Human Factors Issues in a Model Based Systems Engineering Perspective

Daniele Frisoni, Andrea Tocci, Francesco Ciambra, Manuela Nardini
SELEX Sistemi Integrati
Via Tiburtina Km 12,400
00131 – Roma (Italy)
Phone: +0039.06.41504506
E-Mail: dfrisoni@selex-si.com
fciambra@selex-si.com

Abstract. The objective of this paper is the description of design results in the application fields of Human Factors Engineering through an innovative model based systems engineering approach.

Human Factors analyze the system with a human-based approach, looking at the system by the users' perspective, designing interaction with the system according to operator profiles. Operator's interaction with the system is performed through the use of Human Machine Interface mechanism by inserting information to setup system capabilities and checking operational results to monitor system behavior.

The Model Based System Engineering approach allows to build a design structure of system logics through functional and operational chains, focusing on exchanges among system modules. Human Factors studies include also the operator as active part of the functional chains and can therefore be considered as a "module" of the System Model, where all data catalogue is codified in SysML.

This Papers also shows the applications of this concepts in design and modeling of Naval Combat System.

Human Factors in Systems Engineering

Introduction. Human Factors (definition by I.E.A. International Ergonomics Association, 2000) are the scientific disciplines concerned with the understanding of the interactions among human and other elements of a system, and the professions that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance.

Two keywords must be highlighted in the definition: "interactions" and "optimize". Interaction means that the operator is an active entity of the system. Optimization is the objective of the system design.

In order to reach this goal, a top-down functional approach has been followed, that means the whole system has been decomposed into groups of capabilities. On the other side a hierarchical structure of operator roles is defined following operational employment and specific norms and standards.

Assignment of capabilities to roles under constraints of users' workload, responsibility, hierarchy and training is one of the goals of the Human Factors design.

In order to "optimize human well-being and overall system performance" the design must be extended to all the aspects of human interaction. The "real world" around the system has to be part of the model in order to describe Human-System interface.

Human Factors design. The Human Factors approach has seen increasing interest in Naval applications because of embarked crew members' reduction, while increasing the equipments and their capabilities for flexible missions employment of modern multi-role ships.

Therefore Human Factors sciences and engineering are nowadays widely used in the definition of interactions and architecture of Combat Management Systems (CMS) design and crew members' organization for Combat and non-Combat missions of Naval Unit.

The Human Factors design is perceived as critical by the operational branches of Navies. The validation of the System and its acceptance are based on usability assessment of the Human Computer Interface (HCI), which is identified as a fundamental part of the design.

Therefore Human Factors studies have become a relevant part of the System Design and it is now recognized as one of the three main aspects of system design, together with the Requirements Analysis and Interface definitions.

Usability assessment of the system is a process that follows all the design lifecycle, as described in Figure 1.

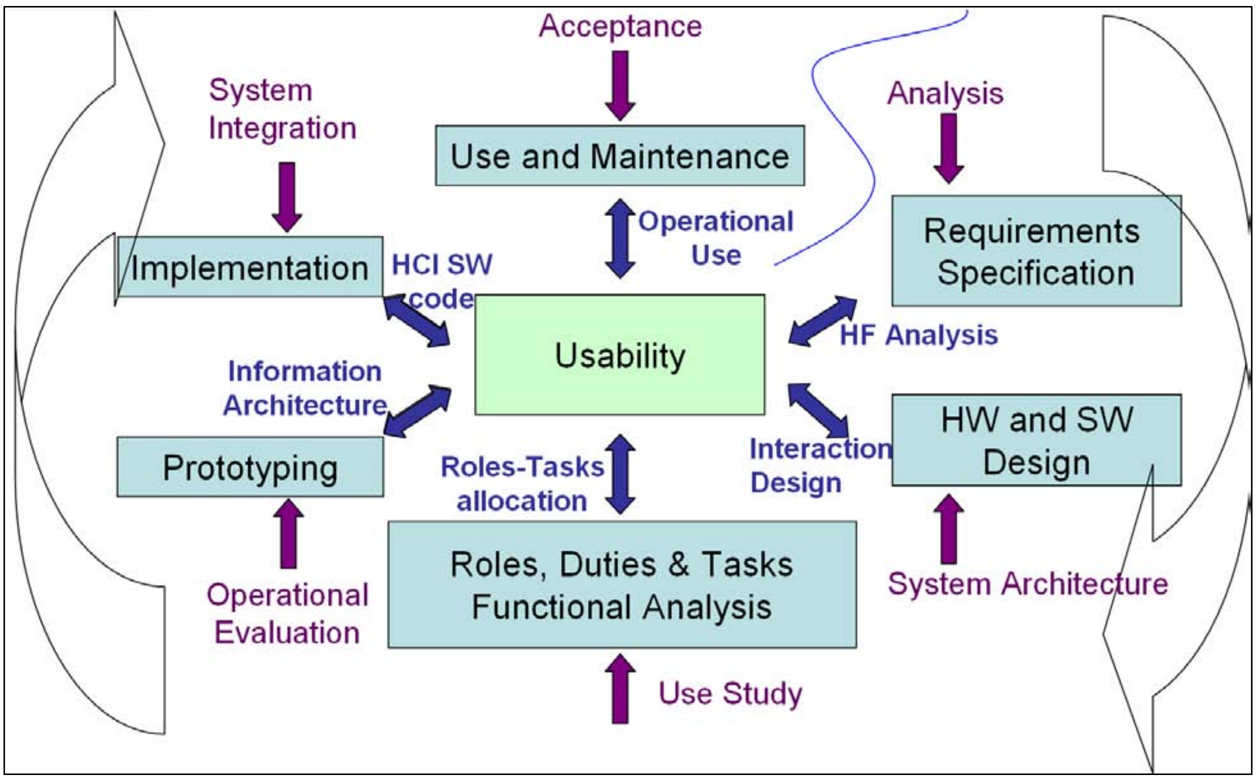

Figure 1. Usability Lifecycle

Following each phase of System Developing (azure boxes) from "Requirements Analysis" to "Use and Maintenance" phase, at each step the usability of the design choices is assessed with operational experts of the customer.

Usability measures customers' confidence on the overall system use and provides hints to the design engineers in order to maximize the benefits of operational feedback.

As the project moves forward, usability feedbacks induce impacts on previous development steps. Returns from the assessment can require changes that could force to re-think design choices.

From a project management point of view, working groups about usability of the systems are widely used to de-risk the whole program plan.

Following Fig. 1 diagram, different aspects of Human Factors are submitted to usability evaluation (blue arrows) with respect to the development phase the program is in:

a) Human Factors Analysis;
b) Interaction Design;
c) Tasks to Roles Allocation;
d) Information Architecture;
e) Human Computer Interface software implementation;
f) Operational Use.

Human Factors Analysis defines two structures:

- Task Analysis Breakdown
- Operator Roles Definition

Task Analysis is performed on system requirements in the early phase of the project. Its goal is to group system capabilities and organize them in modular structures. The minimal item of this decomposition is defined as "task".

The objects of the structure described above are specific with respect to the system. In fact they depend on technologies used and on requirements.

Anyway, for all systems three main areas of capabilities can always be described:

a) **"Gather Information"** includes duties and tasks which are involved in collecting and processing information from the environment and from external entities (e.g. network).
b) **"Conduct Activities"** includes duties and tasks that imply analysis of information, decisional processes, feedback on actions.
c) **"Manage Resources"** includes duties and tasks to manage, command and control resources of the system. The term "resource" in this context is meant with the widest possible meaning (e.g. operators, equipments, tools).

These three definitions describe a workflow that starts with information gathering and representation, goes through analysis of the situations inside/outside the system, then through the elaboration of strategies/tactics of intervention and ends up with the use of system resources to react to the ongoing situation. This flow is continuous and it is replicated until the end of the loop, while the system and the environment evolve.

Operator Tasks are identified defining:

a) Description and other general purpose info
b) Actions: list of the related capabilities, that are provided in order to accomplish the task's objective.
c) Data and information required to perform the task

d) Cooperative environment: operator(s) nominally in charge of the task and possible dependencies from/to the hierarchical organization (e.g. orders flow, delegation)
e) Communications verbal or textual with other operators of the system or with external entities.

Operator Roles definition defines the best crew organization to optimize system performances in different missions and operational scenarios. For systems, like organization of Military Naval Units, the study must also take into account specific norms, standards and training programs used by the customer.

The relationships among operators are defined under constraints like hierarchical dependencies, experience and training, traditions, operational checklists, fields of responsibilities and so on.

Operators are identified listing for each role:

a) Definition and identification of the role (e.g. Admin);
b) Description and explicative info to describe the role;
c) Responsibilities and duties of the role;
d) Relationships with other operators and/or with external actors and entities.

The overall complexity of the system can sometimes be reduced subdividing capabilities in independent sub-components. Therefore operators could be grouped in teams.

A team that "gathers information", another one that "conduct activities" and another one that "manages resources" can be easily defined following system high-level-capabilities. Second-level teams can eventually be defined to further decrease complexity and operators' workload.

A decomposition trade-off has to be found between workload and complexity management on one side and number of operators on the other. Operational requirements can also introduce further constraints in terms of number/skills of people employable in the command and control team.

Well defined fields of responsibility and detailed relationships (both functional and hierarchical) among operators are envisaged to minimize team working mishaps and to avoid inefficient cooperation or hierarchical gaps.

Interaction Design provides technical solutions for HW tools and SW architecture.
Cognitive engineering approach, ergonomics, anthropometry are examples of the disciplines involved in the process of interaction definition. It is defined in design phase of the program.
The interaction of the operator with the system is realized at two levels:

a) Physical level
b) Cognitive level

At a physical level, interaction means the definition of human-computer-interface policies following ergonomic studies about workplace, screens (e.g. resolution and brightness), pointing device usage, operator eye-catching techniques, etc …

At cognitive level, the design of tools is based on process engineering, communication managements, hierarchical operational chains, norms and reference standards for the system's domain. Rules of interactions are decided in order to determine classes of operator actions.

Tasks to Roles Allocation is the process to find optimal solution to the requirement to use the system in the most effective and efficient way.
The first step is to define if different operational configurations are required and to find specific allocations for the different situations.

Different configurations of the system could be activated under different operational scenarios. For example a system could be run by a different number of operators during day-time or night-time, while it is always required to maintain in operative state all the capabilities of the system.

Once the conditions of each operational scenario are defined, a first proposal of system tasks allocation to the foreseen list of roles can be attempted. Further refinements can result from workload assessment and operational evaluation.

The level of flexibility of the allocation can be customized, following operational requirements. Some systems can be designed with a static allocation of tasks to roles, while other systems can require complete flexibility with runtime reallocation of tasks among operators.

Task allocation has to take into account a strong ergonomic constraint: the workload of operators. Workload takes into account responsibility, decision-making processes, cognitive processes and the practical use of the system through its facilities.

Information Architecture is the answer to the complexity of the system and the management by multi-operators distribution of activities. Information architecture solutions are built with three steps:

1) Grouping HCI facilities into operational functions
2) Defining policies for information display
3) Defining actions from the operator to the system (e.g. how to enter data) and vice versa (e.g. how alerts are displayed).

For each operator action, a Human-Computer-Interface (HCI) solution is suggested, using the specific tools employed for the system.
The information architecture is assessed through a prototype of the system HCI. It is often a representation of the final implementation in order to validate look & feel and distribution of the system information.

HCI Software implementation in order to realize what has been designed in the rules definition and through studies. The final Usability assessment and the related operational evaluation tests are performed directly on the interface of the system. This is a critical phase of usability process, because operational evaluation feedbacks could require changes on software implementation.

Operational Use assessment is directly performed on the running system from the target operators in real environment, after the system has been installed and set into work. In the Naval Combat System Domain this step is performed during real operations in a real mission. The usability assessment is performed in the maintenance phase with target users and receiving feedbacks directly from the operational situations.

Human Factors System Modeling

This section shows an innovative model based approach in deal with Human Factors issues using the methodology e usability process described in the previous paragraph and employing SysML Language.

Starting from system specification a SysML requirement is used to represent a textual requirement for Human Factors Analysis. On the System Design Architecture an integrated Model Based Process is performed to represent the Interaction design stage. For the modeling of Use Study Report: Use case, Activity and Class definition with the related diagrams are used to represent the Task Functional Analysis, the Operator Role and its duties and organization. The method rules applied to the Human Factors Model define a link between the Task analysis functional view and the Operator Role architectural view. The operational evaluation is performed on specific views generated with Model Transformation. The System Integration with the Human Factors design is performed as for the system Architecture through the fusion of the System Model with the Human Factors Model.

The System and Human Factors Model represent two different View of the System. From a System perspective a SysML event is used to represent the external actor interaction to the System. The SysML event is also the initial point to describe the internal system behavior through the object sequence diagram.

From a Human Factors perspective the operator interaction with the system is performed with the use of Human Machine Interface techniques (i.e. Console Panel). The operator interaction is in this perspective the object under design.

Hence, the System and Operator views have different approach of a common element: the System-Operator interaction. This concept is summarized in Figure 2.

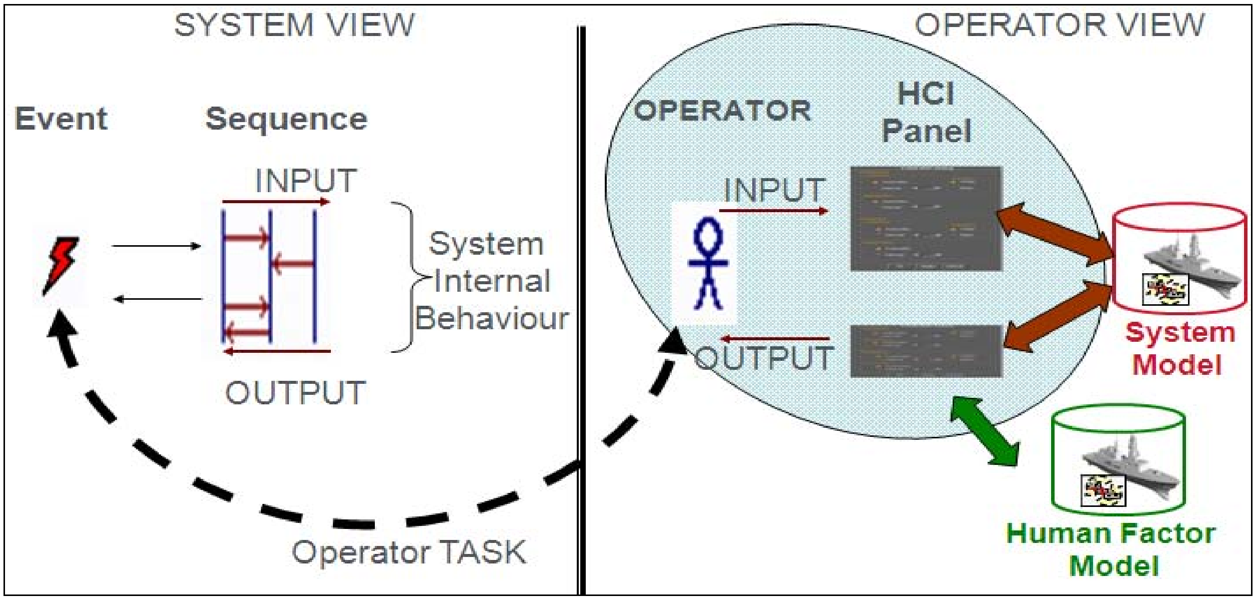

Figure 2. System View Vs. Operator View

One of the important results of this study is the integration of the Human Factors lifecycle in the Integrated System design lifecycle. Both models are parts of a single SysML Model database, and an allocation relationship is performed to link the system model design elements to the Human Factors design elements.

Human Factors model details. This section illustrates the details of how the Human Factor Analysis, the Interaction Design and Task- Role analysis design phases are implemented in the integrated SysML model.

1. Human Factor Analysis
   - Human Factors Requirements Analysis
2. Interaction Design
   - Events
   - Object Sequence Diagram
3. Task- Role analysis
   - Roles Hierarchy specific to Military Naval application, implementing standard references (e.g. NATO standard).
   - Tasks Functional Analysis of the Combat System
   - Tasks Activity Definition
   - Tasks to Roles Allocation in different Readiness States that require specific manning and allocations according to tactical situation

The SysML elements used to model the Human Factor aspects are:

- SysML requirement: to identify the Customer needs from the Human Factors perspective.
- Use Case: to identify the Functional breakdown (FBD) of the main function to realize the human computer interface.
- Activity: to identify the group of action that compose the last function level of the FBD. This activity shall be allocated to the Operator Role depending on the specific Alert state defined.
- Class: To define the Operator Role design in terms of Role and duties. The organization and hierarchy of the operator role is defined using class diagrams.
- Actor: to define Role assignation.

From Human Factor Analysis	**To Human Factor Model**
Requirement Specification	SysML Requirements
Operator Role	Class
Crew Team	Class
Operator Duties	Operation Owned by Op. Role
Doctrine Dependency	Class Diagrams
Task	Use Case
Task Function Analysis	Use Case Diagram
Task Action	Activity Owned by Tasks
Task To Role Allocation	Alert Allocation Stereotype
Action Definition	Movement/Frequency Stereotype

From Human Factor Analysis	To Human Factor Model
Work Load Definition	Parametric Diagram
Alerts	Stereotyped Event

Table 1: Mapping of Human Factor elements into SysML

In the present section the three phases of the Usability lifecycle process are detailed in terms of SysML views used in the Human Factors model study: Requirements Specification, System Architecture Design and Functional Analysis.

Starting from the elicitation of customer needs, a requirement baseline is defined and a functional analysis of the system usability is performed using the Use Case View. The functional decomposition of the requirements is done until the single task definition is performed. Once the Task decomposition is ultimate and the traceability with the requirements baseline is guaranteed, each Task is implemented as a set of elementary operator actions.

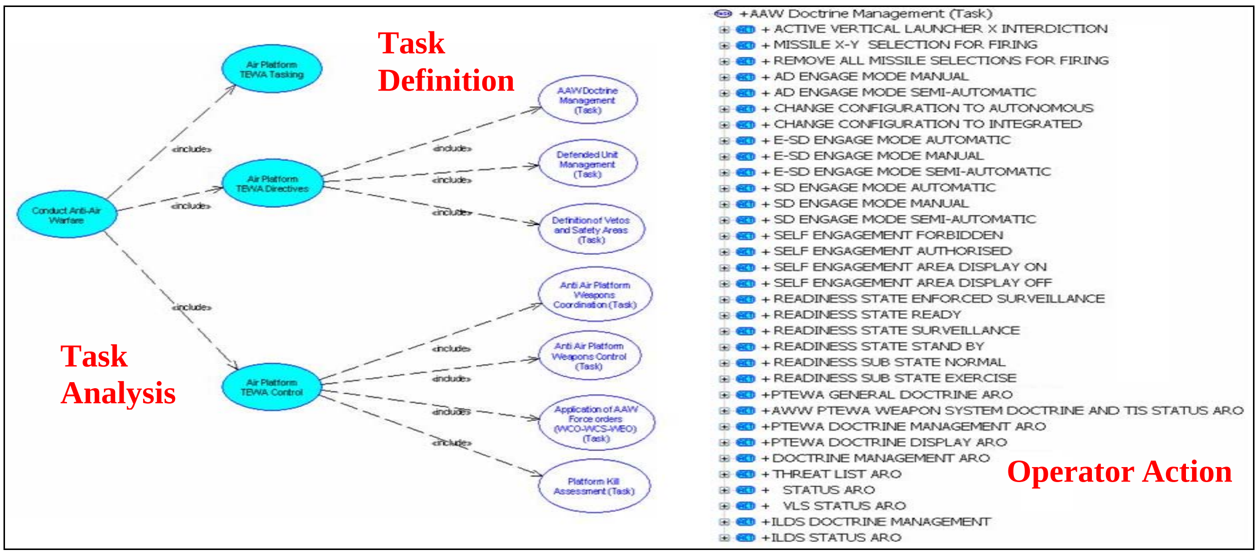

Figure 3. Human Factor Functional View

The operator role analysis represents the Architectural View of the Human Factors aspects. Starting from the crew organization and constraint requirements a SysML model of the Role operator definition and duty is designed. A Class Diagram is used to represent the Crew member organization in terms of Rank structure and hierarchy. This view defined for a single naval ship is directly chained by the Organizational Relationships Chart (OV-4) of architectural frameworks of the whole fleet command and control organization. The Role-Task relationship is performed using a multi-allocation between the Class and the Activity Actions. This approach allows to maintain the Human Factors Functional View and Architectural View full independent each other until the task allocation is performed to a specific solution.

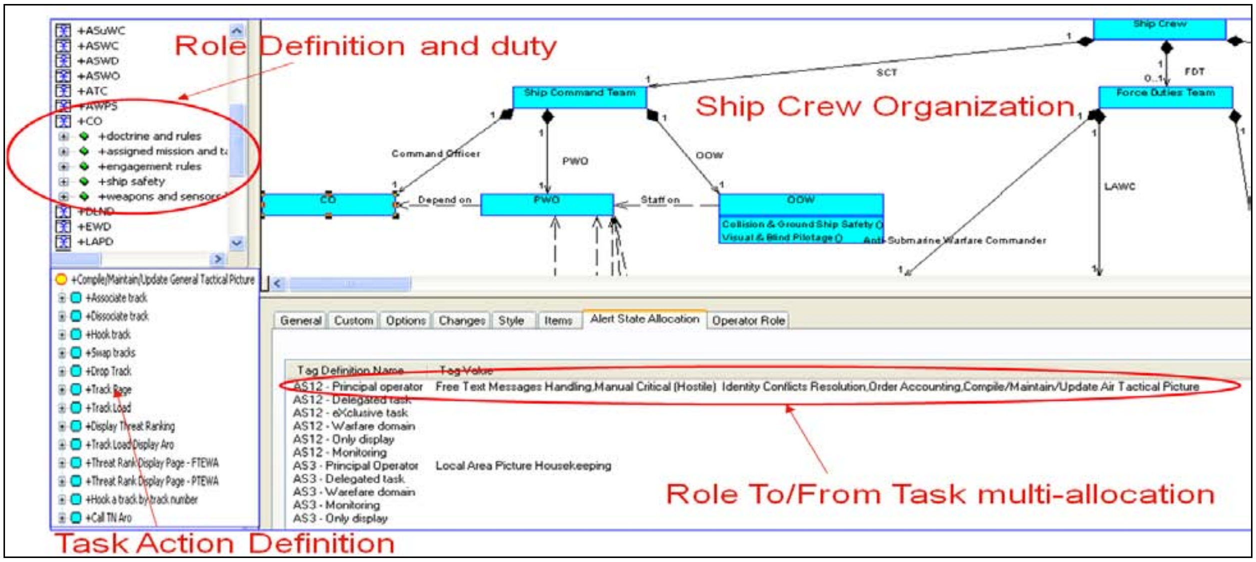

Figure 4. Human Factors Architectural View

The Human Factors Model Design described in the previous section is used to implement the Operator View introduced in the beginning of this section. With the same approach the System Model design is performed using an integrated model based process that covers the entire system lifecycle. Both models, System Design and Human Factors are shown in Figure 5:

- On the left side the allocation of Functional System design to the System implementation;
- On the right side the Human Factor functional analysis and task implementation.

The both side arrow shown in the first picture of this section is performed by the "Allocate to" link between the System Event and the Task Action. In this way is possible to have a check of the system design solution with the Human Factors design solution, in fact, the system event kicks up an internal system interaction defined in the system sequence diagram with the use of software Service Call and Message exchange. The Information carried out by the software service and system message is strictly related to the information that the Operator manages through the Human Machine Interface. At this stage the System Engineer and the Human Factor Engineer can easily review the information details handled by the system and the human machine interface. Another important result of the integration on a single object-based database is the opportunity of design the interface mechanism linking the console panel with the human computer interface software design to avoid the lack of requirements coverage from both sides. Moreover the data structure definition in terms of information data implementation is shared between the System and Human Factors design processes.

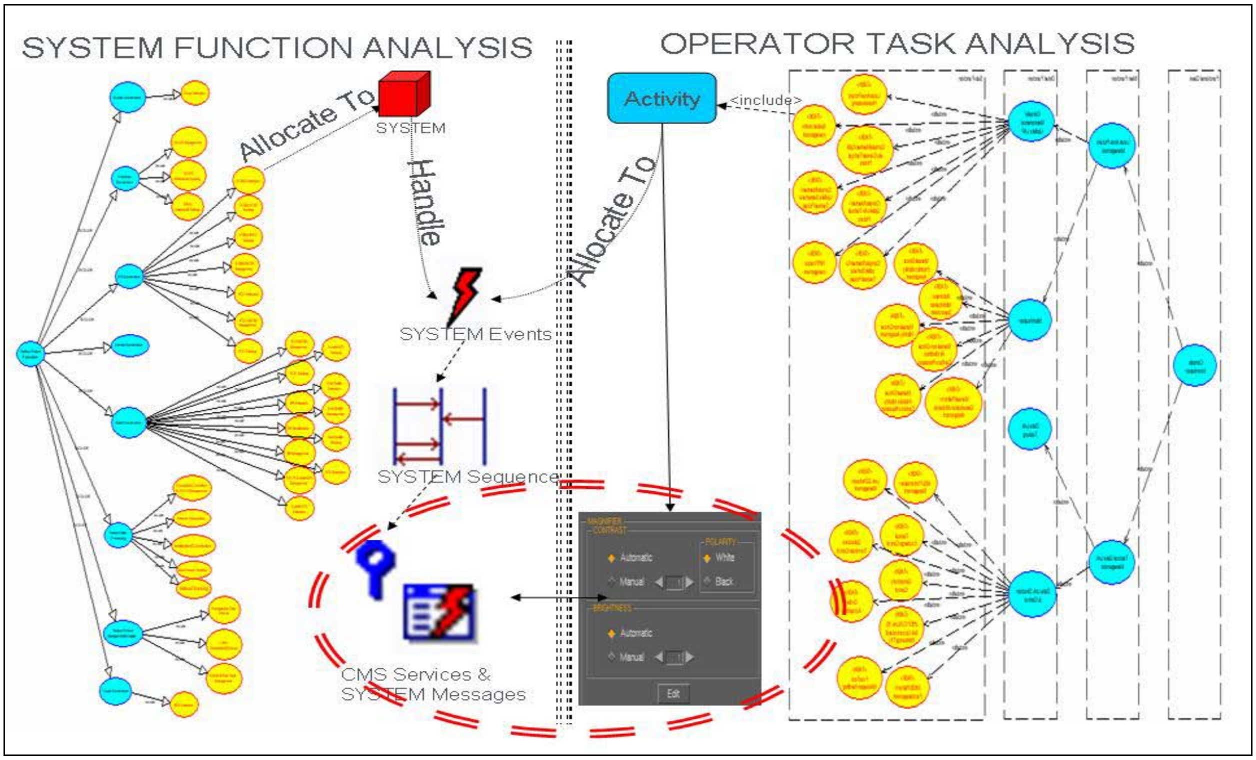

Figure 5. System View vs Operator View in a Model Based Perspective

Benefits. The integration of the Human Factors View with the System View into a unique System Model generates benefits and improvement in each stage of System Life Cycle.

The model based engineering approach in Human Factors design assists in optimizing the Human Computer Interface and hence, what is very important for an efficient team sizing: the operators' workload.

In particular, starting from the information codified into the System model, a specific algorithm has been developed to calculate the operators' workload. It performs calculations on assigned time estimations to every single movement and extracts the action's, task's and duty's assessed workload by grouping actions, following duties-tasks structure.

Every action is weighted by a different number of multipliers with respect to the frequency factor, the stress factor, the operator skills and training factor and the involved decision's responsibility factor associated to the action.

The output of the algorithm is a percentage number, which represents fraction of time spent by operator to carry out his duties and responsibilities. Thresholds can be set to the out coming percentages to warn the Human Factors Engineer of potential overload on specific operators.

The above algorithm allows the *quantitative* estimation of operators' workload thanks to the Human Factor modeling integration with System Model views. The System model born and grows up on the functional modeling approach, that means the whole system is designed and developed around the capabilities that it has to perform in the operative scenarios. The same approach and the integration of system capabilities into operators' tasks and actions allows to assess operators' workload and therefore define the required team size and composition.

The example of the mentioned algorithm with parametric diagrams into the system model is shown in Figure 6.

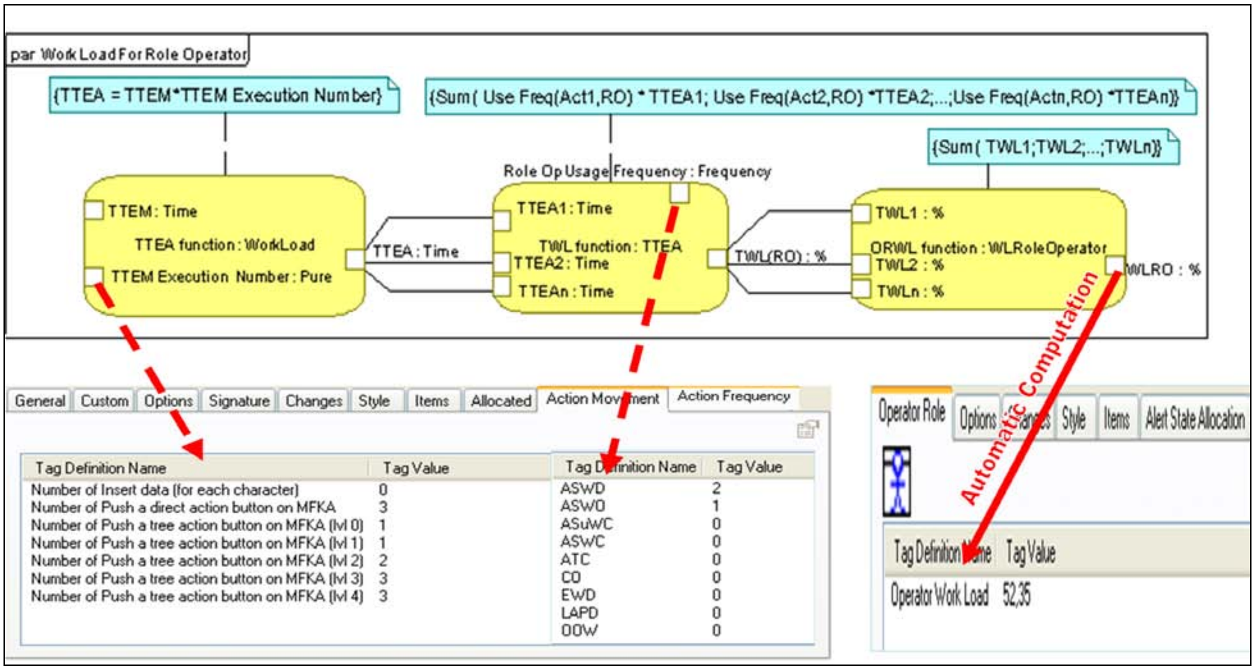

Figure 6. Operators' Workload Assessment Algorithm

One of the most important advantages in modeling Human Factors in the System Model is the possibility to integrate Human Computer Interface data with System data. That issue allows to verify the consistency of Human Computer Interface design with respect to system design that represent the starting point for the development phase of the engineering process.

The integration of Human Factors view into the System model view allows the generation of the primal Human Computer Interface. Linking the Human Factor Model with graphical libraries the exchanged system data can be visualized in the form of Graphical User Interface windows. The resulting objects are a preliminary graphical prototype of the User panels. That is the so-called "Fast Prototyping", an important issue of the project that starting from the early phases of system design allows to anticipate the operational assessment of the Human Computer Interface design and development. In particular, the prototype that has been realized in that way, being based on system model data, allows to optimize the balance between information layout display and system information constraints.

Interface Requirements and Fast Prototyping are both extracted from System Model data and they can be aligned one to the other following design changes and feedbacks. During the development phase, the alignment to modifications and changes is a key issue in a multi-disciplinary, multi-impacts management of changes. Having codified all system data in a single model facilitates the evaluation of changes' impact throughout different design aspects of the system thanks to the strong network of links between Human Factor and System Model elements.

During Integration phase the System Model represents the reference point that is the expected system behavior that during integration and validation phases has to be compared with real recorded data. In particular from the Human Factor point of view the integration of the user in system functional chains, allows the complete verification of data flows to and from the operators. Operational and functional chains are not only key drivers for test plans definition and test descriptions, but also support tools for overall integration with external entities. They are particularly useful to provide insight and verification of the system mechanisms during Acceptance Phase with customers' experts.

Conclusions

The mature experience in System modeling of complex Naval Combat Systems has permitted to extend the application of model based engineering to the Human Factor studies and Human Computer Interface design and definition.

The integration of Human Factor view into a unique System Model has brought a lot of benefits to the whole system design process, in particular the Fast Human Computer Interface Prototype generation that in an automatic way generates the preliminary Graphical-User-Interfaces items (screen interactive windows). The prototype generation, performed at the beginning of the design phase, anticipates the loop of the usability process with the operational experts of the Customer on the first proposal of Human Computer Interface items.

Descending from the integrated model it is possible to automatically extract design documents from the integrated model (e.g. list of system actions designed for each operator, workload assessment).

In the integration phase of the system it is possible to verify the functional chains and check the software implementations following data exchange flows among system items through the operator and vice versa.

Finally this approach allows to build relationship between Human Factors & Systems capabilities in a unique perspective, enhancing the whole system design process efficiency.

References

International Organization for Standardization, ISO 9241 *Ergonomics of Human System Interactions*, `http://www.iso.org/iso/iso_catalogue/`.

Nielsen, J., *Usability Engineering*, Academic Press, 1993

Ciambra, F. and Nardini, M. 2004. *Naval Combat System Design: System Engineering approach and complexity management*. In Proceedings of the Fourteenth Annual International Symposium of the International Council on Systems Engineering (Toulouse). France: INCOSE.

Ciambra, F., Nardini, M., Protano, A., Alessandrini, L. 2007. *Design Method & Model: The Integrated Functional Design of Naval Combat Systems using SysML (Study Case)*. In proceedings of the Maritime Systems and Technology Conference (Genoa). Italy: MAST.

OMG SysML Specification . `http://www.omgsysml.org/#Specification` , 2006.

Technical Board International Council on Systems Engineering (INCOSE). Systems Engineering Handbook , Version 2a, June 2004.

Object Management Group. Systems Engineering Domain Special Interest Group. `http://syseng.omg.org`.

System Engineering with SysML/UML Modeling, Analysis, Design Tim Weilkeins

DoDAF 1.5 Volume I – Provides definitions, guidelines, and background material.

DoDAF 1.5 Volume II – Describes each architecture view work product.

DoDAF 1.5 Volume III – Furnishes the architecture data description.

Biography

Daniele Frisoni received a Master Degree in Aerospace Engineering in 'Università la Sapienza', Roma (Italy) in 1999. Since 2001, he is Human Factors Team Leader for Defence Systems Business Unit (BUSD) division of SELEX Sistemi Integrati SpA. He is member of ANIPLA (Italian Association for Automation).

Andrea Tocci received Master Degree in Computer Engineering from the "Roma Tre" University. Currently he is engaged in Defence Systems Business Unit (BUSD) division of SELEX Sistemi Integrati SpA as a Senior Systems Engineer in charge of naval Combat Systems Design & Modeling.

Manuela Nardini received Master Degree in Telecommunication Engineering from the University of Rome "Tor Vergata". Currently she is employed in Defence Systems Business Unit (BUSD) division of SELEX Sistemi Integrati SpA as a Combat System Senior Engineer. She has defined a formal process for Project Definition of naval Combat Systems based on Model Driven approach using SysML. INCOSE Member.

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 Defence Systems Business Unit (BUSD) of SELEX Sistemi Integrati SpA, 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.