Multi-scale performance evaluation in Naval Combat Systems domain

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Abstract. Performance evaluation of modern and future combat systems in complex operating scenarios is strictly related to modeling and simulation techniques. A "multi-scale" methodology is employed to evaluate performances of naval combat systems in multi-platform operating scenarios (e.g. naval fleet, border control, homeland defence and security) through numerical simulation tools, named *ICS-Sim (Integrated Combat Systems Simulation)*. ICS-Sim allows integration of software simulations models with high degree of accuracy to analyse and evaluate systems performances for studying innovative algorithms (e.g. asymmetrical threats contrast) integrated in a systems of systems simulation environment.

Introduction to multi-scale method

A system is "any set of regularly interacting factors and activities that has definable boundaries and that produces measurable outputs."[1]

In a complex system, elements are so interconnected and their relationship so multifaceted that their properties cannot be properly understood without assessing their interrelationship with each other as well as their relationship with the wider system and its environment.

Describing complex systems and then applying various planning methods and choice models to determine how the systems performance can be changed is the task of complex systems analysis. Analysts have approached complex system, exploiting advances in mathematics and computer simulations, breaking them down into their smaller constituent parts and analyzing these in detail. Cell biologists studied organism in terms of how their component cell systems interact.

In homeland defense and security (HD&S) context, complex systems (large systems or systems of systems) analysis include performance evaluation of each relevant defense component (e.g. air force, naval force, ground force), of their management and coordination (e.g. command and control systems) and of their interactions.

In naval context, modern combat systems during his operating missions have to perform excellent capability of Self-Defense (SD), in addition to a considerable capability to protect other naval platforms which composed a naval fleet or ground assets (LAD: Local Area Defense) against eventual structured attacks of missiles, aircrafts, ships, submarine threats, asymmetrical threats and electronic warfare. These capabilities are realized through a complete and appropriate set of sensors and weapons systems, and through complex logics of management of this equipment (CMS: Combat Management System).

This kind of performances can be usefully measured with complex instrument of numerical simulation and they cannot be evaluated without considering performances of single sub-systems (e.g. surveillance radar, fire control systems, launchers, weapons, CMS).

This scenario clearly design existence of different ‘levels’ of systems and sub-systems, where each one interact with surrounding environment, posses his own performances, interact with systems and sub-systems at same level and determine performances of systems and sub-systems at upper level.

Multi-scale method[2] consists in modeling and simulation of systems/sub-systems with a different degree of detail and accuracy, depending on their ‘level’ of intervention in functional chains which regulate systems behavior in his entirety.

Multi-scale method allows integration, in an unique simulation instrument for complex systems performances evaluation, of performance databases obtained by lower level simulations with increasing accuracy and reliability which share whit integrated simulation the reference scenarios characterization (synthetic ‘real world’ on mission context).

One of the advantages of multi-scale method is possibility to unify different simulation tools developed at different times with different software and different technologies.

At industrial level, this methodology is specially suitable for system integrator and design authority role, because it allows performance integration of equipments which property is reserved by various suppliers and of which cannot dispose of corresponding simulation models.

In the follow of this paper we submit a multi-scale method application performed from the Numerical Simulation Center (CSN) of Business Unit Defense Systems (BUSD) in SELEX Sistemi Integrati about realization of a specific simulation tool (ICS-Sim) for performance evaluation of naval combat systems.

Naval Combat Systems performances evaluation

Performances evaluation of Naval Combat Systems is made by using a Monte-Carlo numerical simulation software named ICS-Sim. ICS Sim structure has conceived to include complex naval combat systems (C/S) modeling with different equipments, through multi-scale modeling of relevant sub-systems (surveillance radar, fire control systems, electro-optical sensors, electro-acoustic underwater sensors, surface-to-surface defense missiles (SSM), surface-to-air defense missiles (SAM), gunnery, torpedoes and electronic warfare each one including multi-scale modeling of its sub-components) and integrated detailed modeling of logic units for control and management of equipments (CMS).

Main functions of ICS-Sim are:

- command and control (CMS) algorithms definition and validation for Threat Evaluation and Weapon Assignment (TEWA) function on Anti-Air Warfare (AAW), Anti-Surface Warfare (ASuW) and Anti-Subsurface Warfare (ASW) domain;

- performance evaluation of entire naval combat systems through measure-of-performance (MOP) and measure-of-effectiveness (MOE);

- participation at performance evaluation of complex systems of systems including other defense system in multi-platforms operating scenarios.

Aim of ICS-Sim tool is to provide detailed performance measures for naval combat systems in every project phase (e.g. prototyping, development, qualification), as well as to validate project choices effectuated during systems and sub-systems development and to improve them and optimize.

Functional Architecture. ICS-Sim functioning is managed from a main program (Monitor) which interrogates all components (CSCI: Computer Software Configuration Item) and manages time synchronization and communication between components. Each CSCI is a multi-scale component (sub-system) model of the combat system under analysis.

From the multi-scale point of view, components may be modeled by means of “performances database” obtained through other simulation instruments. Functional structure of current version of ICS-Sim is delineated in the next figure.

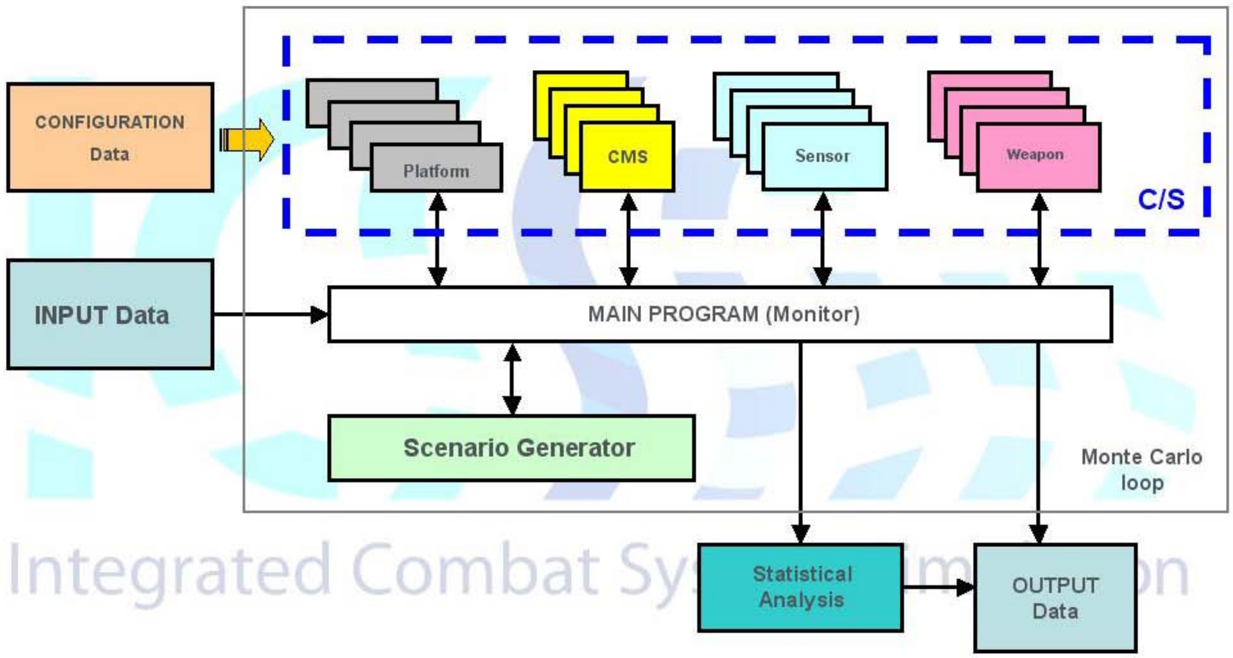


Figure 1: ICS-Sim functional architecture.

ICS-Sim flexibility in terms of diversity of naval combat systems that can be analyzed is synthesized from Configuration Data function. This feature allows the user to configure the combat system through the choice of its components, each of which may in turn be configured through the selection of its modes of operation or its sub-systems (e.g. selection of a surveillance radar model and selection of its instrumental range). Through the configuration data panels, user can be select the category of naval platform (e.g. aircraft carrier, frigate, corvette, patrol ship), the CMS model, the sensors and weapon suite.

Input data for this simulation tool are the ‘simulation control parameters’: number of Monte Carlo runs to be executed, order number of start run, simulation ‘time-step’ and eventual execution delay for code debugging. At input data entry level, user must also select the scenario on which to perform the performance evaluation. ICS-Sim support performance evaluation for One-on-One, Many-on-One or Many-on-Many operating scenarios.

Output data are all performance indicators the user wants to register in order to analyze combat system effectiveness. These indicators are in numerical (text files and tables) or graphical (pictures) format and may be related to the whole system (e.g. PEH: Probability to Escape a Hit) or one or more of its subsystems (e.g. sensor accuracies, weapon kill probabilities).

<u>Monitor</u> module is responsible for management of numerical simulation tool; it makes calls to all the component modules to achieve the correct sequencing between them; handles the progress time with discrete steps (time-step) user selectable; manages the main parameters of 'Simulation Control' (number of runs, run start, possible delay of execution for debugging) ensuring the reproducibility of individual runs; tests in a dynamic manner the conditions of end-run; allows user to select the 'Output Data' to do performance/algorithmic testing. Inside the Monitor module are also made calls to utility functions for generating pseudo-random variables necessary for the functioning of the Monte-Carlo simulation.

Initial.	Run	Paused	Stop	Completed	Saved
0	0	0	0	0	0

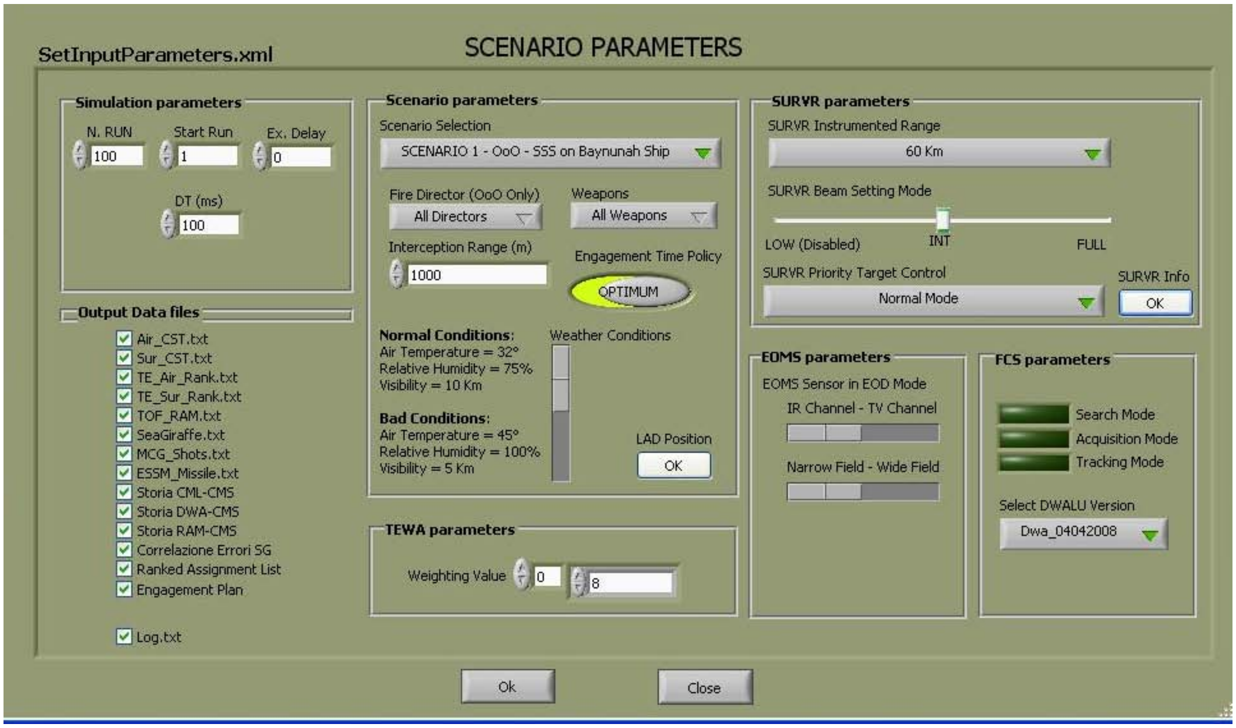
Free Physical memory (%) 64

Free Virtual memory (%) 84

Figure 2: ICS-Sim main panel

<u>Scenario Generator</u> module has the function to generate the characteristic features of user-selected test scenarios. Specifically, scenario generator module summarizes in a shared data area threat types, threat kinematic and electromagnetic characteristics and environmental condition (e.g. sea state, rain, visibility, temperature). For industrial purposes have been implemented to date over 100 different operational scenarios.

Figure 3 show the ICS-Sim main panel to insert/update and configure simulation and scenario parameters.


SetInputParameters.xml

SCENARIO PARAMETERS

Simulation parameters
N. RUN: 100
Start Run: 1
Ex. Delay: 0
DT (ms): 100

Output Data files
☑ Air_CST.txt
☑ Sur_CST.txt
☑ TE_Air_Rank.txt
☑ TE_Sur_Rank.txt
☑ TOF_RAM.txt
☑ SeaGiraffe.txt
☑ MCG_Shots.txt
☑ ESSM_Missile.txt
☑ Storia CML-CMS
☑ Storia DWA-CMS
☑ Storia RAM-CMS
☑ Correlazione Errori SG
☑ Ranked Assignment List
☑ Engagement Plan

☑ Log.txt

Scenario parameters
Scenario Selection: SCENARIO 1 - OoO - SSS on Baynunah Ship
Fire Director (OoO Only): All Directors
Weapons: All Weapons
Interception Range (m): 1000
Engagement Time Policy: OPTIMUM

Normal Conditions:
Air Temperature = 32°
Relative Humidity = 75%
Visibility = 10 Km

Bad Conditions:
Air Temperature = 45°
Relative Humidity = 100%
Visibility = 5 Km

Weather Conditions
LAD Position: OK

TEWA parameters
Weighting Value: 0 8

SURVR parameters
SURVR Instrumented Range: 60 Km
SURVR Beam Setting Mode: INT (LOW (Disabled) – INT – FULL)
SURVR Priority Target Control: Normal Mode
SURVR Info: OK

EOMS parameters
EOMS Sensor in EOD Mode
IR Channel - TV Channel
Narrow Field - Wide Field

FCS parameters
Search Mode
Acquisition Mode
Tracking Mode
Select DWALU Version: Dwa_04042008

Figure 3: ICS-Sim Insert/Update simulation and scenario parametres

CMS modules are all the detailed simulation models of combat management systems designed by SELEX Sistemi Integrati. Only one of these models can be selected to compose naval combat system to be analyzed. CMS module interact directly with sensor modules and weapon modules through the Monitor module. It includes very detailed modeling of the main functions of Threat Evaluation and Weapon Assignment (TEWA) at platform level and inherent automatic logics.

Sensor modules, considering the multi-scale approach, are detailed through ‘performance databases’. These databases are obtained from fine grain simulations (typically not integrated ICS-Sim) and directly linked in ICS-Sim. They contain the relevant performance data of sensors on threat scenarios to be defined in reference. Standard sensor databases consist of following informations: Track Formation Range (TFR) probability, angular and range accuracies, speed accuracies and reaction times, depending on threat characteristics, objective of the attack, weather conditions and their main 'operating modes'.

Weapon modules, in analogy with sensor modules, are detailed through ‘performance databases’. These databases are obtained from fine grain simulations (typically not integrated ICS-Sim) and directly linked in ICS-Sim. They contain the relevant performance data of weapons on threat scenarios to be defined in reference. Standard weapon databases consist of following informations: Single Shot Hit Probability (SSHP) depending on tracks characteristics, weather conditions and their main 'operating modes'. Several weapon systems include special software needed to determine the conditions for use of the weapons themselves (e.g. track attainability). ICS-Sim manage these special software as weapon sub-systems: if possible (consistent with the hardware requirements and the execution time) integrates SW directly, otherwise uses performance databases even in these cases.

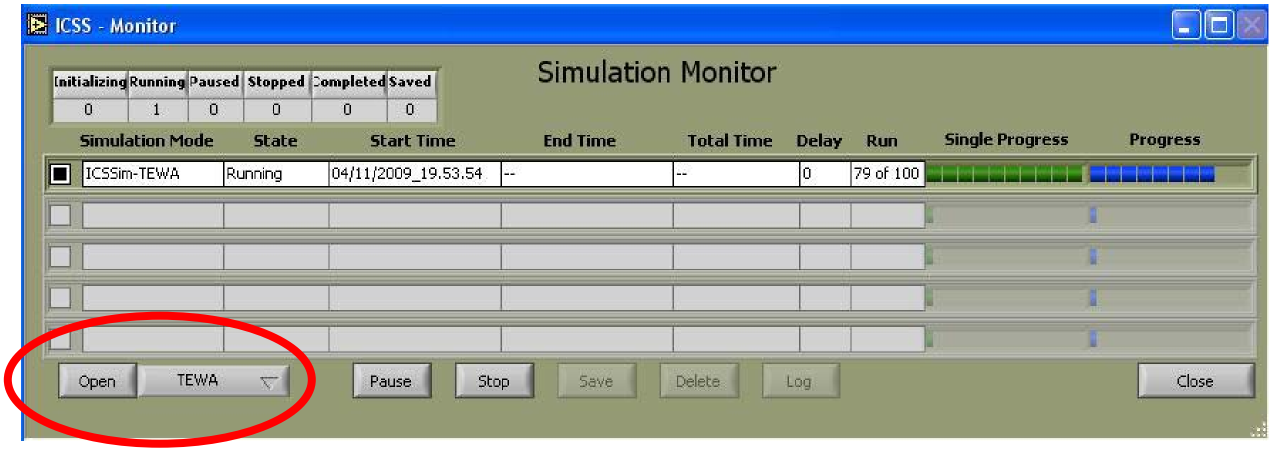
Statistical analysis module contains within it the mathematical tools necessary for statistical analysis of data, either globally or for a single run. In the following are shown examples of statistics extracted from ICS-Sim.

Software architecture. Monitor module and all CSCI components are coded employing a graphical coding language. Each CSCI is structured through one or more CSU (Computer Software Unit) correspondent to singles characteristic visual instruments of graphical object coded language. ICS-Sim for final user tool is constituted by a single executable program constructed by compiling all CSU's of all CSCI's through an apposite 'Application Builder' tool.

Performance results and system analysis

During test executions, ICS-Sim can present to analyzer some dynamical evolutions of operating scenarios. In the following figures some viewers are shown with explanation of analyzer points of interest.

A simulation monitor panel (see figure 4) show progress situation on all simulation test launched with ICS-Sim. ICS-Sim allows multithreading simulation execution.



Initializing	Running	Paused	Stopped	Completed	Saved
0	1	0	0	0	0

	Simulation Mode	State	Start Time	End Time	Total Time	Delay	Run	Single Progress	Progress
■	ICSSim-TEWA	Running	04/11/2009_19.53.54	--	--	0	79 of 100		
☐									
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☐									
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Figure 4: ICS-Sim simulation monitor panel

Highlighted section of this panel allows to select (dynamically open/close) all available viewers. ICS-Sim offers several points of view for naval combat systems analyst:

- PPI (Planar position Indicator) dynamic viewer: indicates global tactical situation, showing all threatening targets and weapons in the scenario under test and their associated tracks;
- CMS dynamic resources management viewer: indicates current status of each component of the combat system under test managed by the CMS;
- TEWA dynamic viewer: presents some tables related to relevant TEWA functions (e.g. selection and ranking process, tracks attainability computation);

In the next figure the PPI dynamic viewer is shown.

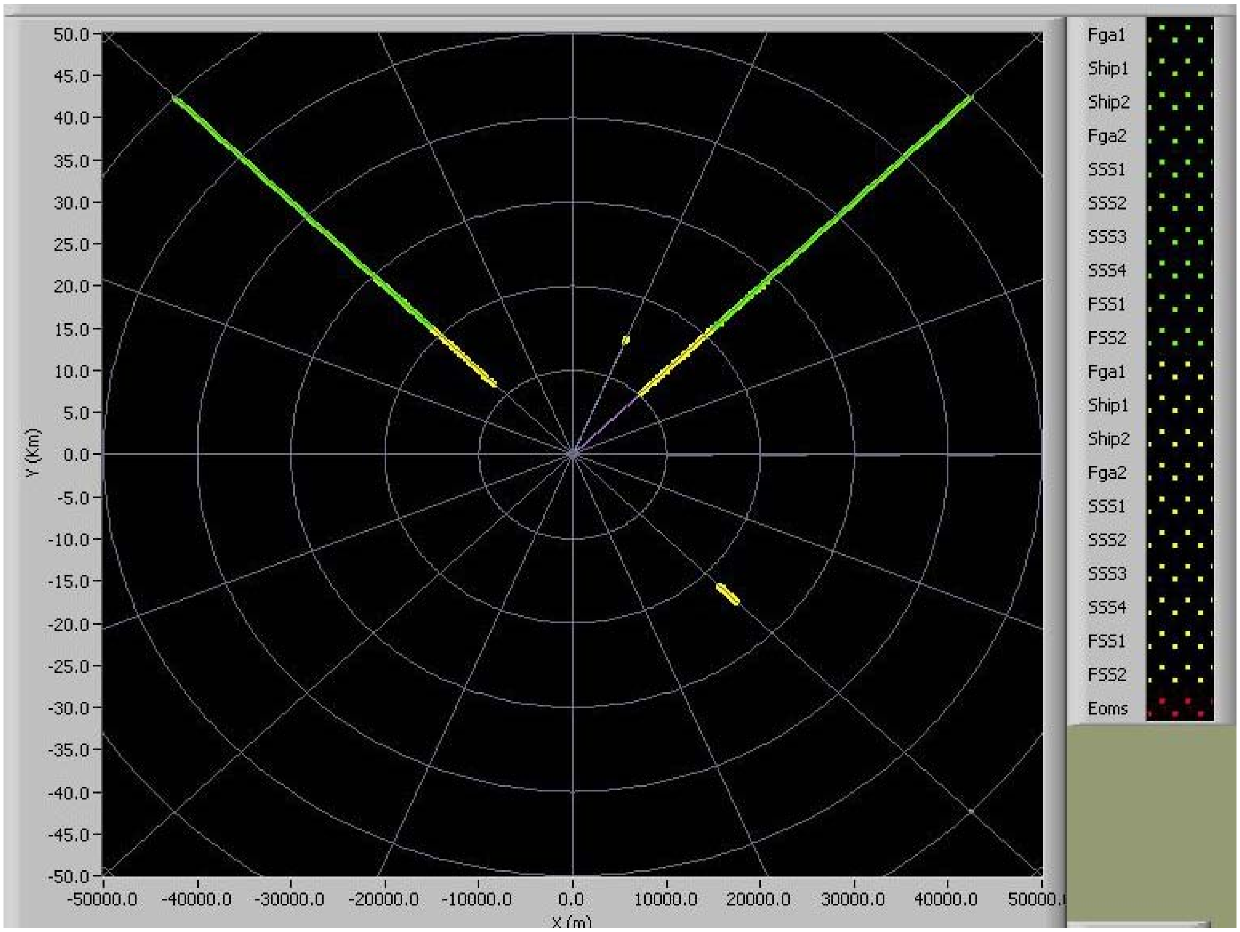


Figure 5 : ICS-Sim PPI dynamic viewer

This PPI viewer (for surveillance radars) allows to monitoring tactical situation during each single Monte-Carlo runs evolution. Targets which are not yet ‘discovered are shown with green plots; targets discovered and subject to radar tracking are shown with yellow plots. Defense weapons employed against threatening targets are shown with little blue or pink plots.

PPI is automatically resized and initialized at each run.

Combat Management System operating situation, in terms of resources management and weapon assignment, are dynamically resumed in the next panel.

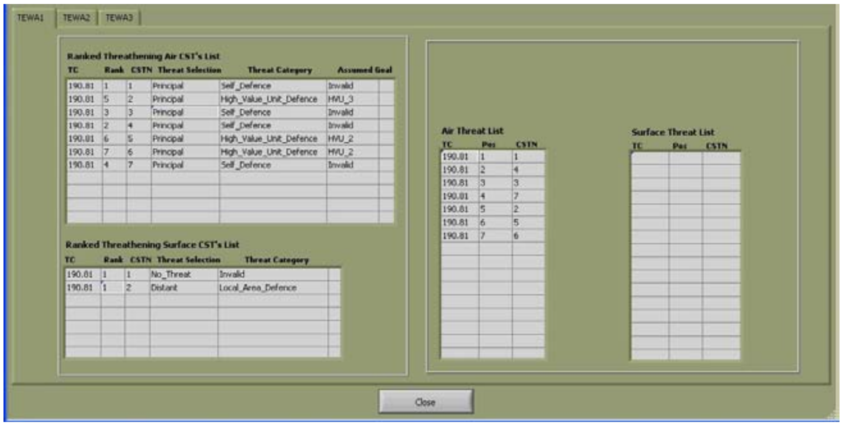
Target Type 2	SG	SG Range	EOMS	FCS	SAM	RAM	MCG	Kill	Final Kill Assessment	Kill Assessment
Fga1	🟩	29468.938	⬛	🟩	🟩	⬛	⬛	🟥	POSITIVE	🟥
Ship1	🟩	24804.382	⬛	⬛	⬛	⬛	⬛	⬛	NOT EVALUATED	⬛
Ship2	🟩	14999.070	⬛	🟩	🟩	⬛	⬛	🟥	POSITIVE	🟥
Fga2	🟩	29531.437	⬛	⬛	⬛	⬛	⬛	⬛	NOT EVALUATED	⬛
SSS1	🟩	21233.210	⬛	🟩	🟩	⬛	⬛	🟥	POSITIVE	🟥
SSS2	🟩	20723.210	⬛	⬛	⬛	🟩	⬛	🟥	PENDING	⬛
SSS3	🟩	21008.210	⬛	⬛	⬛	🟩	⬛	🟥	PENDING	⬛
SSS4	🟩	21698.209	⬛	⬛	⬛	🟩	⬛	🟥	PENDING	⬛
FSS1	🟩	21798.165	⬛	🟩	🟩	⬛	⬛	🟥	PENDING	⬛
FSS2	🟩	21728.164	⬛	🟩	⬛	⬛	⬛	⬛	PENDING	⬛

Figure 6: ICS-Sim CMS management viewer

This is an example of combat system equipped with a surveillance radar, an electro-optical sensor, a fire control system and three weapons type (two kind of Surface-to-Air missiles and a medium caliber gunnery). This viewer shows for each target (first column):

- the relative track formation range by the surveillance radar (third column);
- employment of Electro-Optical sensor to perform engagements (fourth column);
- employment of Fire Control System to perform threatening tracks engagement (fifth column);
- launch of Surface-to-Air missiles to counteract threatening tracks (sixth and seventh column);
- employ of medium caliber gun to counteract residual threatening tracks (eight column);
- last three column indicate current ‘Kill Assessment’ situation: real targets/tracks destruction, CMS kill assessment status for each track and final kill assessment result (negative or positive).

ICS-Sim TEWA viewer (next figure) show several tables which contain relevant information about CMS internal processes (threat evaluation, attainability computation, engagement plan preparation, engagement plan execution).



Ranked Threathening Air CST's List

TC	Rank	CSTN	Threat Selection	Threat Category	Assumed Goal
190.81	1	1	Principal	Self_Defence	Invalid
190.81	5	2	Principal	High_Value_Unit_Defence	HVU_3
190.81	3	3	Principal	Self_Defence	Invalid
190.81	2	4	Principal	Self_Defence	Invalid
190.81	6	5	Principal	High_Value_Unit_Defence	HVU_2
190.81	7	6	Principal	High_Value_Unit_Defence	HVU_2
190.81	4	7	Principal	Self_Defence	Invalid

Ranked Threathening Surface CST's List

TC	Rank	CSTN	Threat Selection	Threat Category
190.81	1	1	No_Threat	Invalid
190.81	1	2	Distant	Local_Area_Defence

Air Threat List

TC	Pos	CSTN
190.81	1	1
190.81	2	4
190.81	3	3
190.81	4	7
190.81	5	2
190.81	6	5
190.81	7	6

Surface Threat List

TC	Pos	CSTN

Figure 7: ICS-Sim TEWA viewer

In this example, TEWA viewer is activated to show current ‘ranked threatening Air/Surface combat system tracks lists’ and ‘Air/Surface threat list’. Tracks which are located into ‘Air/Surface threat list’ are subject by CMS to subsequent threatening evaluations and possibly thy will be engaged.

Statistical analysis

At the end of simulation execution, ICS-Sim presents statistic results, in numerical or graphical format, related to each system/sub-system component and to global combat system. Statistical analysis is a key capability to characterize naval combat systems and his components. In the following we show some typical data result from ICS-Sim statistical analysis features.

Next figures show some examples of ICS-Sim statistical graphs about surveillance radar (track formation range and position accuracies), fire control systems (mode transitions timing), gunnery (SSHP, favorable and unfavorable kill probabilities).

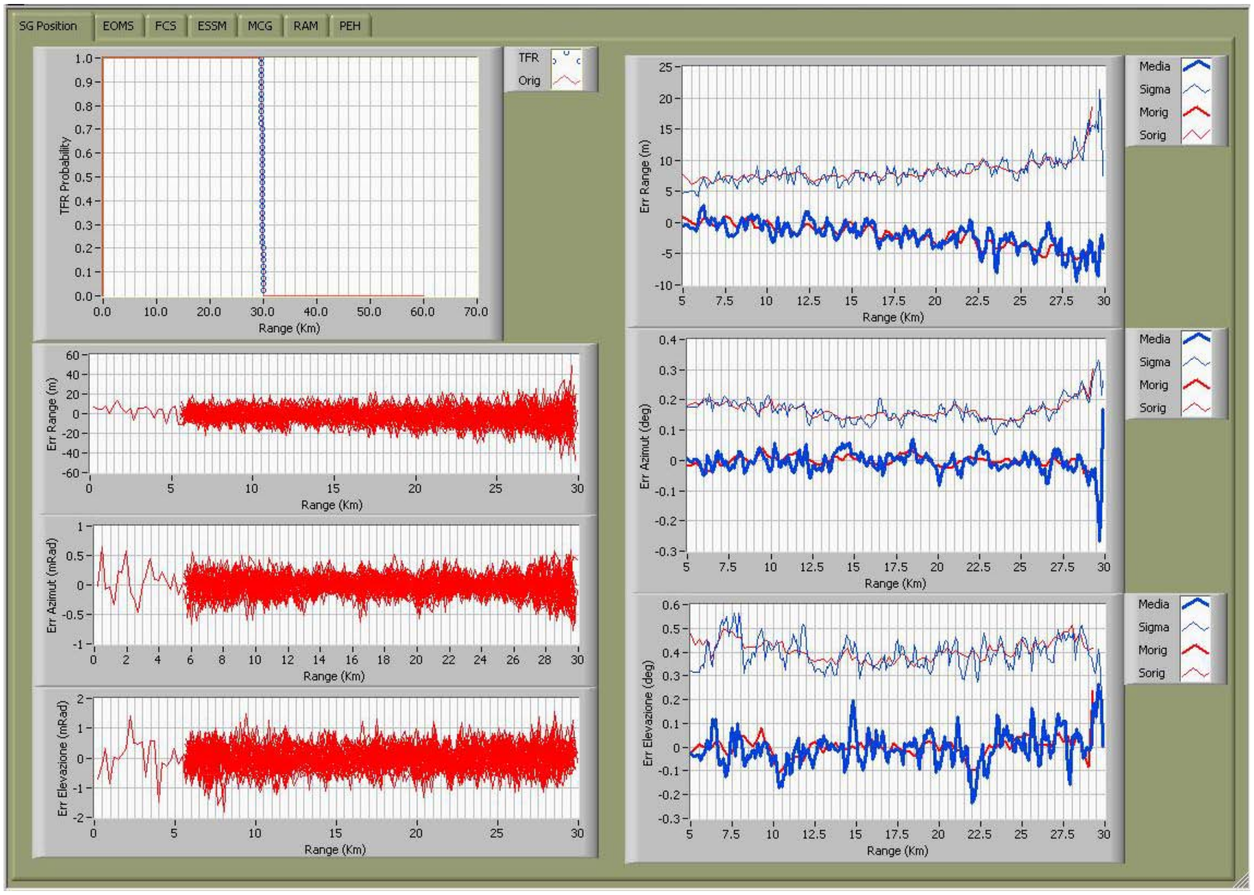


Figure 8: ICS-Sim statistical graph (ex. 1)

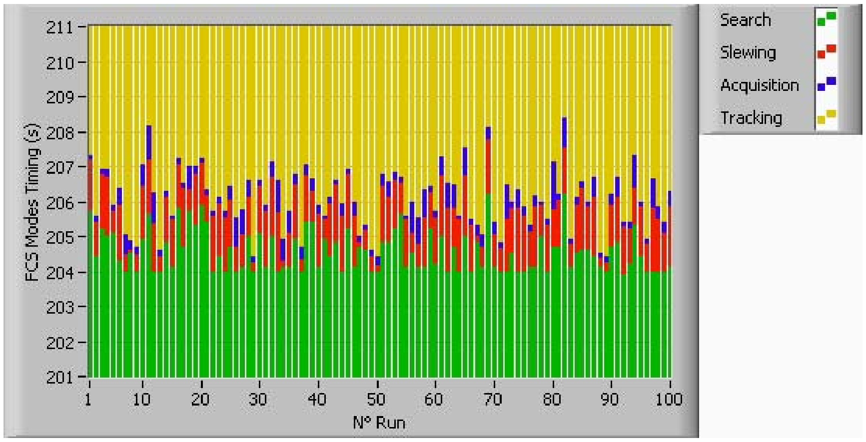


Figure 9: ICS-Sim statistical graph (ex. 2)

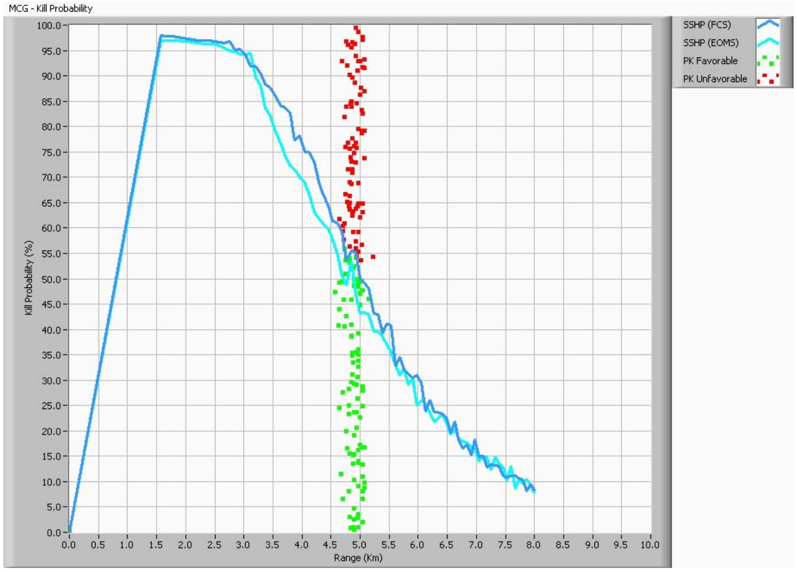
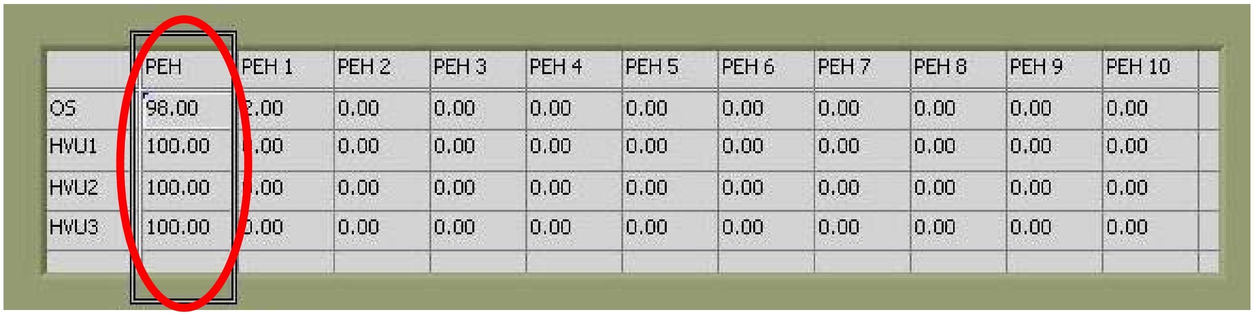


Figure 10: ICS-Sim statistical graph (ex. 3)

The relevant MOP (Measure Of Performance) for a naval combat system is PEH (Probability to Escape a Hit). Following figure show an example of resultant PEH presentation after ICS-Sim execution.



	PEH	PEH 1	PEH 2	PEH 3	PEH 4	PEH 5	PEH 6	PEH 7	PEH 8	PEH 9	PEH 10
OS	98.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HVU1	100.00	.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HVU2	100.00	.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HVU3	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 11: ICS-Sim PEH presentation (ex. 4)

Highlighted area show PEH for each unit of a naval fleet. This value synthesize both Self Defense (SD) and Area Defense (AD) capabilities of the naval combat system under analysis.

Performances evaluation on System Engineering process

Multi-scale methodology and specific simulation instruments are developed and employed by SELEX Sistemi Integrati and are used to aid in performances evaluation of different configurations of Naval Combat Systems in all project phases (e.g. bid, technical proposal, development and qualification).

Starting with a set of operational requirements of the customer, SELEX-SI approach[3] to the design and definition of a Naval Combat System provides first a 'functional modelling' (*ISFM: Integrated Systems Functional Modelling*) of various applicable configurations.

The ISFM plays a fundamental role throughout all the life-cycle of the System, from requirements specification to system integration and test, it allows to understand the feasibility of the system, it helps to give a complete description of Combat System by the architectural and functional points of view and it is the reference point for planning a step by step System integration (cluster integration), defining tests and planning integration and validation activities.

The following schema shows the ISFM in the Project life-cycle of the Combat System and Human Machine Interface Design and Analysis, in correlation with performances evaluation process by numerical simulations instruments (ICS-Sim).

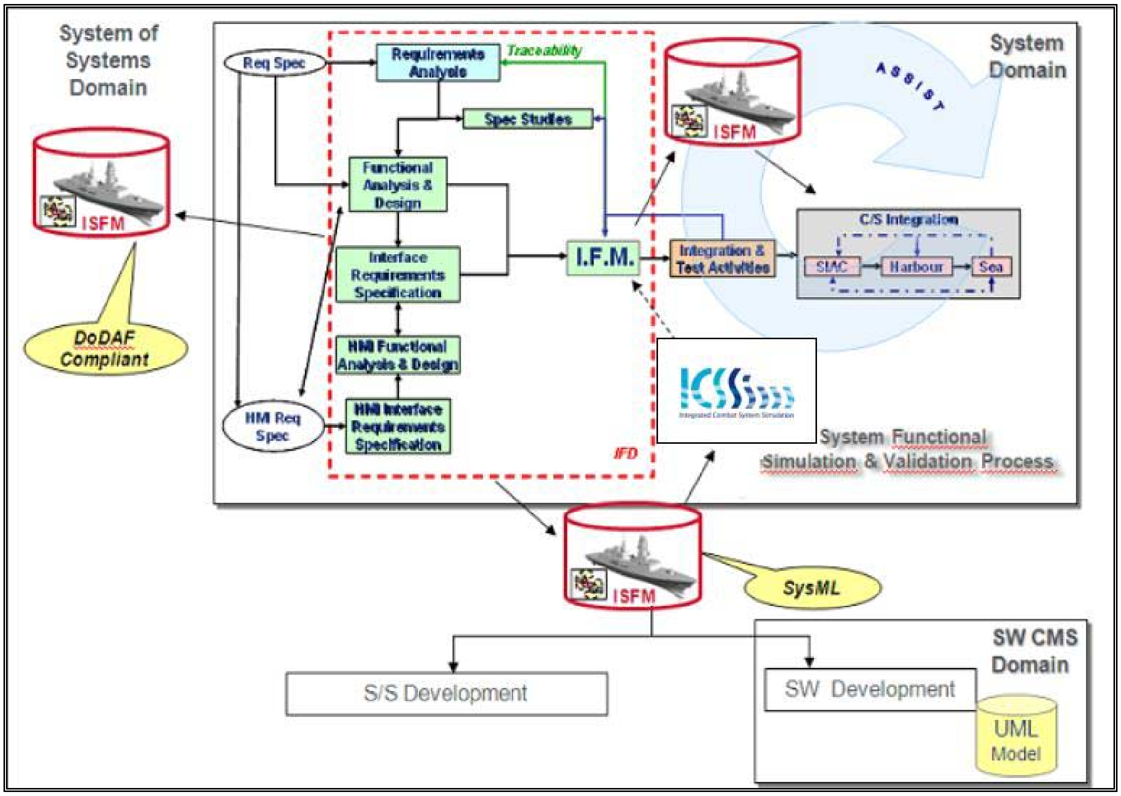


Figure 12: System Engineering process for Naval C/S design and validation

Requirements Analysis. The requirement Analysis provide the realization of a set of activity such to cover all the requirements specification functionality.

Functional Analysis. Functional analysis is a methodology that is used to explain the workings of a complex system. The basic idea is that the system is viewed as computing a function (or, more generally, as solving an information processing problem). Functional analysis assumes that such processing can be explained by breaking down this complex function into a set of simpler functions that are computed by an organized system of sub-processors. The hope is that when this type of decomposition is performed, the sub-functions that are defined will be simpler than the original function, and as a result will be easier to explain.

The Functional BreakDown (FBD) is composed of three specific levels: Main Function, Detail Function and Sub Function. For the C/S the Main function are organized for main Area such Control & Management, Operative and Support. For the HMI functional analysis the Main Function are organized for main Areas such Compile Information, Conduct Mission and Manage resource.

The detail function are organized to specialize each functionality of the Requirement analysis, The Sub Function level is the last leaves of the functional break down and has the property that must be allocate to only one subsystem for C/S case and to only one Operator Role for HMI case. At detail function is defined the interaction in functional chain to provide the parent Main function.

System Functional Simulation and Validation. The System Functional Simulation and Validation is based on the Integrated System Functional Model elements as Activity Diagram, State Diagram and Sequence Diagram at the stage of System Design. The Activity Diagrams contain the functional chain behaviour of the complex system controlled by the Combat System Equipment State Machine. The Sequence Diagram gives the internal algorithms behaviour related to the single function stage.

The following figure shows the VV process on Model Based Approach for System Functional Validation at System Design Phase.

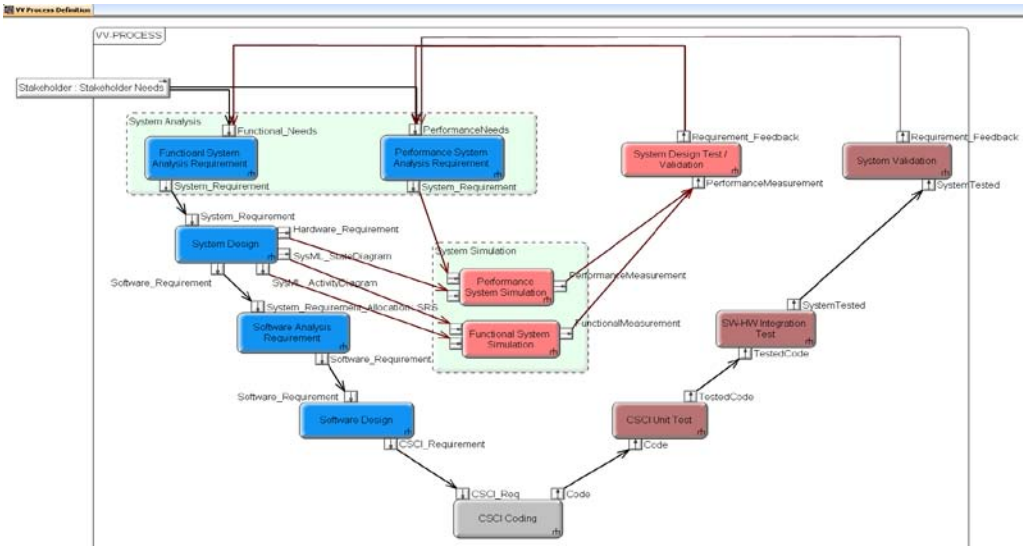


Figure 13: VV- process

System Performance Simulation. This phase of system engineering process is made through an assessment of performance on a basic set of operational scenarios with numerical simulation instruments. Through ICS-Sim the system configurations defined in the previous phases are reconstructed in a simulation environment (Configuration Data), for each of them are automatically linked their database performance (Sensor & Weapons) and the test modes are defined (Scenario Selection, Input Data insertion and Output Data selection). Execution of the simulation runs through ICS-Sim provides a complete set of performance accompanied by relevant statistics (Statistical analysis).

After this process, the system engineer has the opportunity to compare the performances of different configurations (MoE, MoP) and have a support to decide which of the hypothesized configurations provides the best result in terms of meeting the operational requirements of the customer. In case none of the configurations assumed demonstrates satisfactory performances, the system engineer can effectively use the results obtained through ICS-Sim as 'control loop (feedback)' evaluating 'critical points' and redefining / redesigning more effective configurations.

Using ICS-Sim the system engineer can continuously monitor the Combat Systems performance during all phases of the project and make changes or improvements during development to confront with new operational requirements or to optimize the initial design choices. For example, if ICS-Sim shows critical performances on one or more elements of the functional chains of reference (e.g. surveillance sensors, weapons, control logics), the system engineer has the opportunity to intervene exactly where they occur for identifying alternative systems solutions (e.g. use of sensors or weapons or shooting policies more effective) and quickly evaluate the performance improvement.

Conclusions

Capabilities of analysis, simulation and performance evaluation of naval combat systems in multiple configurations, such as integrated performance evaluation of naval combat systems on multi-platform operating scenarios are key competences to efficiently maintain System Design Authority role. Therefore, these capabilities are essential for current programs development, to support new contracts acquisition and, more generally, to innovate products in Defense Systems and Large Systems context.

Multi-scale method applied to analyze naval combat systems through ICS-Sim produced significant results for industrial programs related to Defense Systems.

The approach, methods capabilities and tools constitutes an advanced application in systems engineering capabilities evaluation domain.

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BIOGRAPHY

Elvio Squarcia received master degree in Telecommunications Engineering from ‘Università degli Studi di Pisa’, Pisa (Italy) in 1999. From 2001, he works in ‘SELEX Sistemi Integrati’ and currently hold the position of Numerical Simulation Center Head in the Defense Systems Business Unit.

Vito Gaeta received graduation of ‘Electronical expert’ from ‘IPSIA Duca d’Aosta’, Rome (Italy) in 1979. From 1989, he works in ‘SELEX Sistemi Integrati’ as senior analyst consultant and currently works in Numerical Simulation Center in the Defense Systems Business Unit.

Francesco Ciambra has a master degree in Electronic Engineering and is a senior systems engineer. Currently is the vice president of the Naval Systems engineering Department in SELEX Sistemi Integrati Defence Systems Business Unit, in charge of requirements & performance analysis of Naval Combat Systems. Francesco is a co-Founder of the INCOSE Italian Chapter, and currently is the president elect of the chapter.