(eq) \otimes EQSEL\,(eq)$	**[xviii]**

Obs.: *th* = threat; *TH* = set of threats;
fl = function line; *FL* = set of function lines;
eq = equipment; *EQ* = set of equipments;
ss = subsystem; *SS* = set of subsystems;

$\otimes$ symbol represents a intersection operator

$\vee$ symbol represents the OR operator

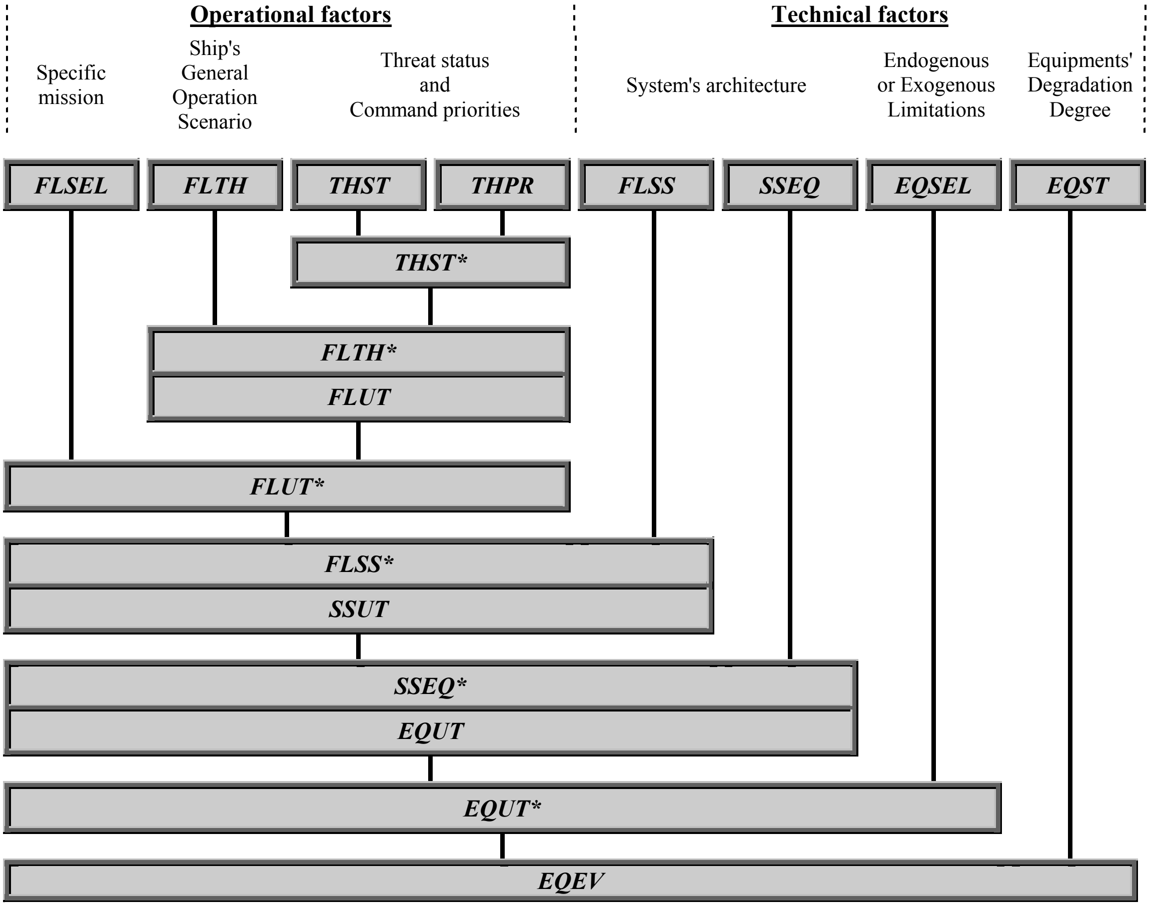


Figure 4 - Evaluation process scheme for repair priorities

Concluding, the data and the operations used in the decision-making rating process has two different purposes. Attributes [i] to [vii] and intermediate results of operations [x] to [xviii] are used for the initialization and control of the decision support process. Element [viii] is the real world status based on what decisions are to be taken, i.e., the input controlled by the remaining elements, that will produce the output [ix]. In this model the data used for initialization and control can be either technical or operational. However, since the input data refers to equipment working status, its character is essentially technical.

3.2.2 Ranking Process

The FDSS Ranking Component performs the hierarchization of the *EQEV* fuzzy set elements with a membership grade greater then 0. This ordered weighted utility list represents the first ranking criterion for the repair priorities of the equipment.

In order to introduce a supplementary discriminating capability, when there are equal priorities of equipment, a new criterion for ranking is used (Simões-Marques and Ribeiro [12]). The new criterion relates with the specialization of the subsystem to which the equipment belongs for some particular purpose. The principle used in the elicitation of this criterion is that, when two equipments are equally rated, the repair of an equipment which is very specific is usually more prioritary then the repair of an equipment of generic use.

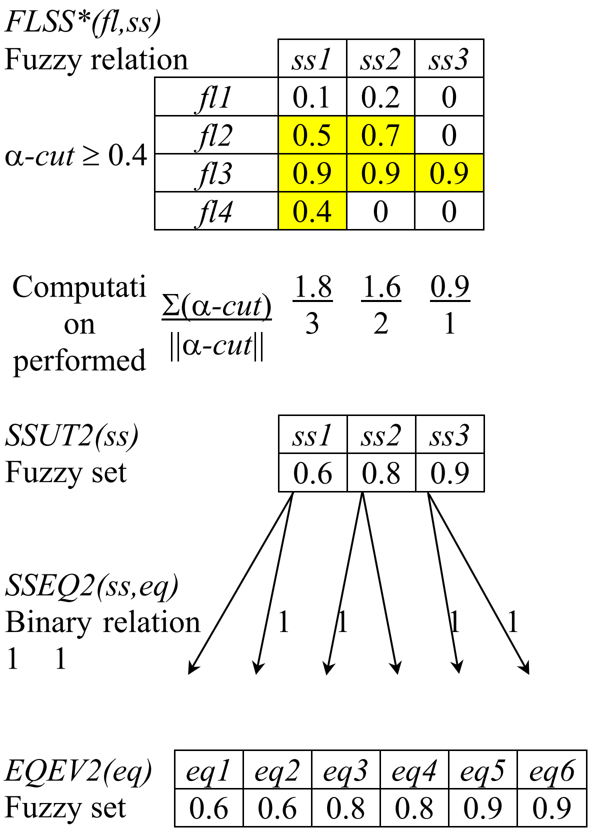
The second ranking defines the *EQEV2* fuzzy set, which evaluates the equipments' specific utility. The evaluation process starts using the *FLSS** fuzzy relation to obtain the subsystem specific utility (*SSUT2*) fuzzy set. In order to obtain the *SSUT2* an α-*cut* is defined to retrieve the most relevant elements in the *FLSS** and then the average is computed by dividing the summation of the relevant values, by the subset cardinality. The greater the computed average value is the greater the subsystem specificity is.

Second, in order to propagate the *SSUT2* to the equipment level, a binary crisp relation *SSEQ2* is used. This relation indicates if there is, or not, a relation between subsystem and equipment sets.

Third, the aggregation of the *SSEQ2* fuzzy relation with the *SSUT2* set originates the *SSEQ2** fuzzy relation. Fourth, the reduction of the *SSEQ2** fuzzy relation to an *EQEV2* fuzzy set is performed by columns, choosing the maximum value.

Figure 5 illustrates the *EQEV2* fuzzy set computation process assuming an α-*cut* of 0.4.

With the resulting *EQEV2* we achieved the final ranking for the specificity of equipment. Figure 6 illustrates an equipment repair priorities assignment proposal computed by the FDSS evaluation component. The values obtained with the first and second criteria are shown in the first two tables and the final prioritization of equipment repair is depicted in the last table. The *EQEV2* fuzzy set used is the same as in Figure 5.



FLSS(fl,ss)*
Fuzzy relation

α-*cut* ≥ 0.4

	ss1	*ss2*	*ss3*
fl1	0.1	0.2	0
fl2	0.5	0.7	0
fl3	0.9	0.9	0.9
fl4	0.4	0	0

Computation performed	$\frac{\Sigma(\alpha\text{-}cut)}{\|\alpha\text{-}cut\|}$	$\frac{1.8}{3}$	$\frac{1.6}{2}$	$\frac{0.9}{1}$

SSUT2(ss)
Fuzzy set

ss1	*ss2*	*ss3*
0.6	0.8	0.9

SSEQ2(ss,eq)
Binary relation

EQEV2(eq)
Fuzzy set

eq1	*eq2*	*eq3*	*eq4*	*eq5*	*eq6*
0.6	0.6	0.8	0.8	0.9	0.9

Figure 5 - Example of *EQEV2(eq)* fuzzy set computation process

	1st Ranking Criterion	**2nd Ranking Criterion**
	EQEV	*EQEV2*
eq1	0	0.6
eq2	0.7	0.6
eq3	0.5	0.8
eq4	0	0.8
eq5	0	0.9
eq6	0.7	0.9

	Priority Proposal
1st	***eq6***
2nd	***eq2***
3rd	***eq3***
4th	-
5th	-
6th	-

Figure 6 - Example of FDSS proposal for equipment repair priorities assignment

3.3 Model validation and Evaluation

Two types of scenarios were used for testing. First, stress situation scenarios were used, where the Equipment Status (*EQST*) corresponding to a situation of total inoperativity of all equipment and the results for several Threat Status combinations were evaluated in order to validate the

FDSS equipment ranking coherence. Second, known scenarios extensively trained onboard ships and for which the different solutions adopted by the decision-makers are also known, were used. The decision proposals obtained were compared with the solution considered optimal and detected deviations were analyzed and used as feedback to correct initial data in the knowledge and data bases.

From the data available until the moment it is possible to say that substantial gains, both in time and in decision quality, resulted from the employment of the proposed FDSS. The evaluation was performed with video recordings of basic combat exercises, in ships of the class. Detection, processing and decision times were measured. Very significant time reductions were found in the two last phases. Depending on the adopted architecture the reduction might:

- be exclusively centered in the processing and decision times internal of the WSB, in a single station configuration;
- be extensive to time consumed in the communication circuits (by voice) for information collection and order transmission, in a computer network configuration.

However, during the FDSS implementation and exploitation, some problems were detected, such as system survivability in combat situations (robustness), interface ergonomics aspects and an eventual tendency of the decision-maker to resign from his responsibility in the decision process.

Regarding the robustness of the FDSS, it is necessary to make it as independent as possible from ship supply, portable (to allow easy evacuation, in case of a near incident) and flexible (allowing alternative paths, in a network environment). If the working stations are portable computers, the two first requirements are met.

The ergonomic question is particularly sensible in the conception of the user's interface, because it is desirable the coexistence of different formats according to the decision-maker needs.

Finally, the decision-maker must be aware that the FDSS purpose is to support him, not to replace him.

4. Conclusion

The FDSS discussed in this paper has two components, the Evaluation and the Ranking Component.

The Evaluation Component is responsible for the Rating Process of the FMADM methodology used. This process evaluates Operational and Technical factors in order to compute an Equipment Utility (*EQUT**) fuzzy set. This set is used as control in the final rating computation, where the Equipments Status (*EQST*) fuzzy set is the input data and Equipments Evaluation (*EQEV*) fuzzy set is the output data.

The Ranking Component is responsible for the Ranking Process of the FMADM methodology used. The Equipments Evaluation (*EQEV*) fuzzy set is the input data that produces a descending priority list of equipments to repair. In order to solve ambiguities resulting from equality of importance grade, at the end of the rating process, a second evaluation process is computed based in an equipment specificity criterion. The resulting fuzzy set (*EQEV2*) is used as control data in the Ranking Process.

Figure 7 presents a schematic diagram of the complete rating and ranking process.

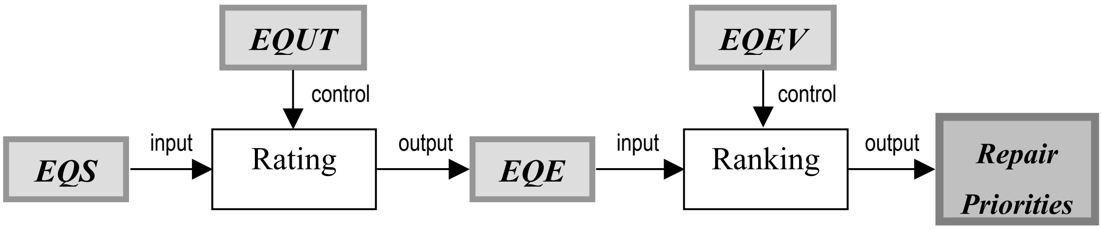


Figure 7 – The complete model schematic diagram

As shown is this paper, the model application in the military domain is rather appropriate to the management of repair priorities of equipments, under battle conditions.

The developed FDSS is to be used, under battle situation, in the Portuguese Navy "Vasco da Gama" class frigates in the management of equipments repair priorities, whose maintenance responsibility is assigned to the Weapons Engineering Department.

The model validation showed that the fuzzy multiple attibute decision making (FMADM) method adopted is adequate for this type of problems.

The model evaluation indicates that the fuzzy decision support system (FDSS) provides high control over the dynamic parameters, together with the possibility of supplying reliable proposals, in a short period of time. The next step of this project is the final implementation in a single station user.

Finally, let us say a word about the evolution of the model in the near future. There is work already undergoing to incorporate a human resources management component. This component will assign the technicians to repair the equipment ranked by the current version. The method to be used is also the FMADM, where attributes are, for example, technicians ability and proximity degrees to perform the maintenance of a faulty equipment.

Glossary

eq	Equipment
EQ	Equipments set
EQEV	EQuipment EValuation fuzzy set
EQEV2	2nd criterion EQuipment EValuation fuzzy set
EQSEL	EQuipments SELection crisp set
EQST	EQuipment STatus fuzzy set
EQUT*	Aggregated EQuipment UTility fuzzy set
FDSS	Fuzzy Decision Support System
fl	Function Line
FL	Function Lines set
FLSEL	Function Line SELection crisp set
FLSS	Function Line to SubSystem fuzzy relation
FLTH	Function Line to THreat fuzzy relation
FMADM	Fuzzy Multiple Attribute Decision Making
FMODM	Fuzzy Multiple Objective Decision Making
N.R.P.	Navio da República Portuguesa (Portuguese Republic Ship)
SEWACO	SEnsor and WeApon COmmand and Control System
ss	subsystem
SS	Subsystems set
SSEQ	SubSystem to EQuipment fuzzy relation
th	threat
TH	Threats set
THPR	THreat PRiority fuzzy set
THST	THreat STatus fuzzy set
WSB	Weapons Section Base
WED	Weapons Engineering Department

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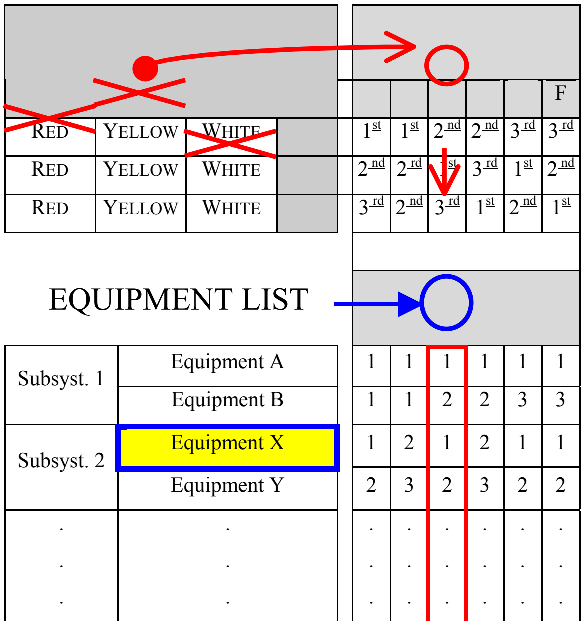


Figure 1 – Example of the actual manual process using a decision table

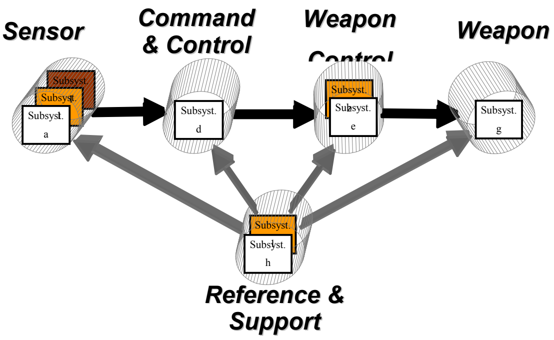


Figure 2 –Resources sequence needed to the function line of a weapon

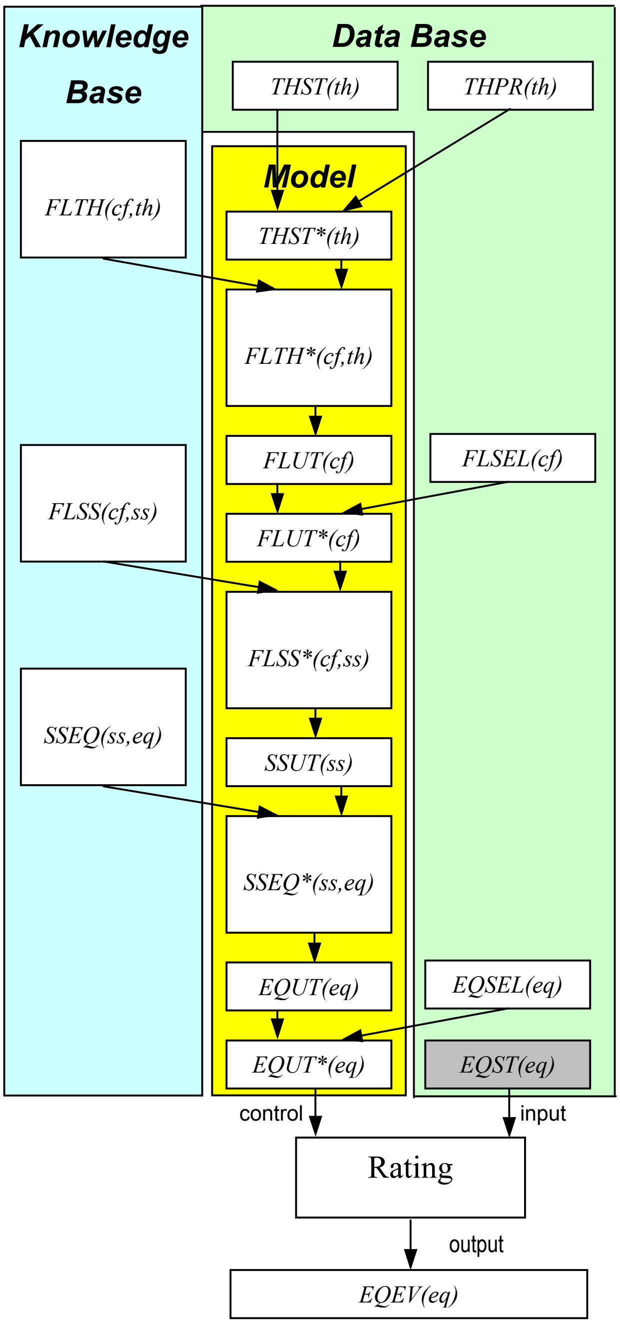


Figure 3 - The Data and Knowledge Bases of the FDSS

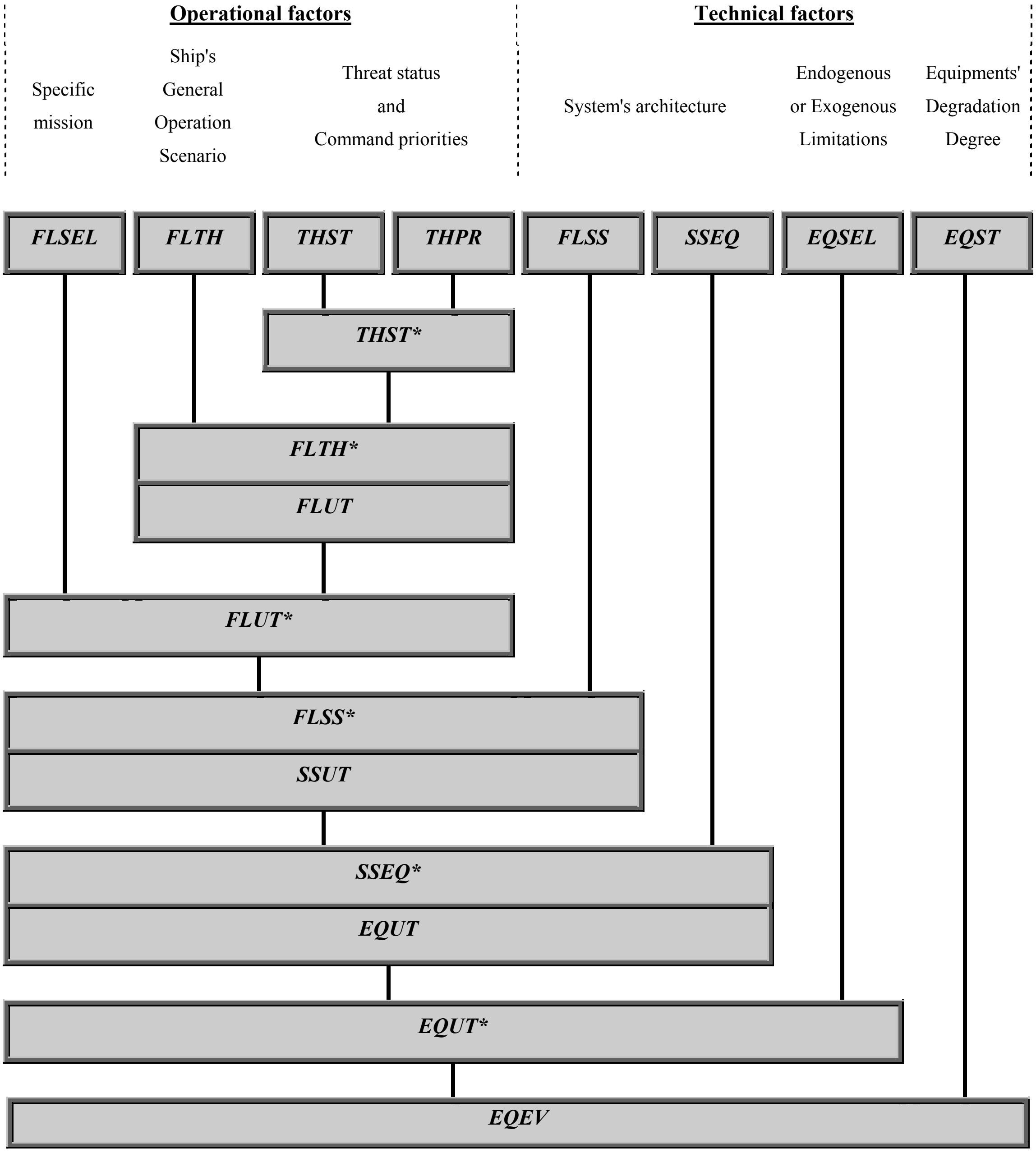
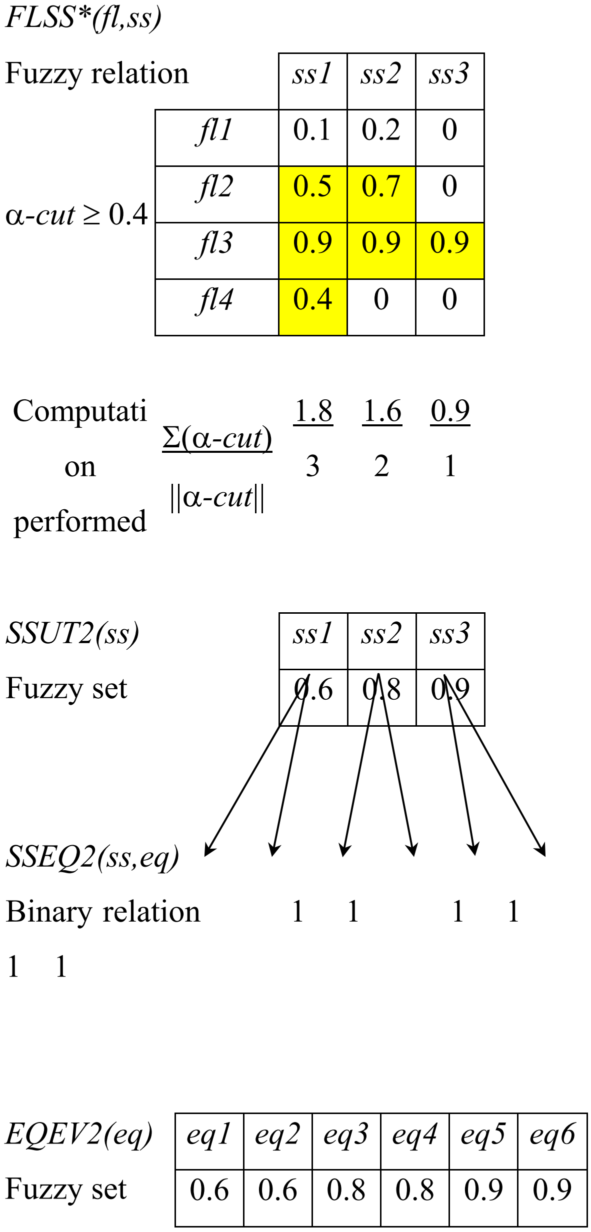


Figure 4 - Evaluation process scheme for repair priorities

Figures and Tables



FLSS(fl,ss)*

Fuzzy relation

α-*cut* ≥ 0.4

	ss1	*ss2*	*ss3*
fl1	0.1	0.2	0
fl2	0.5	0.7	0
fl3	0.9	0.9	0.9
fl4	0.4	0	0

Computation performed $\frac{\Sigma(\alpha\text{-}cut)}{\|\alpha\text{-}cut\|}$ $\frac{1.8}{3}$ $\frac{1.6}{2}$ $\frac{0.9}{1}$

SSUT2(ss)

Fuzzy set

ss1	*ss2*	*ss3*
0.6	0.8	0.9

SSEQ2(ss,eq)

Binary relation 1 1 1 1

1 1

EQEV2(eq)

Fuzzy set

eq1	*eq2*	*eq3*	*eq4*	*eq5*	*eq6*
0.6	0.6	0.8	0.8	0.9	0.9

Figure 5 - Example of *EQEV2(eq)* fuzzy set computation process

	1st Ranking Criterion *EQEV*	**2nd Ranking Criterion** *EQEV2*
eq1	0	0.6
eq2	0.7	0.6

	Priority Proposal
1st	***eq6***
2nd	***eq2***

eq3	0.5	0.8	3rd	***eq3***
eq4	0	0.8	4th	-
eq5	0	0.9	5th	-
eq6	0.7	0.9	6th	-

Figure 6 - Example of FDSS proposal for equipment repair priorities assignment

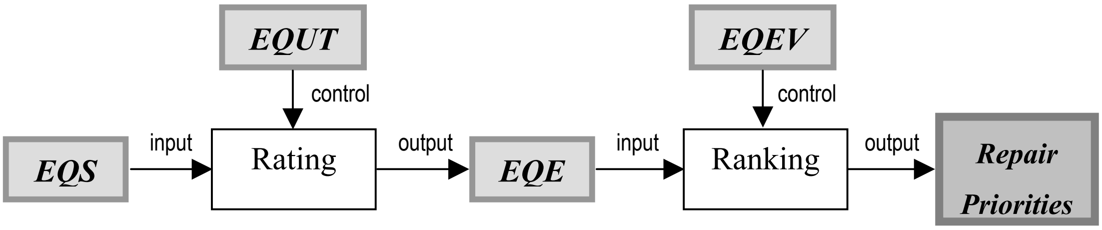


Figure 7 – The complete model schematic diagram

Table 1

Factors to consider in priorities evaluation		
Operational	*1.*	general scenario in which the ship is to operate, considering geographical factors and available *intelligence* about hostile platforms and weapons;
	2.	ship specific mission;
	3.	threats degree of presence and importance, established in accordance with command priorities;
Technical	*4.*	system's architecture, considering different functional areas and subsystem/ equipment interconnections, importance and existing redundancies;
	5.	logistic or technical limitations, endogenous or exogenous, which affect equipment employment or repair capability;
	6.	faulty equipment degradation level.

Table 2 - Example of a *FLSS* relation, expressed as linguistic terms

Utility		**Subsystems**			
		ss_1	ss_2	ss_3	…
Function Lines	fl_1	Fund	Desir	Fund	…
	fl_2	Impt	Fund	Fund	…
	fl_3	Desir	Desir	Fund	…

Obs.: Desir = Desirable;
Impt = Important;
Fund = Fundamental

Table 3 - Formalization summary of factors considered in the evaluation of priorities

Formalization of the factors to the evaluation of the priorities	
$FLTH(fl,th) = \{((fl,th),\mu(fl,th)) \mid (fl,th) \in FL \times TH\}$	**[i]**
$FLSEL\ (fl) = \{\ \mu_{FLSEL}(fl) \in \{0,1\} \mid fl \in FL\}$	**[ii]**
$THST\ (th) = \{\ \mu_{THST}(th) \mid th \in TH\}$	**[iii]**
$THPR\ (th) = \{\ \mu_{THPR}(th) \mid th \in TH\}$	**[iv]**
$FLSS\ (fl,ss) = \{((fl,ss)\ ,\ \mu(fl,ss)) \mid (fl,ss) \in FL \times SS\}$	**[v]**
$SSEQ\ (ss,eq) = \{((ss,eq),\mu(ss,eq)) \mid (ss,eq) \in SS \times EQ\}$	**[vi]**
$EQSEL\ (eq) = \{\ \mu_{EQSEL}(eq) \in \{0,1\} \mid eq \in EQ\}$	**[vii]**
$EQST\ (eq) = \{\ \mu_{EQST}(eq) \mid eq \in EQ\}$	**[viii]**
$EQEV\ (eq) = EQUT^{*}(\ eq) \otimes EQST\ (eq)$	**[ix]**
$THST^{*}\ (th) = THST\ (th) \otimes THPR\ (th)$	**[x]**
$FLTH^{*}(fl,th) = FLTH(fl,th) \otimes THST^{*}\ (th)$	**[xi]**
$FLUT(fl) = \bigvee_{th=1}^{n} \mu_{FLTH^{*}}(fl,th) \quad \text{for all } fl$	**[xii]**
$FLUT^{*}(fl) = FLUT(fl) \otimes FLSEL\ (fl)$	**[xiii]**
$FLSS^{*}(fl,ss) = FLSS(fl,ss) \otimes FLUT^{*}\ (fl)$	**[xiv]**
$SSUT(ss) = \bigvee_{fl=1}^{m} \mu_{FLSS^{*}}(fl,ss) \quad \text{for all } ss$	**[xv]**
$SSEQ^{*}\ (ss,eq) = SSEQ\ (ss,eq) \otimes SSUT\ (ss)$	**[xvi]**
$EQUT(eq) = \bigvee_{ss=1}^{k} \mu_{SSEQ^{*}}(ss,eq) \quad \text{for all } eq$	**[xvii]**
$EQUT^{*}(\ eq) = EQUT(eq) \otimes EQSEL\ (eq)$	**[xviii]**

Obs.: *th* = threat; *TH* = set of threats;
fl = function line; *FL* = set of function lines;
eq = equipment; *EQ* = set of equipments;
ss = subsystem; *SS* = set of subsystems;

$\otimes$ symbol represents a intersection operator

$\vee$ symbol represents the OR operator