Operational Availability (Ao) of Warships

a complex problem from concept to in service phase

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***Abstract*— Budgets for defense are shrinking and human resources are becoming more critical, while operational needs, to face new threats, and availability requirements of Warships are increasing. This requires a new design approach - based on operational availability (Ao) - for Warship and associated support system, in order to achieve the best balance between Ao and Life Cycle Cost (LCC) along the whole operative life. During the in service phase, a measurement process (of Ao and other appropriate KPI) is to set up in order to adjust or improve Warship availability performances. To achieve these goals, proper design processes, methods, models and tools (analytic and simulation based SW tools, or statistic SW tool and recording devices) are key factors. All the above areas have been handled and developed by OSN in the FREMM Program that is an "Availability based Contract".**

Keywords — Operational Availability, PBL, CfA, Supportability, KPI, Life Cycle Cost, SW tools.

I. Introduction

The key factors to achieve the optimal ratio between Ao and LCC of a Complex System (a Warship for example and associated support system) all along the life cycle are:

- a contract based on availability requirements long enough to ensure return on investment for the Supplier,
- integrated design processes oriented to availability and supportability of the System,
- appropriate design methods and evaluation models,
- SW tools for analysis, evaluation and measurement,
- appropriate devices to record the health status of equipment,
- procedures agreed with the Customer to review measured data.

Another important factor is the chance to maintain post design processes alive after commissioning in order to improve/adjust the System (and equipment) and associated support system to take into account feedbacks from field (including measurements) or following changes of Customer needs and usage scenario.

An availability based contract or "Contracting for Availability" (CfA) is a special type of Performance Based Logistic (PBL) or Performance Based Contracting (PBC). FREMM (FRegate Europee MultiMissione) is an OCCAR Program for French and Italian Navies, and it is a CfA based on two availability requirements during TGS (Temporary Global Support) period (initial part of Ships life cycle): the operational availability (Ao) and technical availability (A_T).

The technical availability is a function of operational readiness and "down times" when Ships are not at sea (but at quay or in arbor/dockside for maintenance).

This paper is focused on operational availability approach for the Italian Frigates, since Ao requires a more innovative and comprehensive approach for design and support.

II. Definitions

A. Availabilities

AVAILABILITY can be expressed as the probability that the system or equipment used under stated conditions is in an operable and committable state at any given time.

Availability can depend on several parameters. It can be influenced by Reliability & Maintainability characteristics of the system/equipment and, dependent on the type of availability, the logistic support provided, and the required probability of mission success. The system should be designed such that an individual hardware or software failure does not result in a critical failure while operating under predefined conditions. The logistics support factors include personnel skill, training, spares supplies, technical manuals, etc. [1-3]

OPERATIONAL AVAILABILITY (Ao) is the probability that a system/equipment at any instant in the required operating time operates satisfactorily under stated conditions where the time considered includes operating, corrective and preventive maintenance, administrative and logistic delay time [1-3]

OPERATIONAL READINESS is the ability of a military unit to respond to its operation plan(s) upon receipt of an operations order. (A function of assigned strength, item availability, status, or supply, training, etc..) [4]

B. Performance Based Logistics

PBL is a result oriented contract, a new approach of contracting integrated logistic support for complex products (such are ships, weapon systems and aircrafts): vendor or supplier compensation/penalties are linked to actual achieved performance and the provided support services.

The DoD expresses PBL objectives as [5]:

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- "[…] outcomes are acquired through performance-based arrangements that deliver Warfighter requirements and incentivize product support providers to reduce costs through innovation"
- "[…] to compress the supply chain and improve readiness for major weapons systems and commodities"
- "[…] integrated, affordable, performance package designed to optimize system readiness and meet performance goals for a weapon system through long-term support arrangements with clear lines of authority and responsibility".

The supplier is awarded according to the level of system performance, for example, according to the achieved Availability of a warship or an aircraft: system performance responsibility is shifted from the customer to the supplier.

Performance and result depend on process productivity, quality, innovation, efficiency and effectiveness and will be expressed and measured by Key Performance Indicators or a combination of them.

The above definitions point out the real objectives of CfA/PBL approach: improve readiness, reduce logistic footprint and delay, and finally reduce costs.

C. SMART

A best practice is to ensure the selected metrics (KPI) satisfy the "SMART" test. Selected metrics should be [3]:

- S = Specific: clear and focused to avoid misinterpretation, specifying the allowable range or threshold.
- M = Measurable: the unit of measure is specified and tied to underlying data to allow for meaningful statistical analysis.
- A = Attainable: achievable, reasonable, cost-effective, and credible under expected Concept of Operations (CONOPS)
- R = Relevant: tied to Warfighter requirements, appropriate to the Product Support Integrator and Provider specific level of scope and responsibility, designed to motivate the right long-term behavior, and linked to appropriate incentives.
- T = Timely: doable within the given time frame.

D. Availability Demonstration

The availability tests are based on the assumption that a system can be treated as being in one (and only one) of two states, "up" or "down" [4]. Up time is noted as "X_i" and downtime as "Y_i".

The Availability measure is given by:

$$A^R = \frac{1}{1+Z_R} \tag{1}$$

$$Z_R = \frac{\sum_R Y_i}{\sum_R X_i} \tag{2}$$

where A^R is the maximum likelihood estimate of Availability.

The significance of the measure depends on A_0, A_1, risks α/β and test duration (R or T).

The main parameters to be considered in the tests are:

- H_0: (null hypothesis): $A \geq A_0$
- H_1: (alternate hypothesis): $A < A_1$
- A_0: objective value for A
- A_1: acceptable value for A ($A_1<A_0$)
- Producer's risk (α) is the probability of rejecting H_0 when it is true (probability of rejecting good equipment);
- Consumer's risk (β) is the probability of accepting H_0 when it is false (probability of accepting bad equipment).

Two types of availability demonstration tests are defined and could be performed:

*1) **FIXED-SAMPLE TEST PLANS**:* based on having the system performs a fixed number of cycles R. The result is R pairs of times-to-failure and down times (X_1, Y_1),...., (X_R, Y_R).

The critical values, C and A_c, and number of up/down cycles, R, are determined so that the significance test satisfies the consumer and producer risk requirements (α/β) by the following formula:

$$\rho_0 = \frac{A_0}{1-A_0} \qquad \rho_1 = \frac{A_1}{1-A_1} \tag{3}$$

$$\rho_0 Z_R > C \text{ reject } H_0 \tag{4}$$

$$\rho_0 Z_R \leq C \text{ accept } H_0 \tag{5}$$

$$P(\rho_0 Z_R > C|A_0, R) \leq \alpha \qquad P(\rho_0 Z_R > C|A_1, R) \leq \beta \tag{6}$$

$$Ac \geq \frac{\rho_0}{\rho_0 + C} \text{ accept H0} \tag{7}$$

and using the Fisher–Snedecor c.d.f. (in [4], deeper details.)

Generally the following statements are true:

- the closer A_1 is to A_0, the larger sample size is required
- the smaller the α specified, the larger sample size is required
- the smaller the β specified, the larger sample size is required.

2) **FIXED TIME SAMPLE PLANS***:* system performs consecutive up/down cycles until a fixed-time T has elapsed. In this case the test time is fixed and the number of cycles is random.

Considering A(T) the measured availability at the end of test, the critical availability A_c and the test time T are chosen so that the significance test satisfies the risk requirements (α/β):

$$\text{A(T)} < A_c \text{reject } H_0 \qquad A\text{(T)} \geq A_c \text{accept } H_0 \tag{8}$$

$$P(A(T) > A_c|A_0, \text{T}) \leq \alpha \quad P(A(T) \leq A_c|A_1, \text{T}) \leq \beta \tag{9}$$

and using the standardized normal c.d.f.[4].

III. Design for Operational Availability

The life cycle of a System can be described by the following steps (figure 1):

Fig. 1. Life Cycle.

that is:

- Concept
- Feasibility
- Design and Development
- Manufacturing
- In service
  - Deployment and fielding
  - Operation and support
- Disposal.

In order to achieve an optimal balance between operational availability and life cycle cost for the Customer (and desired revenue for Industry), the development phase requires the following aspects be well thought-out:

- design for supportability to define (requirements), develop and "test": reliability, maintainability, testability, availability, and maintenance features to be built-in the product including obsolescence mitigation aspects;
- design of support elements (spares sizing, Special Tools & Test Equipments, training and training aids, data and technical manuals, PHS&T, facilities requirements, info system, etc..) taking into account support requirements during the In-Service phase;
- fielding analysis to assess the need to improve and/or to adapt Customer facilities and capabilities in order to ensure operation and support of the product;
- upgrade Customer support system if necessary;
- to issue a post production support plan to define how to ensure the Support Services after production including obsolescence mitigation;
- design of Support Services (including processes and procedure) taking into account measure needs (KPIs) in order to ensure the required service level and continuous improvement.

The integration of above aspects with all the other design features of a System in a comprehensive engineering effort is tricky to achieve but is the only way to reach:

- an optimal balance between the Ao and life cycle cost;
- customer satisfaction;
- services level objectives;
- augmented value for the Customer and Industry margins.

Since, typically, in the earliest phase more than 80% of LCC is committed, implementing a PBL approach during the development phase gives the opportunities to prioritize requirement with major impact on supportability (e.g., reliable, maintainable, and affordable) and measurements.

Long-term contracts, from concept to a significant part of the life cycle (better if up to disposal), is a must for a PBL implementation since service Providers perform their best and make investment to achieve service level if the contract is long enough to reach return on investment.

A. *Operational Availability Models*

To design a Warship for operational availability effectively, it is necessary to take into account what OSN calls "Whole Warship (WW) interactions" or transversal connections shown in the following Fig. 2, i.e.:

- ship characteristics
- ship performances
- crew capabilities
- operational scenarios
- R&M figures of installed equipment
- limitations for maintainability due to accessibilities constraints of platform.

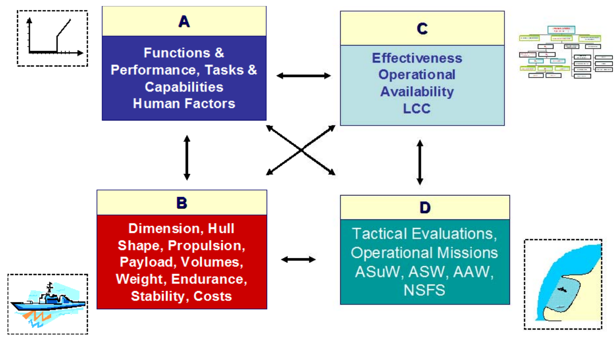

Fig. 2. Warship Interactions.

Therefore it is necessary to define and apply appropriate models that could take into account above parameters and relationships, in order to evaluate operational availability of the ship, to apportion R&M requirements to the equipment installed on it, and to sustain design (including System Design Review - SDR and Critical Design Review - CDR).

Afterwards more complex models are to be adopted to size and validate the support system (spares, tool and test equipment, facilities, on board and dockside maintainers, etc..) of the Ship.

The conceptual model adopted by OSN to describe mathematically the "Ao of Warship" is outlined in the following Fig. 3; it has been used for the apportionment of requirements to the equipment to install on the Ship and takes into account maintainability constraints and on board support capabilities.

The same conceptual model has been used for the Critical Design Review and in the following phases, but tools and computation techniques are different in order to fit with availability of data and complexity to manage, reducing area of approximation.

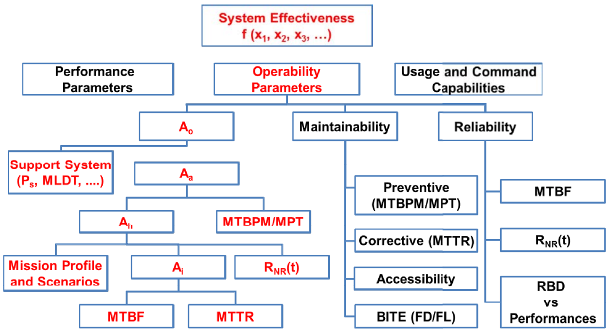

Fig. 3. Ao Business Model.

Since a Warship is employed in a wide range of missions, the associated objectives and expected performances vary accordingly; moreover they vary during the phases or assets of a single mission.

So the equipment configuration becomes time dependent, and the associated RBD (Reliability Block Diagrams) are different for each phases of the range of missions.

Then multi-phase [6,7], multi-mission and multi-scenario models (RBD) for Ao have been developed to provide the required evaluations, taking into account warship capabilities, mission critical functions and duty cycle of equipment.

The Reliability block diagrams can involve different warship breakdown level, starting from equipment or system level until LRU/SRU level (line or shop replaceable item level) according to the need.

B. TOOLS

In order to control the complexity of a Warship that is characterised by many variables and interactions, and by a huge number of items, a SW suite has been conceived and developed (integrating also MOTS – Modified Off The Shelf –

SW on OSN specs) to perform Ao evaluations for each phase of the life cycle (see Fig. 1).

The OSN SW Suite for Ao evaluation, named **DiOp_NAV**, is made by three modules that allow specific evaluations for the different life cycle phases:

DiOp_PREL is based on analytical models/techniques (Markov) and average parameters for preliminary Ao evaluation to be used from concept up to design phase; it:

- takes into account models based on RBD, maintenance policy, maintainability & environmental constraints, mission phasing
- is used for apportionment and predictions, trade-offs and alternatives (in terms of system configuration)
- it is used for preliminary sizing of on-board support.

DiOp_PROG (the MOTS) is based on Monte Carlo simulation (see Fig. 4 for a conceptual schema) and "uses" data up to LRU from Ship LSAR/LSDB (Logistic Support analysis Record/ Logistic Support Data Base, the same data used for LCC analysis) for Ao evaluation and validation of support system from production phase all along the in service phase; it takes into account:

- models based on RBD, maintenance policy, maintainability & environmental constraints, mission phasing;
- takes into account on board and dockside support system organisation and sizing for trade-off,

and it can be used for:

- decision support and assessment of improvement proposal;
- assessment of changes in the scenario (financial and operational) and Navy support policy;
- decision support for planning of "out of area" missions (trade-off evaluation of support system alternatives and arrangements, geographical configuration, and deployment of a Naval Squadron).

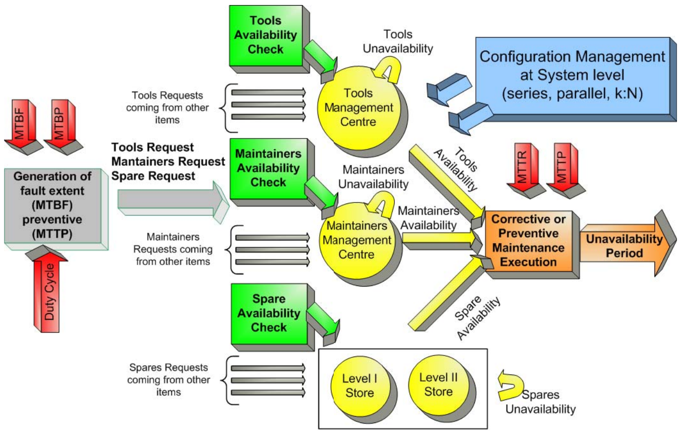

Fig. 4. Conceptual Schema of Ao simulator

DiOp_MIS is based on statistic models and computes field data (ship equipment health status, Fig. 5) for a direct "measurement" of Ao achieved by Ships at sea during the Operation and Support phase. Its static algorithms are based on acceptance test of availability according to methods (Fixed-Sample or Fixed Time) described in the § 10.8.1 of [4] – see definitions point D for short information - and takes into account the applicable RBD for the applicable missions, phasing and so on.

In the following Fig. 5 is reported a simple example on how the health status of a complex system (NHA System level – next higher assembly level), like a Combat System, depends on the applicable RBD for missions and cycles.

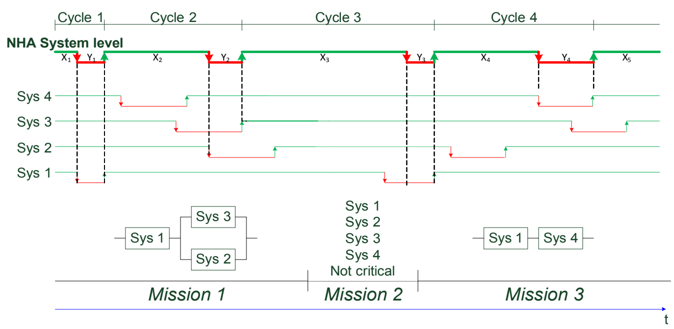

Fig. 5. Event measure for Ao example

The measurement tool consists of an "Ao Recorder Device" installed on board of the Ships to record the health status of the equipment involved in Ao evaluations.

Recorded data are the input to the DiOp_MIS tool for the statistic availability evaluation of the deployed Ships.

C. Output Example

The following pictures, graphs and data are only example and not related to FREMM program.

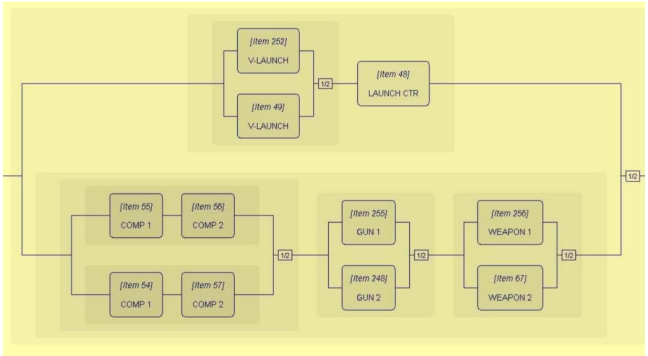

Fig. 6. RBD from DiOp_Prel

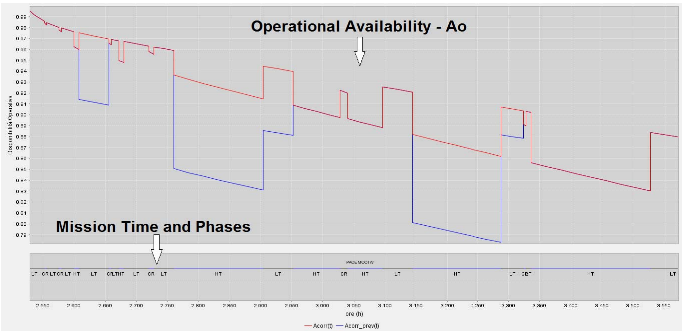

Fig. 7. Ao diagrams from DiOp_Prel

Fig. 8. Ao diagrams from DiOp_Prog.

D. Key Performance Indicators and Metrics

The success of a PBL implementation depends on accurately established metrics; in our case it is the Operational Availability, but some lower performance indicators (the diagnostic KPI) must be defined and measured because [5]:

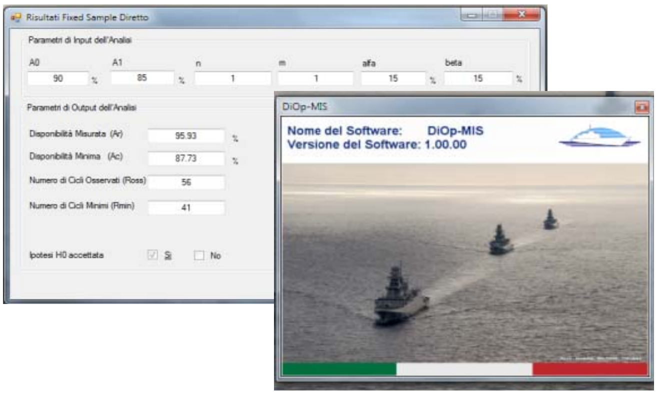

Fig. 9. Screenshot from DiOp_Mis (results of the test).

- the measurement of only highly aggregated performance indicator (Ao for instance) is not enough to identify improvements on operational system (Ships) and/or support system;
- contracts involve in general a temporary group of suppliers each of them is responsible only for its contribution to performance (i.e. support for a certain sub-system) and not for highly aggregated performance;
- If a supplier does not perform or manage all functions contributing to Ao, considerations must be given to identifying appropriate metrics (other than Ao) for which the suppliers may properly be held accountable;
- even if there is a Prime Contractor, it is necessary to identify the appropriate metrics (other than Ao) for which the suppliers may properly be held accountable.

KPI should be Specific, Straightforward, Measurable and Relevant (SMART, see definitions) to the customer's requirement, therefore linked to the top-level requirements - availability or readiness – in order to let diagnosing and troubleshoot the problem be in the ship or support system, i.e.:

- failures of processes and service;
- poor reliability of the equipment;
- poor maintainability (MTTR and reparability rates);
- limited capability of operation and maintenance personnel;
- weakness of the supply chain (MLDT, TAT, PLT, PNSS, ..);
- low level of stocks;
- etc..

and in order to let Supplier find out and propose the best solution.

So the measurement apparatus for FREMM TGS, required to measure the Ao level during the committed service period (5 years) and in the remaining part of the Frigates life cycle (30 years in an evolving scenario), is represented in the following Fig. 10. It consists of four parts all developed for FREMM Program:

- **SIC** (part of IT Navy Information System) conceived to sustain in service support engineering processes of the Fleet, including configuration and obsolescence management, FRACAS (Failure Reporting, Analysis, and Corrective Action System) and maintenance engineering, and metrics of support system (with appropriate KPIs).
- **Ao Recorder** installed on board of Frigates (**OAMD** – Operational Availability Measure Device).
- **DiOp_Mis.**
- **DiOp_Prog.**

DiOp_Mis performs Ao tests at defined periods (once a year for example), while the SIC provides diagnostic KPI of the support system to point out problems or weakness in case the Ao test goes not ok.

Test performed by DiOp_Mis is based on availability demonstration theory (see definitions) using the population of times-to-failure that could occur from the equipments under test (considering mission and applicable RBD) recorded by OAMD (see above). The objective of test is to answer to the question "Does the item meet or exceed (not by how much) the specified minimum requirement?"

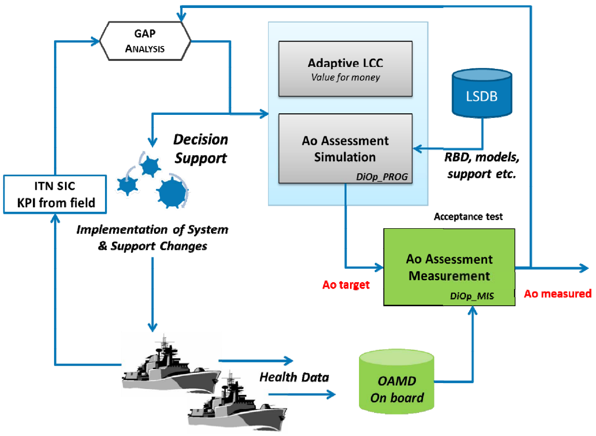

Fig. 10. Conceptual Schema of Measure Apparatus for Ao.

The Gap Analysis is the process that identifies and proposes corrective actions to fix problems, or adjust services or to improve the support system to an higher level of performances.

The adaptive LCC assessment makes life cycle cost of the proposed corrective actions to evaluate their economical affordability (budget constraints and value for money approach).

The Ao assessment simulations by DiOp_Prog have to simulate - before implementation - the performances of proposed solutions, or the effect of modifications to deployment of the Ships, usage and operative scenario, reduction of the support budgets, changes in the support organisation, modifications of the support system, configuration changes to the Ships, and so on.

IV. The FREMM Program: Approach and Roadmap in Short

The Operational Availability is the key process to:

- design for supportability of Frigates;
- design of support system;
- measure, improve and optimize ships and support system during in service phase.

TGS approach requires a predictive system: the Supplier identifies needs, forecasts and plans tools and resources to initiate service on a system, before deployment of the Ships with a progressive road map (see Fig. 11).

As a consequence, during ILS (Integrated Logistic Support) development, industry evaluated (sensitivity analysis) the theoretically-achievable availability level (A_{OTH}) adopting an accurate modeling, based on functional analysis and allowed degradations, with associated Reliability Block Diagrams, and on board and dockside support system sizing (i.e. spares and tools, personnel, facilities skills and capabilities, etc..).

The theoretically-achievable availability level was evaluated with and without contractual constraints (i.e. the budget allowed for spare parts).

Starting from these evaluations the real availability level is measured during the first years of TGS; the objective is to set-up a progressive achievement of availability level and to correct deficiencies of equipment or support system, that is:

- to measure the actual Ao for the Ships from field data at beginning of TGS (with no penalties);
- to define and evaluate by trade off the required corrective actions and improvements to products (in terms of reliability or maintainability) and to support system (in terms of organization changes, material management and spares level adjustment, new spares acquisitions, personnel skill, maintenance plan and procedures);
- to complete deployment of corrective actions and improvements;
- to verify the achievement of target availabilities during the last part of TGS (with penalties, if any).

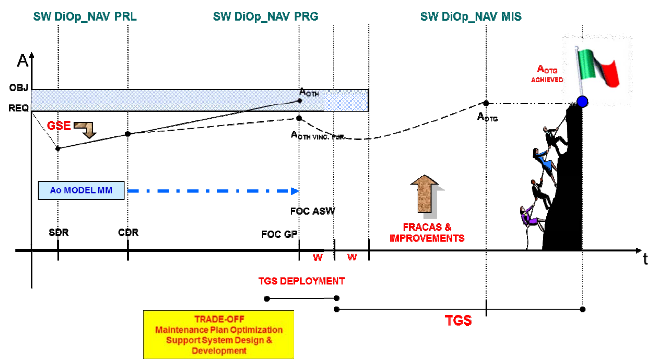

Fig. 11. Conceptual road map for FREMM Ao achievement.

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