

A Framework for Integrating Human Factors in the Early Stages of Ship Design: Application to the Mess Halls of a Surface Combatant

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The new F-110 frigates project is currently in the conceptual design and definition phase. General arrangement has to be defined; there are many demands and proposals of changes. One of them is the design of the most crowded areas, the mess halls. The aim of this article is to provide the Spanish Navy Staff with a decision tool that helps in determining the optimal distribution of the future F-110 mess halls. For this purpose, a new “analytical decision maker” model was designed providing advanced statistical methods and computer pedestrian simulations within multicriteria decision-making framework that allows optimizing conceptual designs. To reduce subjectivity, crew movement simulations and statistical methods were added to the multicriteria decision model, thus creating a less-subjective decision tool. A sensitivity analysis was conducted to check the robustness of results. An integrative decision and design approach are necessary for broad acceptance of human factors adoption within naval architecture design.

Keywords: multicriteria; statistical analysis; pedestrian modeling; mess hall; human factors & ergonomics; frigates

1. Introduction

1.1. Ship design and human factors

Ship design is a complex challenging process that requires the successful coordination of many different disciplines and that necessarily involves trade-offs between competing interests to achieve a balanced result. Hence, ship designers need to understand the complex interaction between different design drivers and their influence on the final solution, always being aware that the cost of rework may become drastically high if errors are found in the later stages of the design.

There are many project management methodologies used in ship design, although most of them identify two broad phases in the design process: basic design and detailed design. The former stage,

also known as conceptual design phase, determines the vessel’s principal dimensions and the power requirements that will satisfy the ship’s defined main purpose and its techno-economic prerequisites (Molland 2008). From those general requirements, the project progresses by defining increasingly detailed variables that are introduced and evaluated iteratively.

Conventionally, ship design follows an “outside-in” approach, where the compartments to be included are arranged after a hull form has been determined. Therefore, the initial or preliminary ship design is seen as the most crucial phase, as flaws in the ship design concept may result in a number of costly modifications or even in a complete redesign of the ship (Caprace & Rigo 2010). Thus, it has been reported that more than 70% of the cost implications are committed in the first design phase, although less than 5% of the expenditure is made during this first phase (Pawling et al. 2017).

The changes incorporated at the end of the design process of a ship are the main factor that contributes to the increase in the construction costs of the ship (Keane & Tibbitts 2013). Design

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reviews and collaboration with stakeholders using an integrated data environment have proven to be an effective means to reduce problems at the waterfront (Grogan & Borthen 2010).

The traditional ship design is based on the point-based design better known as ship design spiral (Evans 1959); the designer confronts different design drivers: payload, stability, seakeeping, speed, economy, etc. in a sequential and iterative manner until a single balanced design meets all requirements. As the number and complexity of cases increases, the set-based design (SBD) was adopted in the initial ship design. The SBD delays the detailed specifications until the trade-offs between design drivers are fully understood, allowing concurrent design effort, thanks to this system, work time can be saved with parallel working mode. The goal of the SBD is to get a global optimization design instead of a local optimization. The increasing complexity of naval ships has evolved the ship design process to a system design process (Tepper 2010). A new change was made by model-based system engineering (MBSE) in industry, first introduced by the Boeing Corporation. The MBSE key concepts are three-dimensional (3D) digital definition, the evolution from document-based to model-based approach, knowledge engineering integration, and process virtual simulation (ASME 2012). MBSE provides a formalized process for developing systems architecture and applies the modeling to support system requirements, design analysis, verification, and validation activities from the early stage of the ship design phase to the later life cycle phases (Estefan 2008).

In the early-stage design, the focus has been traditionally placed on ship powering, stability, strength, and seakeeping, with less importance given to the personnel who will eventually operate the ship (Andrews & Pawling 2008). In fact, designers do not always have direct interactions with end users or a deep understanding of their work demands, which frequently leads them to rely on their own experience to anticipate end user behaviors (Darses & Wolf 2006). Although it is well documented that there may be important differences between designer and end user perceptions for a given system (Hsu et al. 2000), and therefore the offered solution may not fulfill the expectations of the ship operators.

General arrangement (GA) drawings, which are defined through the conceptual design phase, illustrate the basic physical dimensions and the layout of a ship, including side and cross-sectional views of the different compartments, location and arrangement of bulkheads, superstructures, and major equipment affecting the structural design, the stability, and the performance of the vessel (Van Dokkum 2011). Generally, GA drawings do not include complete system details such as auxiliary equipment, piping, valve placement, or electrical structures, which may not be specified until the proper ship construction phase at a shipyard. Furthermore, GA drawings rarely provide a completely accurate representation of the constructed work environment because issues related to ship operations and evolutions are traditionally included as design constraints only when the broad form of the ship layout has been defined. This may cause important design inefficiencies and ultimately affect the crew operations and safety on board (Mallan et al. 2015).

Innovative methods and tools allow designing the ship layout mixing volumes and planes in any fashion managing ship subdivision constraints (e.g., bulkhead locations, required tank volumes, or deck areas.) during the design process (De Koningh et al. 2011).

In recent years, growing importance is being given to the role of the human element in shipping operations and the benefit of including human factors and ergonomics (HF&E) within the early

phases of the conventional ship design process (Rumawas & Asbjørnslett 2014). Thus, ship design has undergone a notable evolution toward a more holistic approach that integrates different areas of knowledge such as naval architecture, multidisciplinary engineering, or human factors and that uses advanced design tools such as multiphysics simulations throughout the entire ship project (Xuebin 2009). The need to raise informed awareness of the human element throughout the design process of a new-build ship has been recognized by the Maritime Safety Committee of the International Maritime Organization. It led to the publication of the key factors that contribute to facilitate the operational demands, increase personnel tasks efficiency, and minimize the occupational risks on board (International Maritime Organization 2006a, 2006b).

According to the International Organization for Standardization (ISO), the objectives of human-centered design (HCD) include enhancing the effectiveness, efficiency, and overall satisfaction for all users of a given system, while reducing the risk associated with inadequate usability, accessibility or user experience (International Organization for Standardization 2018). When applied to ship design, HCD typically refers to the following aspects or dimensions (Lloyd's Register 2009): habitability (qualities that determine whether a ship is suitable to live in), workability (qualities and conditions that facilitate the operation of the vessel), controllability (qualities that allow to operate the vessel with proper response and reliability), maintainability (qualities that facilitate the maintenance of the ship), maneuverability (ability of the ship to behave as intended under any weather and sea conditions), survivability (qualities that allow the crew to prevent hazards from developing further and to survive themselves, along with the proper vessel and cargo), occupational health and safety (conditions and qualities that guarantee a safe working environment), and system safety (capability for risk assessment and management).

Naturally, the design of a particular system or space distribution in a ship should evaluate different aspects included in one or more of the dimensions listed above. For instance, the design of common rooms such as accommodation spaces, galleys, mess rooms, recreational spaces, or cabins is principally influenced by aspects related to the habitability such as indoor comfort conditions or accessibility and also by factors associated with the survivability such as evacuation routes and firefighting facilities. The study of aspects related to design and survivability in warships is addressed by Jeong et al. (2018) and Boulougouris et al. (2017). Planning the layout of those kinds of areas in a ship is, therefore, a major challenge because there are considerable space restrictions while the mobility, security, and communication of the crew and passengers must be maximized. This is particularly relevant for warships, where the available space is very limited, the outfit density is elevated, and functions and capabilities demanded to the workforce are complex (Grant 2008; Keane et al. 2016). Thus, designing optimal layouts for common areas in warships that hold numerous staff with diverse duties on shift works is critical to achieve a good personnel flow, i.e., to provide safe, comfortable, and smooth people moving with minimum waiting times.

1.2. The room layout design process

In general, the room layout design process is based on the methodology described in ISO 11064 (International Organization for Standardization 2000), ISO 6385 (International Organization for

Standardization 2016), and ISO 9241-220 (International Organization for Standardization 2018). In addition, for military applications, it is common to follow the specific design criteria published by the U.S. Department of Defense (2012). In particular, the layout design process for naval rooms can be split into three overlapped and iterative phases with modifications to support the specific requirements, as described in the following paragraphs (McKay et al. 2013).

- 1) Analysis: it consists in collecting the data of operational conditions, intended functions, room size and features, manning concept, required equipment, ingress/egress requirements, and population anthropometric measures, among others. At this stage, high-level guidelines provide valid design criteria on areas such as communications, accessibility, safety, and security for warship room layouts.
- 2) Layout development: in this phase, design process guidelines provide a description of a room design process, tailored specifically for the naval context. This guidance is provided to allow designers to create a layout that meets the high-level guidelines described in the previous phase.
- 3) Layout evaluation and assessment: additional details on the process described in the previous phase are provided. Besides, plan and conduct tests are performed. An evaluator will assess whether the process described in the previous phase was followed appropriately and whether the developed layout meets the high-level guidelines.

1.3. The F-110 frigates project

The Spanish Navy currently have two different types of surface combatants in service: six units of the Santa Maria F-80 class (Fig. 1, up), which will fulfill their estimated operative life in 2022 after 35 years of service; and five units of the Álvaro de Bazán F-100 class (Fig. 1, down), the oldest of which counts on 14 years of service. Within the major Spanish Navy military program for the coming years, it is planned that the F-80 units are replaced by brand-new F-110 frigates during 2027. According to the programmed schedule, the order of execution of five frigates will be signed in 2018, being the first one laid down by 2020, launched by 2021 and operative during 2023 (Ministry of Defense 2017).

The new F-110 frigates are projected to be modern and complex weapon-equipped warships integrating advanced systems that help the Spanish Navy fulfill operational and strategic missions for the defense and security of the country and its allies. F-110 project is currently in the conceptual design phase, so the GA and final layout of the different rooms are yet to be defined (González-Cela et al. 2018). Principal parameters in conceptual design are: displacement of 6100 ton, overall length of 145.0 m, maximum beam of 18.6 m, depth to the main deck of 9.6 m, design draft of 4.9 m, maximum speed of 35 knots, and accommodation capacity of 187 crew. Both the main surface combatants of the Royal Norwegian Fridtjof Nansen-class frigates and the Royal Australian Navy Hobart Class air warfare destroyer derive from the Navantia F100 frigate. In February 2018, it was announced that a design based on the F100 class was selected as one of five finalists for the U.S. Navy's FFG(X) program.

1.4. Purpose and scope

The present study responds to a request made by the Spanish Navy regarding the layout development for the mess halls of the



Fig. 1 Frigate F-80 (up), Frigate F-100 (down) (www.armada.es)

future F-110 frigates, once the extrapolation of current F-100 mess halls design (Fig. 2) is discarded as an option for the new units. As mentioned earlier, it is crucial to consider human factors when addressing the optimal distribution of rooms in warships, particularly in the case of crowded common spaces such as mess halls. This requires the use of a human-centered framework, which supports the integration of the end users' perspective since the initial phases of the design process and enables the development of an optimal solution through the iterative evaluation of HF&E.



Fig. 2 Seamen's mess hall of a Spanish Navy vessel (www.armada.es)

Therefore, the primary objective of this work is to provide the High Staff of the Spanish Navy with an advanced design framework that helps in determining the optimal layout of the future F-110 mess halls between three layout alternatives that are currently under consideration. The work has been developed through the evaluation of multiple design criteria defined by experts in the field, considering, inter alia and human factors. This tool will be the result of integrating the analytic hierarchy process (AHP) and different computer pedestrian simulations within multiple criteria decision-making (MCDM) framework that seeks to reduce the subjectivity of the results. It is intended that the developed tool can serve as a more general framework that facilitates the integration of human factors in ship design projects.

This article is structured as follows: first, the new “analytical decision maker” model is described in Section 2. Then, Section 3 summarizes the information to be evaluated in this study and represents the problem, which could be seen as the first stage in the room layout design process (see Section 1.2). The MCDM is approached, simulations of the three layout alternatives are performed, and we discuss the multicriteria analysis results. Finally, some conclusions are drawn in Section 4.

2. Methods

2.1. MCDM

The MCDM occurs when the decision maker intends to achieve multiple objectives, which are usually contradictory or antagonistic between them, by selecting a single alternative among a number of choices. There are different techniques available to address the MCDM problem, such as weighting methods, AHP, Elimination and Choice Expressing Reality (ELECTRE), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) among others. AHP has had a great theoretical and applied impact. In addition to being a well-known and easy-to-use MCDM method, the AHP stands out for its applicability and adaptability to various situations. Moreover, the AHP method enables to deal with complex problems and to encompass both qualitative and quantitative criteria. The nature of human-based criteria introduces inconsistencies, and expert’s preferences between two attributes may be swayed by personal experiences resulting in illogical comparative relationships. Comparing the AHP process with simpler decision processes has shown that AHP is surprisingly accurate, although not exact (Kerns 2011).

Researchers have been used widely in other Spanish Navy projects, working with experts’ subjective opinions and find it an appropriate method for prioritizing alternatives in the present work. Because of the fact that the AHP method is known and used in the Spanish Navy, the understanding and collaboration with the experts of the Navy are more expedite (Michaeli et al. 2014).

AHP provides a means of decomposing a problem into a hierarchy of subproblems, which can be more easily embraced and subjectively evaluated. Thus, the problem is divided into a hierarchy of goals, criteria (c_i), subcriteria (sc_{ij}), and alternatives (a_i) as shown in Fig. 3. Data are collected from experts or decision makers, in a pairwise comparison of alternatives, on a qualitative scale proposed by Saaty (1990).

AHP establishes an $n \times n$ pairwise comparison matrix $A = (a_{ij})$ where experts’ judgments are quantified. Judgments must be consistent, so it requires that if $a_{ij} = k$, then $a_{ji} = 1/k$. Also, $a_{ii} = 1$ in

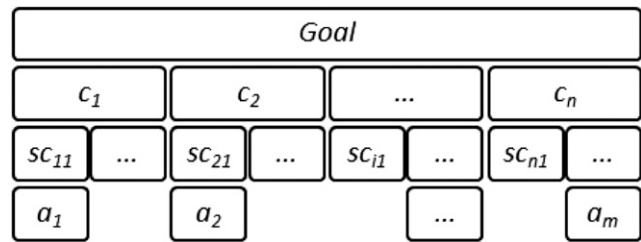


Fig. 3 AHP hierarchy

the diagonal elements of A . To rank the decision alternatives, determination of the relative weights is required. It can be determined by normalizing A into a new matrix $N = (w_{ij})$, where $w_{ij} = a_{ij}/\sum a_{ij}$. The relative weights are computed as the row average. Then, A is consistent if $A \cdot w = n \cdot w$. AHP computes the consistency ratio (CR) as $CR = CI/RI$, where CI is the consistency index of A and RI is the random consistency of A (Saaty 2012).

The general stages of the AHP method are usually the following.

- 1) Modeling: a hierarchical structure is constructed and all aspects considered relevant in the resolution process are represented: actors, scenarios, elements, and interdependencies. The goal to be achieved is placed at the top of the hierarchy. The problem of decision is to choose the alternative that best matches to the achievement of the goal placed at the top of the hierarchy.
- 2) Evaluation: in the second stage, the preferences and wishes of the actors are incorporated through the judgments included in the so-called square matrices of comparison by pairs. The objective of this stage is to create a vector of priorities that evaluates the relative importance that the decision unit gives to each criterion. The decision maker must determine the priorities by comparison in pairs and, thus, determine the relative weights of the criteria. A qualitative assessment of the importance of the criterion must be made and then go to a scale, previously established, to obtain the numerical values that correspond to its assessment. To determine the weight vector, the eigenvector theory is used by finding the Perron–Frobenius eigenvector (Brunelli 2015), which corresponds to the maximum eigenvalue of the pairwise comparison matrix, $A \cdot w = \lambda_{\max} \cdot w$. The weights of the criteria and subcriteria were provided by a survey conducted with Navy experts and by using utility functions. Using the defined scale, the experts evaluated the relative importance of the criteria and subcriteria in the pairwise comparison matrices.
- 3) Prioritization and synthesis: this stage provides the different priorities considered in the resolution of the problem. It is carried out once the priority vectors of all the alternatives have been obtained with respect to each criterion (or subcriterion). What is sought is to obtain the vector of preferences of each alternative with respect to the criteria. This procedure is repeated for each criterion.
- 4) Sensitivity analysis: the degree of sensitivity is assessed from the result obtained in a decision by making changes in the priorities of the main criteria of a problem.

A change in the priority of a certain criterion is carried out, keeping the proportions of the priorities of the other criteria, so that all of them, including the changed criterion, once modified, will go

on adding the unit. This analysis consists of making changes in the value of weight and watching, numerically and graphically, how this change affects the rest of the weights in the problem and the prioritization of alternatives.

To implement the AHP methodology a custom software tool developed for the Spanish Navy has been used: ADLA, the acronym of Action Lines Decision Aid.

2.2. New decision-making support model

The new “analytical decision maker” model proposed in this work is based on a hierarchical structure of evaluation criteria developed by a team of experts in the same way as the traditional AHP approach. However, it goes a step further in reducing subjectivity by including advanced statistical methods and simulations to support the final decision.

This new methodology is outlined in Fig. 4 and can be summarized as follows.

- 1) Step 1: it consists of the accurate understanding and definition of the problem. The project manager and the Navy expert’s team detail the requirements of the mess halls’ layout, and foremost, important and critical evaluation criteria. All aspects considered relevant in the decision process must be considered.
- 2) Step 2: a hierarchical structure of evaluation criteria with weightings is modeled in collaboration with the Navy experts working individually.
- 3) Step 3: a statistical design of experiments (DOE) and computer simulations are performed to investigate the response of the different layout alternatives to subcriteria involving human factors. This step is introduced with the aim of providing objectivity to the decision-making process.
- 4) Step 4: a multicriteria analysis, named “subjective analysis,” is performed using the AHP methodology, and pairwise comparison matrices are evaluated according to the subjective judgments of the experts. Weights are

assigned to the criteria established in step 1, and possible alternatives are prioritized.

5) Step 5: a sensitivity analysis is performed, which determines the decision robustness.

6) Step 6: decision. Afterward, data obtained in the simulation have been incorporated to a new improved multicriteria decision problem.

2.3. Simulation of mess halls

This section describes the two types of simulations performed in the third step of the methodology presented. The first simulation assesses the evacuation of the mess halls because of a clear for action (CA) situation, in which the crew have to stop what they are doing and immediately go to their CA combat station. The other simulation consists of studying several possible scenarios in which lunch is prepared.

Different modeling methods were considered for this study; among them is the analytical queuing theory, which is effective for this kind of analysis but only when relations of service providers and recipients are static like bank counters (Tanizaki & Shimura 2016). However, most modern simulators use the following methods: system dynamics, discrete event, and agent-based modeling, covering each method a specific range of abstraction level. System dynamics assumes very high abstraction, and it is typically used for strategic modeling. Discrete event modeling supports medium and medium-low abstraction, whereas agent-based models use medium-high or high abstraction. Agent-based modeling is a relatively new method compared with system dynamics and discrete event modeling. In fact, it was largely an academic topic until simulation practitioners began using it some 15 years ago. Agents in an agent-based model may represent very diverse things: vehicles, units of equipment, projects, products, ideas, organizations, people in different roles, etc.

Pedestrian movement, a particular case of agent-based modeling is an important part of designing facilities such as shopping centers, airports, railway stations, stadiums, and lately, ships. These

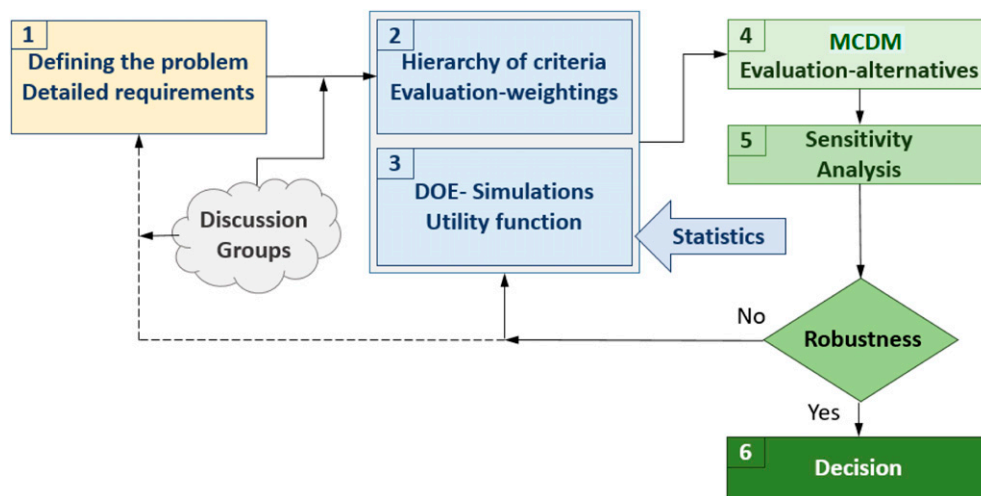


Fig. 4 New decision-making model

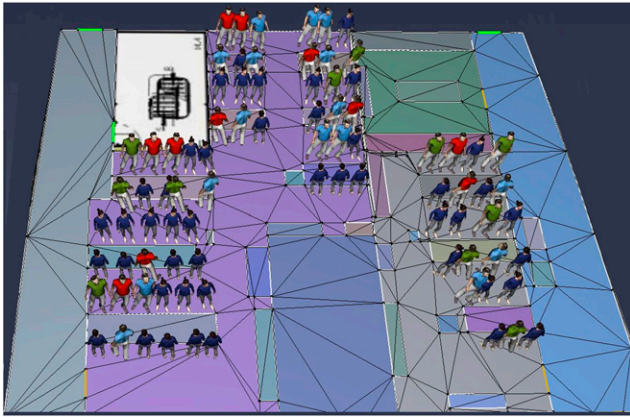


Fig. 5 Triangular mesh for evacuation paths in mess hall

analyses can help architects and engineers improve their designs, facilities owners review a potential change to a building, and civil authorities simulate possible evacuation routes. Because pedestrian flows can be complex, they require a full-blown simulation. Pedestrians follow basic rules that have been determined by detailed theoretical studies; they move at predetermined rates, they avoid physical spaces such as walls and other people, and they use information about the crowds that surround them to adjust their distance and speed. The results have been proven many times in field studies and customer applications (Borshchev 2013).

2.3.1. Simulation of CA evacuation. The pedestrian egress software Pathfinder, developed by Thunderhead Engineering (Thunderhead Engineering 2018), was chosen to carry out this simulation. This is an agent-based egress simulator that uses steering behaviors to model occupant motion. It provides two primary options for occupant motion: a Society of Fire Protection Engineers (SFPE) mode, which implements the concepts in the SFPE Handbook of Fire Protection Engineering (Nelson & Mowrer 2002), and a steering mode, which is based on the idea of inverse steering behaviors first introduced by Reynolds (1999) and later refined by Amor et al. (2003).

Pathfinder's steering mode allows more complex behavior to emerge naturally as a byproduct of the movement algorithms,

eliminating the need for explicit door queues and density calculations. Pathfinder uses a 3D geometric model. Within this geometric model is a navigation mesh defined as a continuous two-dimensional triangulated surface referred to as a "navigation mesh." Occupant motion takes place on this navigation mesh. The navigation mesh is an irregular one-sided surface represented by adjacent triangles. In Pathfinder, obstructions are implicitly represented as gaps in the navigation mesh because occupants can only travel on this mesh, as shown in Fig. 5. The navigation geometry is organized into rooms of irregular shape, whose boundaries cannot be crossed by any occupant. Thus, the travel between two adjacent rooms occurs through doors which are represented as green blocks. A door, which does not connect two rooms and is defined on the exterior boundary of a room, represents an exit door.

Each occupant has a proper behavior assigned in the user interface. Such behavior dictates a sequence of goals (go to exit, go to room, go to waypoint, wait, etc.) that the occupant must achieve in the simulation. When occupants have a destination to seek, they need a plan on how to reach it, a path to follow, and a way to follow the path while dealing with dynamic obstacles along the path, such as other occupants. The path is calculated as a sum of local targets, which take into account a multicriteria cost function, occupant preferences, and priorities assigned by the user. Pathfinder uses the A star search algorithm to create waypoints that form the path (Nilsson et al. 1968).

2.3.2. Pedestrian modeling of mess halls. Modeling F-110 mess halls is a complex task involving the reproduction of a self-service's process where seamen form a queue to wait for the meals, meals are served, and then seamen wait for a vacant seat and mutually adjust their distance and speed to the crowd. The modeling of this process must combine two simulation methods: pedestrian movement with a discrete event.

The AnyLogic modeling software was chosen for this study because it is the unique simulation software tool that supports the three methods described earlier, allowing simulation of crew flow and service times for the three mess halls' layout alternatives considered. It permits creation of metrics such as the total travel time between specified points and vary the experiments to highlight these metrics during times of peak congestion. Furthermore, it allows importing background layouts, floor plans, and maps and creation of multiple 3D views that facilitate the understanding of the pedestrian flow (Borshchev 2013).



Fig. 6 Alternatives layout: 4 (left), 5 (center), and 6 (right), green arrows: access doors

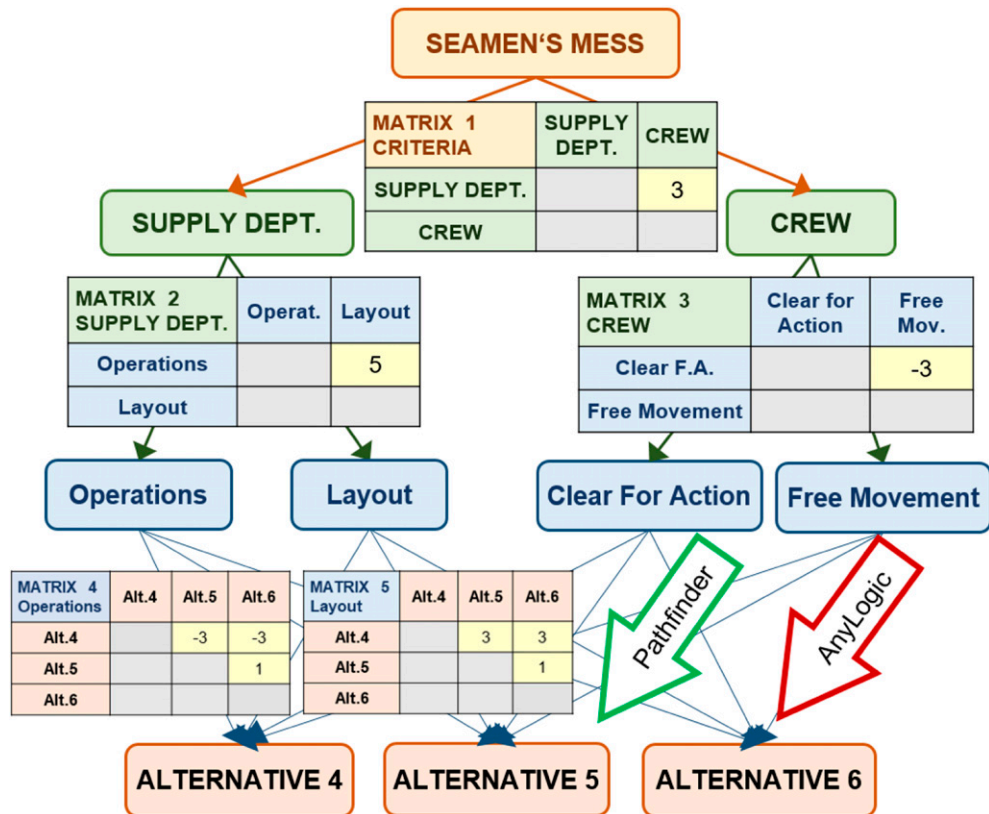


Fig. 7 Multicriteria matrices

3. Characterization of the multicriteria decision problem

3.1. Description of the layout alternatives

Three alternatives were selected among six considered initially, all of them are placed at the second deck.

- 1) Alternative 4 (Fig. 6, left): the seamen's mess hall (red outlined) has 62 seats, an area of 73 m² and only one entrance door (green arrow). It is adjacent to the Chief Petty Officers' (CPO) mess hall, the galley, the self-service, and



Fig. 8 Seamen mess hall CA simulation

the dishwasher room. Dairy storage space for provisions and the bakery are also at the second deck. The officers' mess hall is located at the upper deck, with a dumbwaiter (blue square) feeding meals from the kitchen to the second deck. There are one self-service bar and a tray store for each mess hall, so used trays can be left at them or at the dishwasher room service windows.

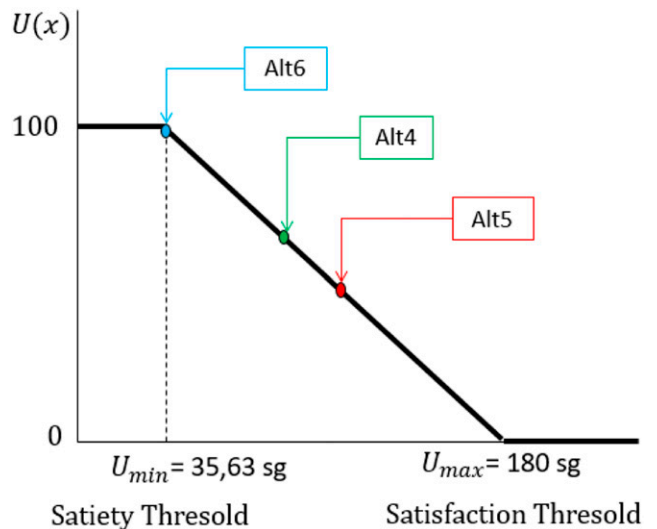


Fig. 9 CA subcriteria utility function

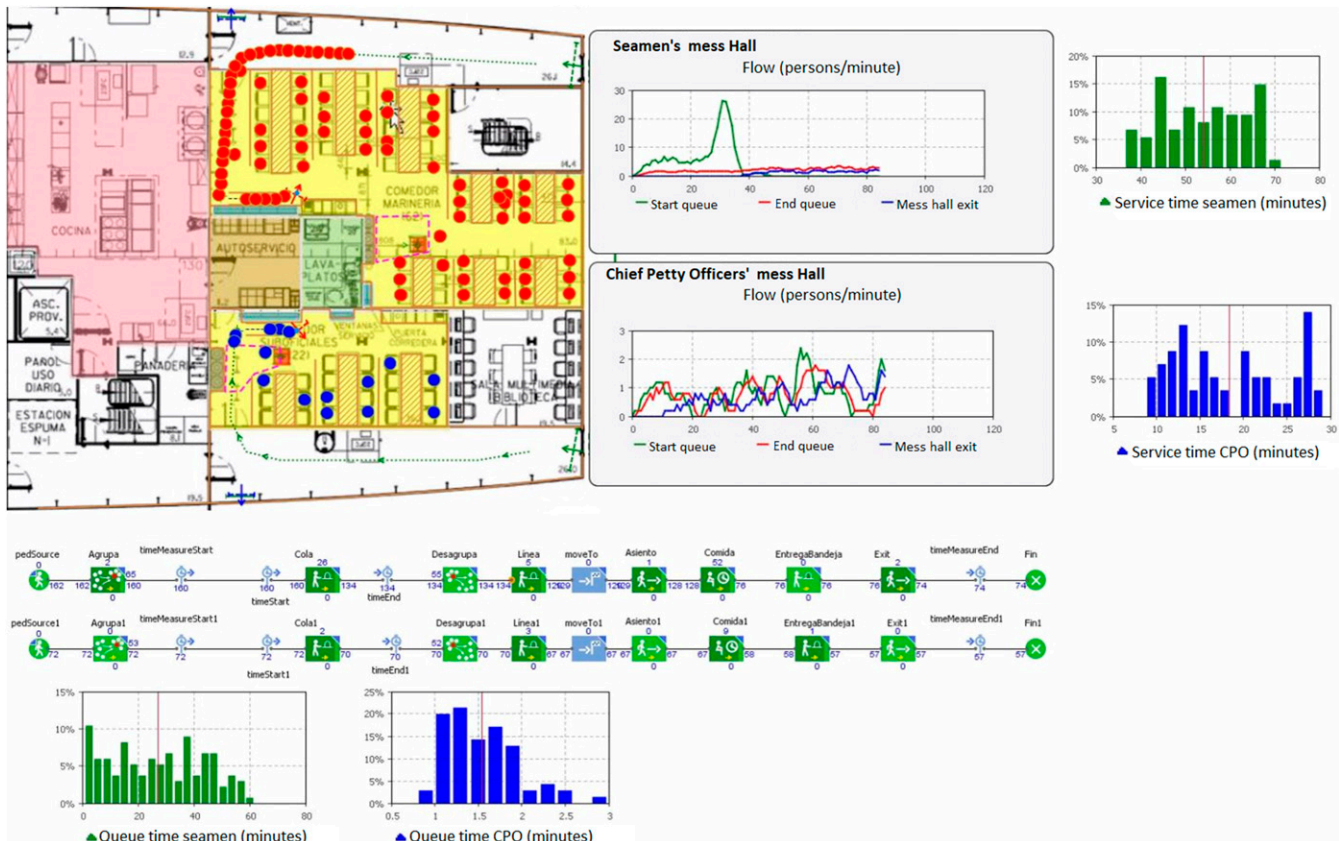


Fig. 10 AnyLogic simulation with 162 agents

- 2) Alternative 5 (Fig. 6, center): the seamen's mess hall (red outlined) has 64 seats, an area of 75 m² and only one entrance door through a stairway enclosure. It is adjacent to the CPO's mess hall, the galley (which includes the bakery), and the self-service. The officers' mess hall and the dishwasher room are also at the second deck. There is no dairy storage space for provisions. As in alternative 4, there are one self-service bar and a tray store for each mess hall, but in this case, used trays cannot be left in the dishwasher room because the tray store passes to the dishwasher room through the self-service room.
- 3) Alternative 6 (Fig. 6, right): the seamen's mess hall (red outlined) has 62 seats, an area of 68 m² and two entrance doors through a stairway enclosure. It is adjacent to the CPO's mess, the galley (which includes the bakery) and the self-service. The officers' mess hall and the dishwasher room are also at the second deck. There is no dairy storage space for provisions. As in alternative 5, there are one self-

service bar and a tray store for each mess hall, being possible to leave the used trays only at the tray store.

3.2. MCDM

3.2.1. Definition of the evaluation criteria. The optimal design of mess halls must answer the following questions raised by the Spanish Navy High Staff: Is the design well suited to allow a personnel flow movement during the meals? Does an average queue wait time can be estimated and reduced? Would the personnel flow movement be adequate if the crew increased by 18 members? How the kitchen, dishwasher, and mess halls layout must be organized?

The response given by each of the layout alternatives to the questions raised by the Spanish Navy were evaluated in follow-up meetings in conjunction with a team of three officers with broad experience in the management of kitchens and mess halls in similar warships. As a result, the multicriteria matrices shown in Fig. 7 and the matrices described in the following paragraphs were obtained.

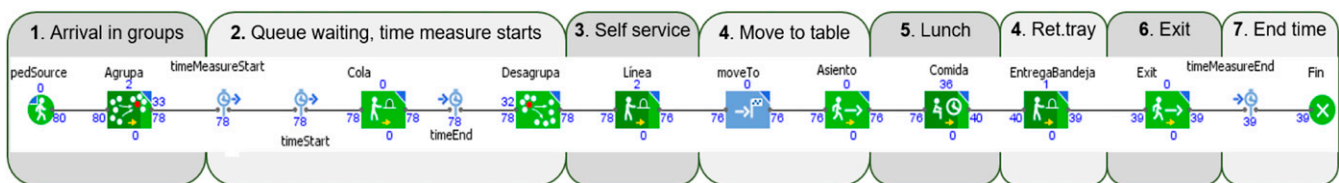


Fig. 11 Process flowchart of AnyLogic simulation

Table 1 Simulation with arrival rate scenarios

| | Rate 80 | | | Rate 160 | | | Rate 340 | | |
|---------------------------|---------|--------|--------|----------|--------|--------|----------|--------|--------|
| | Alt. 4 | Alt. 5 | Alt. 6 | Alt. 4 | Alt. 5 | Alt. 6 | Alt. 4 | Alt. 5 | Alt. 6 |
| Dining room occupied time | 125.00 | 125.30 | 125.70 | 125.00 | 124.80 | 124.00 | 120.00 | 123.60 | 122.20 |
| Time spent by agents | 48.94 | 50.68 | 49.40 | 64.73 | 64.89 | 64.82 | 70.98 | 70.43 | 70.64 |
| Waiting at queue time | 6.52 | 8.65 | 6.63 | 21.92 | 21.95 | 21.84 | 28.28 | 28.19 | 28.09 |
| Average speed | .562 | .556 | .557 | .548 | .548 | .527 | .522 | .507 | .467 |

Two main criteria with two subcriteria each were considered for the evaluation of the three layout alternatives described earlier. The first involves the supply department, i.e., the supply and cooking-related services. In particular, the following subcriteria were applied.

- 1) Operations—supply: issues related to food and meal movement, galley and bakery operation, self-service bars, and dishwasher
- 2) Layout: issues related with service of mess halls such as garbage collection and tray movement to the dishwasher, mess halls, and kitchen cleaning

The second criterion involves the crew, being related to seamen movement under the following situations.

- 1) CA: time to evacuate mess halls and take up posts
- 2) Free movement: queue time, mess halls' congestion, and time to leave mess halls

3.2.2. Subjective evaluation of alternatives. The criteria duty and crew involve one matrix, subcriteria with each criterion involve two matrices, and the three alternatives rating with operations, and layout subcriteria involve two matrices. CA and free movement involve two utility functions. Figure 7 shows the hierarchy of criteria and subcriteria applied in the AHP methodology.

A datasheet table with five subjective matrices (matrix 1 for criteria, matrices 2, 3, 4, and 5 for subcriteria) was drawn up and sent to the expert officers for filling according to the Saaty scale, which was simply restricted to odd numbers.

As Fig. 7 shows, matrices 4 and 5 evaluate alternatives with regard to subcriteria Operations and Layout. Alternatives 5 and 6 are preferred to alternative 4 with regard to subcriteria Operations, and alternative 4 is preferred with regard to Layout subcriteria.

Once the answers of experts were received, subjective opinions and consolidated matrices were ready; the two objective subcriteria

must be evaluated with simulation software: Pathfinder and AnyLogic.

4. Human factors into the decision-making process through simulations

As part of the methodology to add objectivity to the selection of the optimal mess hall layout, a study of the crew subcriteria (CA and free movement during lunchtime) has been performed through simulations. The following describes the principal considerations made for designing these simulations: time data collection at frigates and Landing Helicopter Dock (LHD), statistical processing, and utility functions design. These steps are a part of the methodology to add objectivity to the decision-making process and choose the better alternative.

4.1. CA simulation with Pathfinder

To evaluate the three layout alternatives with regard to CA evacuation subcriteria, a series of simulations were made with agent movement modeling software Pathfinder (see Section 2.3.1). This situation requires every crew member to occupy his or her position as soon as possible and the Commander must be informed about any fault. Simulations allow measuring the evacuation time of the seamen's mess hall fully occupied (as shown in Fig. 8), being a time interval of 3 minutes accepted as satisfactory.

The following variables were considered for simulating the CA evacuation.

- 1) Crew speed: uniform distribution between 2.04 m/sec and 2.17 m/sec. These values are based on real data measured at different Spanish Navy vessels, although they have been slightly altered for confidentiality reasons, which has a minor influence on the final results.

Table 2 Hypothesis test summary (ANOVA contrast)

| | Rate 80 | | Rate 160 | | Rate 340 | |
|---|---------|-----------------|----------|-------------------------|----------|-------------------------|
| | Sig. | Decision | Sig. | Decision Alt. 6 | Sig. | Decision |
| Mess hall occupied time is equal between alternatives | .91 | Null hypotheses | .90 | Null hypotheses | .24 | Null hypotheses |
| Time spent by agents is equal between alternatives | .54 | Null hypotheses | .98 | Null hypotheses | .78 | Null hypotheses |
| Waiting at queue is equal between alternatives | .34 | Null hypotheses | .99 | Null hypotheses | .91 | Null hypotheses |
| Average speeds are equal | .29 | Null hypotheses | .01 | Refused null hypotheses | .01 | Refused null hypotheses |

Sig., Significance level.

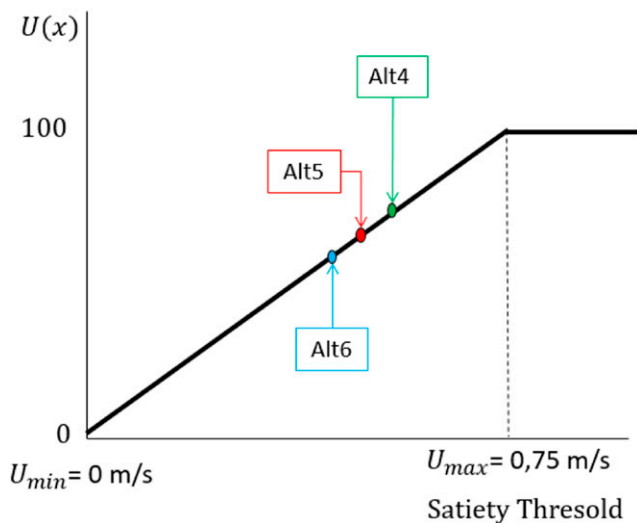


Fig. 12 Free movement subcriteria utility function

- 2) Door choice (only affects to Alternative 6): uniform distribution between 15% and 100%. An agent has endeavor to address toward the nearest door, if it has a queue (more than four agents per square meter), a random door choice allocation of 15% means that agent will address with 85% of probability to an alternative door.
- 3) Initial delay: uniform distribution between 1 and 5 sec. It represents the reaction time of agents when they hear the alarm. Delay or awareness time (A) in civil vessels is longer, it begins upon initial notification (e.g., alarm) of an emergency and ends when the passenger has accepted the situation and begins to move toward an assembly station (should be 10 minutes for the night time scenarios and 5 minutes for the day time scenarios) (International Maritime Organization 2007).

According to some studies on evacuation, a logarithmic distribution models the evacuation times but other studies consider normal distribution (Casadesus & Garriga-Garzón 2009). Usually, building evacuation experiments are simulated with a heterogeneous population (ages and mobility) so, evacuation times are longer and an asymmetrical distribution fits better. In civil vessels, the walking speed is given for a predefined demographic distribution of the passengers and crew population and is sampled from a uniform distribution with parameters taken from relevant studies into pedestrian dynamics (Galea 1998).

In this study, the crew knows very well the vessel and do regular training in evacuation procedures, so normal distribution is considered better to fit evacuation time.

As stated earlier, every crew member must occupy his position and Commander must be informed about any fault within 3 minutes. Figure 9 shows linear utility function $U(x)$, in which the maximum utility corresponds with the lowest egress time (Alt6 = 35.63 s), and the minimum utility corresponds to egress time greater than 180 s, that is unacceptable.

- 1) Egress time Alt. 4 = 63.79 seconds
- 2) Egress time Alt. 5 = 82.69 seconds
- 3) Egress time Alt. 6 = 35.63 seconds

4.2. Lunchtime simulation with AnyLogic

Simulations of seamen movements during their lunch in the mess hall were conducted with AnyLogic software (see Section 2.3.2.). Before the design and performance of these simulations, time data were collected during breakfast, lunch, and dinner of seamen in three warships: two F-100 frigates (“Blas de Lezo” and “Cristóbal Colón”) and the LHD “Juan Carlos I.”

Data collected were arrival hours and arrival rates of seamen to mess hall, meal service, table time, and finish-egress time. Based on the observed arrival rate patterns, it was decided to simulate three different scenarios that correspond with exponential distributions of the crew arrival:

- 1) The worst case in which all seamen arrive within the first 15 minutes (Exp. 340)
- 2) All the seamen arrive within the first 30 minutes (Exp. 160)
- 3) The crew arrive within the first 60 minutes (Exp. 80)

The line service time is the time elapsed during the choice and service of the meals. The goodness of fit to the Normal distribution of the line service times for breakfast, lunch, and dinner was tested. Only lunch times fitted to normal distribution (.69; .31). Simulations with three arrival date scenarios and lunch times collected were performed for the three mess halls: seamen, CPOs, and officers. All replications were carried out with the same assumptions. Because the crew work on alternating three shifts, two of three personnel plus 18 extra men were considered as shown in Fig. 10.

To perform an accurate mess halls modeling, all necessary stages to measure waiting and activity time must be identified. AnyLogic agent-based modeling provides a pedestrian library with blocks that model every real activity or delay. The simulation carried out includes the most relevant stages of the lunch process in the seamen mess hall, as illustrated by the flowchart represented in Fig. 11.

Table 3 Alternatives and multicriteria

| | | Supply department 75% | | | Crew 25% | | |
|--------|--------|-----------------------|-----------------------|-------------------|-----------|---------------|--------------------------|
| | | Total (%) | Operations 83.30% (%) | Layout 16.70% (%) | Total (%) | CA 25.00% (%) | Free movement 75.00% (%) |
| Alt. 4 | 25.01% | 21.92 | 14.29 | 60.00 | 34.29 | 32.47 | 34.89 |
| Alt. 5 | 37.34% | 39.04 | 42.86 | 20.00 | 32.22 | 27.19 | 33.89 |
| Alt. 6 | 37.66% | 39.04 | 42.86 | 20.00 | 33.50 | 40.34 | 31.22 |

Eight steps with 11 blocks and four-time measure points were modeled. Every block represents an operation, resource or process, the blue color being associated with discrete event modeling and the green color with pedestrian modeling. For example, the first block is PedSource and generates pedestrians. This flowchart can be explained as follows.

- 1) Arrival in groups: the crew arrive in small groups
- 2) Queue: the crew wait and takes an empty tray; a queue is formed and timing starts
- 3) Meal service: queue-timing end is registered; seamen choose the meal which is served on the tray
- 4) Move to the table: agents seek an empty place at the tables
- 5) Lunch: agents spend time (10–40 minutes) eating according to data registered at the warships
- 6) Return tray: after finishing lunch, agents carry the tray to the tray rack
- 7) Exit: agents leave the mess hall
- 8) End: finish time for each agent is registered

The sample size for each alternative and arrival rate scenario was set at 10. Statistical analysis was applied to know the number of replicates necessary to estimate the population mean of mess hall occupied time within a confidence interval of 3 minutes.

Table 1 shows average results obtained with rates of 80, 160, and 340 persons per an hour.

A hypothesis test was performed on results achieved to evaluate if there were significant differences between the sample populations mean, by an analysis of variance (ANOVA) contrast as shown in Table 2.

The null hypothesis was not rejected in favor of the alternative with a significance level of .05 for all time measures except for the equality of averages. Alt. 6 showed the slower average, it is justified because of its smaller size that saturates with 18 extra crew.

Lower speeds occur with an arrival rate of 340 because the mess hall is busier; therefore, these speeds are taken to build the linear utility function:

- 1) Average speed Alt. 4 = .522 m/sec
- 2) Average speed Alt. 5 = .507 m/sec
- 3) Average speed Alt. 6 = .467 m/sec

Figure 12 shows linear utility function $U(x)$, in which the maximum utility corresponds with the average speed that assigns AnyLogic Uniform (0.5; 1.0) m/s, i.e. 0.75 m/s and the minimum utility corresponds to zero speed, no flow (blockage).

Intermediate calculations were performed to evaluate the final valuation of the alternatives. Both criteria SUPPLY DEPARTMENT and CREW with their weights appear in the first row of Table 3. Weights of subcriteria contribution to the different alternatives are displayed in rows below criteria ones. Subjective criteria SUPPLY DEPARTMENT that weights 75% according to with expert's valuation contributes with the same weight (39.04%) to Alt. 5 and Alt. 6 alternatives. Objective criteria CREW value slightly better Alt. 4 but contribute with similar assessments (34.29%, 32.22%, and 33.50%) to all alternatives because Pathfinder and AnyLogic compensate their different simulations between alternatives. In the global assessment of mess hall alternatives, Alt. 6 appears to be the best evaluated with 37.66% followed very closely by Alt. 5 with 37.34%.

4.2.1. Sensitivity analysis. The previous ranking depends on the assessments, weightings, and modeling of the method. At this point, it is needed to verify if the decisions are enough robust and not

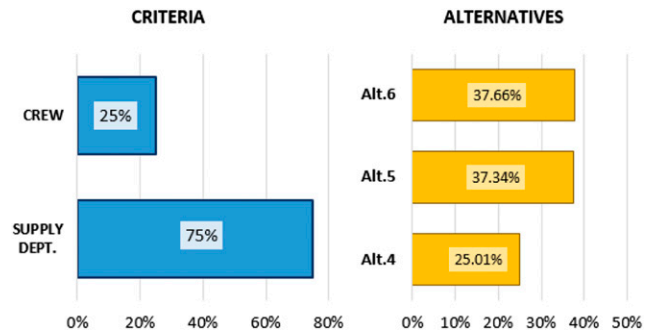


Fig. 13 Assessment according to expert's weightings

affected by slight changes in the weights, or if on the contrary, some small change in the subjective weighting assigned by an expert changes the result.

A sensitivity analysis was made to check the criteria and subcriteria weighting robustness. Criteria weightings are modified to evaluate the impact on the priority between alternatives.

Criteria weightings (blue bars chart) and results obtained from an alternatives' assessment of the improved multicriteria (yellow bars chart) as in Fig. 13, which shows that Alt. 6 alternative to be the best evaluated with 37.66% closely followed by Alt. 5, such close values require a sensitivity analysis.

As Fig. 14 shows, if SUPPLY DEPARTMENT criteria weighting is reduced from 95.68% to 4.32% preferences would switch to Alt. 4 closely followed by Alt. 6. This change of criteria's weighting (more than 70 points below) seems unlikely; thus, the robustness of criteria weighting is satisfactory. There is only a slight difference between Alt. 5 and Alt. 6, the balance between them depends on objective criteria based on evacuation and flow pedestrian modeling mess halls.

5. Conclusions and future lines

Traditional early-stage ship design approaches can be time-consuming because of the large number of possible solutions. This is especially relevant to the exploratory design required for the GA of a warship surface combatant, which hold high outfit density and complexity.

This article has developed and demonstrated the use of an "analytical decision maker" to achieve an optimal solution for the layout of the seamen mess hall in the new in the early stage design

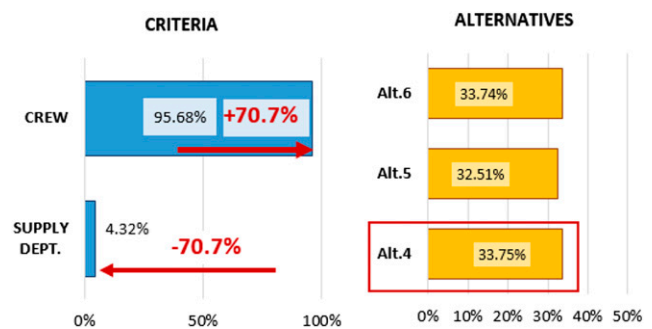


Fig. 14 Subjective criteria weighting assignment

process. Furthermore, the use of advanced statistical methods and computer pedestrian simulations within an MCDM framework allows optimizing the conceptual designs based on experts' requirements, including operational effectiveness and cost while significantly reducing project risk.

This work aims to aid to the High Staff (EMA) of the Spanish Navy in the decision which is going to take about the design of the seamen's mess hall in the new frigate F-110, where three alternatives are used. From the three alternatives proposed by the shipyard, the Alt. 6 is the best valued. This is the outcome of an "analytical decision maker" that has reduced subjectivity, using the AHP method, simulation and statistics. The work process was carried out in accordance with the methodology outlined and developed to achieve the objectives. This process can be summarized in the following steps.

- 1) Representation of the problem: a hierarchical structure of evaluation criteria has been created in collaboration with expert supply department officers. All aspects considered important in the decision process have been represented.
- 2) Evaluation of criteria: three expert officers, individually and anonymously, have evaluated the criteria and assigned a value based on importance between criteria.
- 3) Contributions of the alternatives: the expert officers have assessed the contributions of the three alternatives to the subjective criterion SUPPLY DEPARTMENT. Regarding the objective criteria CREW, and with the intention of responding to the questions raised by the EMA, a simulation of the eviction times was carried out by software. The data obtained have been statistically processed and a utility function has been designed to evaluate the contributions of the alternatives to the CA Eviction subcriterion.
- 4) Real data of crew drills in mess halls were collected onboard of two frigates and one LHD warships.
- 5) Pedestrian simulation using data collected from drills onboard. The results obtained from the simulation have been statistically processed and a utility function has been designed to evaluate the contributions of the alternatives to the subcriterion Freedom of Movement.
- 6) MCDM AHP was conducted with the help of the ADLA software, which implements the Saaty algorithm, the alternatives for the final decision have been hierarchized.
- 7) Sensitivity Analysis: robustness analysis of the model has been carried out, which prove the model is very robust to changes in criteria.
- 8) Decision: after having analyzed the previous steps, it can be concluded that the best-valued alternative is Alt. 6. However, it is convenient to remember that this decision is made from the point of view of the user and it does not take into account other possible engineering or economic criteria. Therefore, Alt. 6 is the best valued alternative with the approach proposed by the EMA regarding fluency, queuing time, service time, kitchen and organization of mess hall, etc.

It is considered that the following results have been achieved for the proposed objectives.

- 1) Applying the multicriteria decision technique for choosing the best mess hall: it has been fully achieved because it has

been possible to carry out the AHP methodology with the indispensable participation of Navy experts with extensive experience as heads of the service.

- 2) Provide objectivity to the multicriteria analysis: despite the impossibility of reaching complete objectivity, this work is considered to have reached the proposed aim. It has been possible to carry out the statistical analysis of the actual data, providing the results to the simulations. With all this, it has also been possible to assess the alternatives with regard to one of the two criteria in an objective way.

To implement a model able to be validated, some future lines are proposed. In the first place, counting on an onboard analyst, more data could be collected about the behavior of the staff and the performance of a mess hall. Second, with the help of the software AnyLogic or others, to perform the simulations of the three mess halls (sailors, noncommissioned officers, and officers) simultaneously, including the movement inside the kitchen (delivery in the self-service area, the collection of trays, the transit of pots with food, etc.). As an immediate future line, a new multicriteria analysis, to include more experts who can add engineering and economic criteria is desirable. Finally, the presented work focuses its attention on the stage of evaluation and selection of alternatives, although in future works, the possibility of integrating the generation and evaluation of alternatives could be studied.

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