REPORT

TITLE: MAT€S Final Report Abstract

DRL Item or D.R.D. No: STEP 3B

CONTRACT No: **13886/99/NL/JG**
Improving the Effectiveness of the Model and Test Philosophy applied by ESA Programmes

SIGNATURE AND APPROVALS ON ORIGINAL

PREPARED: MAT€S INDUSTRIAL CONSORTIUM

CHECKED: V. BASSO

APPROVED: G. ANDRINA

AUTHORIZED: P. GIORDANO

STUDY MANAGER: P. MESSIDORO

DATA MANAGEMENT:

INTRODUCTION

The Assembly Integration and Verification (AIV) process has an important impact on space project schedule and cost.
In particular the Model and Test Philosophy, which is strictly connected to the project verification approach has a big influence on the overall AIV process. In fact the selection of proper verification strategies in terms of methods (i.e. test, analysis, inspection, etc.), levels (i.e. system, subsystem, equipment) and stages (i.e. qualification, acceptance, pre-launch, etc.) is a driving factor in establishing an optimum AIV program.
The associated Model Philosophy (i.e. structural/thermal model, electrical model, flight or protoflight model) dictates the requirements for test levels and duration's. The consequent test philosophy, from equipment to system levels influences cost and time considering the importance of the test campaign in terms of involved manpower, facilities, Ground Support Equipment and duration.

The increased cost and schedule constraints of space projects require an optimization of the AIV process, which has to be based on a risk assessment exercise supported by dedicated analyses. This exercise should take into account, among others, parameters such as the Test Effectiveness applied to the selected Model and Test Philosophy in comparison with proper standards.

The definition of Test Effectiveness is related to the presence of anomalies during the spacecraft mission. The theory of failure investigation states that a test is effective if it is able to determine a significant portion of these defects before flight. Similarly a Model and Test Philosophy is effective if it allows, through a proper combination of Physical Models and Test requirements, a maximization of the probability to discover defects prior of flight (i.e. minimization of mission risks) within the applicable project cost and time constraints.

The specific Models and Test Requirements are generally derived from the applicable standards by means of a proper tailoring, taking into account the project peculiarities. The European Verification and Testing Standards, for instance the European Cooperation for Space Standardization (ECSS) E-10-02 and E-10-03, are mainly based on tradition or "good practice" and the few studies in this field considered old and limited data.
New requirements, based on recent Model and Test Effectiveness (MAT€) data systematically collected and analyzed, are necessary to substantiate and improve the above standards and consequently to improve the derived Model and Test Philosophies.
While Institutes and industry in the US are regularly addressing the Model and Test Effectiveness, see for example The Aerospace Corporation (TAC) and NASA JPL initiatives, no systematic process is active in ESA or in the European Industry. Definitively also in Europe the interdependencies between the Model and Test Philosophy and the in-orbit performance needs more attention.

The Model and Test Effectiveness Database (MAT€D) is the European initiative to answer to the above identified needs and expectations. It can represent a European repository of the most significant AIV process data of space projects and offers, with the application of suitable methodologies, the possibility to analyze the collected data in order to improve the European AIV standards and approaches. The results will be beneficial to all the European space community and more in general to the world-wide space community.

The MAT€D data and the associated methodologies represent the fundamental output of the Model and Test Effectiveness Study (MAT€S) whose results are summarized in the content of this Final Report Abstract.

2. STUDY OBJECTIVES AND LOGIC

The MAT€S has been carried-out, under the ESA contract No. 13886/99/nl/jg "Improving the Effectiveness of the Model and Test Philosophy Applied by ESA Programs", by an industrial consortium including Alenia Spazio (ALS) as prime contractor (involving expertise from both Turin and Rome plants) and Astrium GmbH (the former Dornier Satellite System in Friedrichshafen) as subcontractor.

The contract is part of the ESA General Study Program (GSP) and covered an 18 months time frame (i.e. from November '99 until May 2001).

In line with the background scenario described in the above introduction, the detailed MAT€S objectives were the following:

- To assess the state-of-the-art in the MAT€ domain and the available data sources
- To analyze the AIV process as defined in the European Standard (i.e. ECSS) identifying cost drivers and improvement trends
- To identify the methodologies for the analysis of the associated AIV data
- To realize a prototype of the MAT€D which basically archives anomalies on ground and in-orbit and other AIV data of the Space Programs
- To populate the MAT€D with data from several projects in development and operation (from application and scientific missions)
- To carry-out a first set of analyses to demonstrate the validity of the concept and the associated methodologies
- To recommend methodologies for the utilization of the analysis results in view of the European standards updating and maintenance
- To evaluate future development towards an operative system in which project AIV data are collected and common statistics originated.

The Fig. 2-1 shows the logical flow of the study activities in the three different phases where Progress Meetings and Reviews with ESA are also indicated. For instance Step 1A means Step A of Phase 1.

The following sections summarize the details of the MAT€S activities and the associated results.

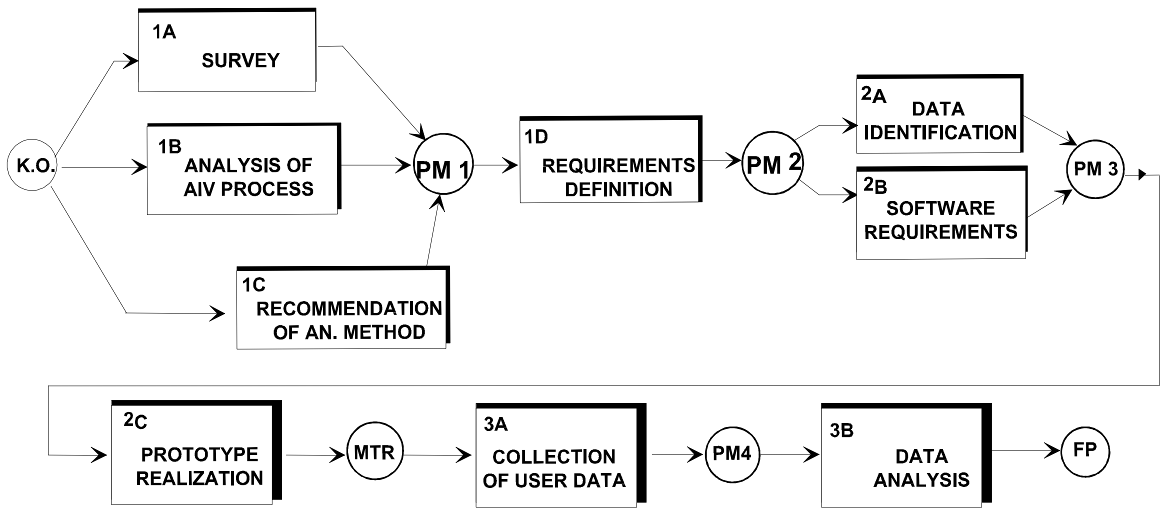

Fig. 2-1 - MAT€S STUDY LOGIC

3. STUDY RESULTS

3.1 Survey

The activities activities carried-out in the **step 1A "Survey"** included the assessment of the state-of-the-art for the MAT€ in Europe and the world, as well as the possible study data sources in industry and in ESA.

Concerning the **MAT€ state-of-the-art**, a total of 150 References (i.e. papers, reports, etc.) have been evaluated and its content summarized on the basis of the experience of the MAT€S Industrial Consortium.
Contradictions in the available data have been highlighted which confirm the need and the potential benefits of the study.

In terms of Model and Test Philosophies, reflected in the applicable standards, significant differences (in terms of type of test, margins, levels and duration) exist between the approaches applied in Europe and in US as highlighted in previous studies.
For example, Fig. 3.1-1 shows discrepancies between ESA and MIL Standards for equipment qualifications, as resulting from an ALS internal study (1996).

TEST	CATEGORY OF EQUIPMENT												NOTE
	ELECTRICAL EQUIPMENT	ANTENNAS	BATTERIES	VALVES	FLUID/PROP. EQUIPMENT	PRESSURE VESSELS	THRUSTERS	THERMAL EQUIPMENT	OPTICAL EQUIPMENT	MECHANICAL EQUIPMENT	MECH. MOV. ASSEMBLY	SOLAR ARRAYS	
Functional & Perf. [1]	R	R	R	R	R	R	R	R	R	-	R	/R	1. Before and after env. Tests 2. Acoustic or Vibration 3. On sealed pressurized equipment 4. In orbit active equipment 5. On equipment exp. to vacuum or sensitive to it 6. Eq. for manned spacecraft
Thermal Vacuum [5]	R	R	R	R	R	O	R	R	R	O	R	/R	
Thermal Cycling	R	R/-	R/-	R/-	R/-	O/-	R/-	R/-	R/-	R/-	R/-	/-	
Vibration	R	R[2]	R	R	R	R	R	R	R	R/O	R	/R[2]	
Acoustic	-/O	R[2]	-	O	O/-	-	-	-	-/R[2]	O/-	O	/R[2]	
Shock	R	O	O	O	O	-/O	O	O	O	-/O	-/O	/O	
Acceleration	O	R	O	O/-	-	O	-	-	R	-	-/O	/O	
Humidity	O	O	O	O	O	O	O	O	O	O/-	O	/O	
Pressure	R[3]	-	R[3]	R	R	R	R	-/O	-	-	-/R[3]	/-	
Leak	R[3]	-	R[3]	R	R	R	O	O	-	-	-/R[3]	/-	
EMC/ESD	R	O	-/O	R/-	O/-	-	O/-	-	-	-	-/O	/-	
Life	O	O	O/R	O	O	O/R	O/R	O	O	O	O	/O	
Microgravity [4]	R/	R/	-/	R/	R/	-/	R/	-/	R/	R/	R/		
Physical Properties	R/	R/	R/	R/	R/	R/	R/	R/	R/	R/	R/		
Audible Noise [6]	R/	R/	R/	R/	R/	R/	R/	R/	-/	R/	R/		

R = REQUIRED **O = OPTIONAL** **- = NO REQUIREMENT** **ESA/MIL STD** **DISCREPANCIES**

Fig. 3.1-1 – EQUIPMENT QUALIFICATION (ALS)

The European common practice in Model Philosophy, reflected in the ECSS "Verification" standard E-10-02A (17/11/98), is the "hybrid approach". This means at system level partial qualification models associated with the protoflight model, in presence of tendencies towards protoflight approach in one-of-a-kind spacecraft and prototype approach on production/constellation. The European common practice in test philosophy consists in a suitable tailoring of the applicable standard ECSS "Testing" (E-10-03) on the basis of the project peculiarities.

The American practice is reflected in standards like:

- MIL-PRF-1540 C with the associated MIL-HDBK-340A
- NASA GEVS (Goddard)
- NASA JPL D-13277 ("Faster, better and cheaper")
- NASA SSP41172 (Space Station)

In Japan it exists the NASDA-STD-15 which reflects basically the European practices.
At international level an ISO WD 15864 is actually in preparation.

In terms of identification of AIV cost drivers and risks, studies are in progress in ESA and in industry which investigate concepts like: concurrent engineering, design to test, activities standardization, paperless work-flow, robust design, automation of integration checks, non-invasive testing, analysis of test added value, digital mock-up and simulation.
For example Fig. 3.1-2 shows the islands concepts resulted by the analysis of the AIV process in its first application on the Globalstar satellite series production in ALS.

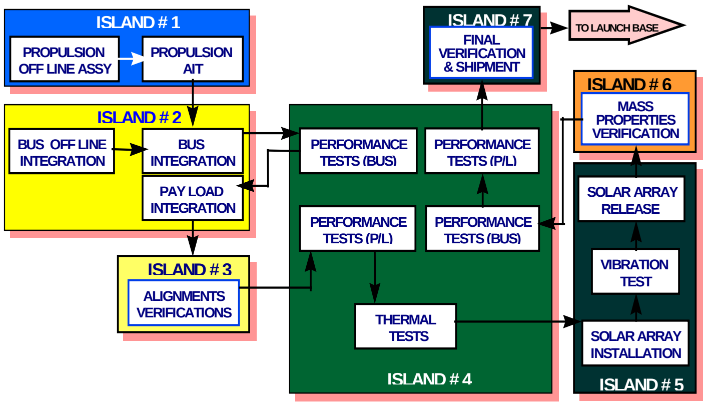

Fig. 3.1-2 – ACTUAL GLOBALSTAR ISLAND CONCEPTUAL ORGANIZATION (ALS)

In USA three schools of test philosophies are followed:

- Full system verification approach (reflected in MIL-STD and NASA GSFC documents)
- Faster, Better and Cheaper (reflected in NASA/JPL "risk management" approaches)
- Process control approach – 6 sigma (reflected for instance in the IRIDIUM Project)

Detailed studies identified as major cost drivers: unit level thermal qualification, vehicle level thermal and dynamic acceptance. Fig. 3.1-3 shows for instance the actual situation for the vehicle level dynamic test requirements.

In terms of test effectiveness, the recent European initiative are few and sporadic, nevertheless their results confirm, for one-of-a-kind spacecraft, the effectiveness of functional, EMC and thermal testing and the reduced importance of vibration; for mass production acceptance, the possibilities to apply the lot testing concept (e.g. thermal vacuum test performed only every a certain number of S/C's on the basis of the process results).

In USA NASA Goddard and JPL carried-out several test effectiveness studies based on their SOAR and P/FR failure databases.
In particular JPL performed an "Environmental Test Effectiveness Analyses (ETEA)" study funded by NASA HQ (see in Fig. 3.1-4 a typical result).
TAC is performing the most complete test effectiveness analyses based on their Space Systems Engineering Database (SSED), deriving the test effectiveness of system acceptance test campaign (acoustic 15%, thermal up to 80% with 4 cycles) and the Model and Test Philosophy Effectiveness (i.e. probability of early flight failures as a function of the index of thoroughness with respect to the MIL-STD-1540).

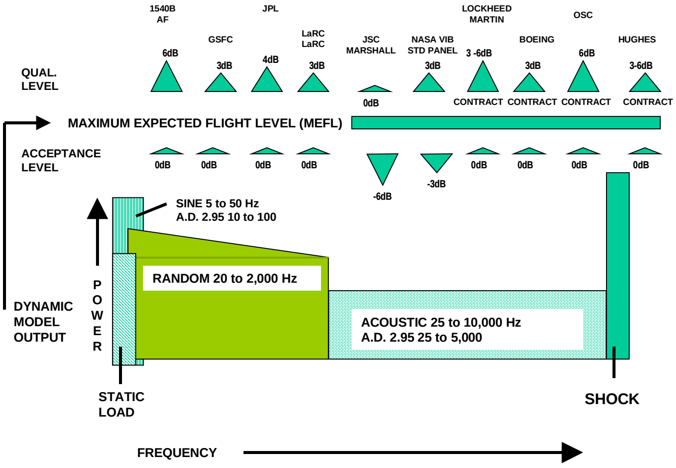

Fig. 3.1-3 – COMPARISON OF VEHICLE – LEVEL DYNAMIC TEST REQUIREMENTS (NASA)

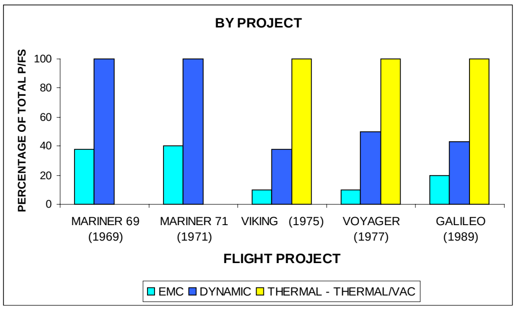

Fig. 3.1-4 – EQUIPMENT LEVEL PROBLEM/FAILURES VS TEST ENVIRONMENT (NASA/JPL)

Fig. 3.1-5 shows an example of Test Effectiveness algorithm in the acceptance campaign as per TAC analyses.
US industry carries-out sporadic initiatives mainly in presence of mass production projects.

In terms of failure frequency distribution during test and flight, the European results indicate for example that: 1) in the case of series production testing, after completing a few satellites (three in the ALS Globalstar experience), the level of failures due to design problems is almost zero; 2) in the case of feed-back from the flight anomalies, the critical hardware are gyro's and high thrust propulsion and mechanisms on which more test screening is suggested.

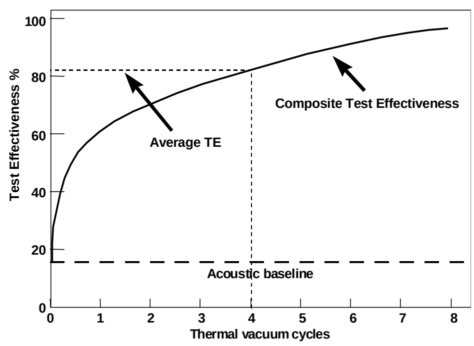

Fig. 3.1-5 – EXAMPLE OF TEST EFFECTIVENESS ALGORITHM (TAC)

In the rest of the world, TAC is studying the concepts of: reliability growth (each exposure to environments increases the reliability – see Fig. 3.1-6), on-orbit failure distribution (due to redundancies the hardware life is maintained almost unchanged), infant mortality (increased failure distribution during first 90 days in-orbit).
The Canadian CSAT results based on a public domain failures database involving in particular commercial TLC satellites, are that: the infant mortality theory has to be demonstrated; the most critical S/S's in terms of number of failures are Payload, AOCS and TT&C; if the cost impact on the mission is considered, the importance of RCS and mechanisms increases.

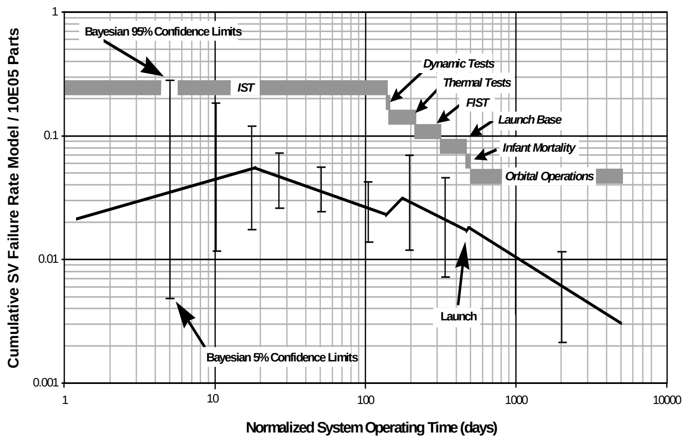

Fig. 3.1-6 – NORMALIZED SV DUANE RELIABILITY GROWTH (TAC)

In terms of alternative Verification Methods, in spite of the different definitions of the verification methods, both in Europe and USA more emphasis is put on analysis and simulation in alternative or complement to test while alternative testing methodologies are being investigated in thermal test (e.g. infrared technique on Globalstar in ALS and on M-SAT in SPAR/DFL), EMC test (self compatibility approach on XMM and new statistical approach in USA), Mechanical Test (centrifuge, transient, force control technique, new shock and accelerated vibration techniques).

In terms of heritage vs risk, the tendency of the maximum re-utilization of hardware/software is confirmed, limiting the new development areas to those peculiar to the mission, absorbing the subsystem level in the system activities, adopting modular approach with recurrent platforms, (see for example XMM/Integral experience).

In terms of margin vs risk, in Europe studies have been carried-out on design margins like the "In Orbit Feedback" (Astrium-F) on margin optimization and ACTOR (ALS) introducing the "robust design" concept. The European test margins common practice is reflected in ECSS-E-10-03.
In USA: VITRO Corporation compared different margin philosophies and proposed new test margin values and new design margin approaches like "robust design" concept.
NASA summarized US industrial and government philosophies on test margins, which supported reduction of conservatism's in certain areas (e.g. qualification margins from 6dB to 3dB in dynamics).

In terms of realism in the environmental specifications, the most interesting experience in Europe is the standardization of mechanical and vibration tests requirements carried-out by Intespace and reflected in ECSS-E-10-03 "Testing" standard. In US a request of reduction in conservatism's is emerging from the industry.

Concerning the second objective of the Step 1A of the study, related to the **possible data sources**, a total of more than 300 (i.e. AIV documents, failure data bases etc.) have been identified on 24 different projects (7 of which available for the study). It has been confirmed that, in general, sufficient data exist (in terms of quantity and quality) in the industrial consortium to adequately pursue the study objectives. Additional support from ESA and Italian Space Agency (ASI) has been considered necessary to improve the level of information for the on-orbit anomalies.

3.2 Analysis of the AIV Process

The activities carried-out in the **step 1B "Analysis of the AIV process"** included the investigation of the typical ESA AIV process with the derivation of the relevant cost/time drivers and the identification of the expected trends towards more effective Model and Test Philosophies.

Concerning the **investigation of the typical AIV process**, the standard ESA process has been compared with actual projects (7) recently carried-out in the industrial consortium. The resulting standard AIV process activities (65) have been investigated and the cost/time drivers identified.

In terms of AIV process investigation, the typical activities have been analyzed taking into account industrial consortium experience on ESA and non-ESA projects (including commercial). Particular emphasis has been devoted to the AIV activities involving environmental testing and associated AIV tools (e.g. GSE, Test Facilities, etc.). A synthesis table has been filled including the following information for each activity: Requirement source(s), links with other verification activities, typical duration/cost, time/cost drivers, time/cost parameters, alternative method and associated risks. From the synthesis, the following results have been derived: top ten AIV process activities in terms of duration (see Fig. 3.2-1), top ten AIV process activities in terms of cost, distribution of total and specific costs for the identified groups of activities, percentage of Manpower, Documentation, Facility and GSE direct cost in the total AIV process (see Fig. 3.2-2).
The relevance of integration activities and associated GSE costs has been confirmed, while thermal and mechanical tests have been highlighted as the most important in the environmental campaign together with the associated facility cost.
Concerning the second objective of step 1B (i.e. **the expected trends in Model and Test Philosophies**), a survey of ESA project groups has been performed through a questionnaire and the results have been analyzed; in addition the industry perspective has been evaluated.

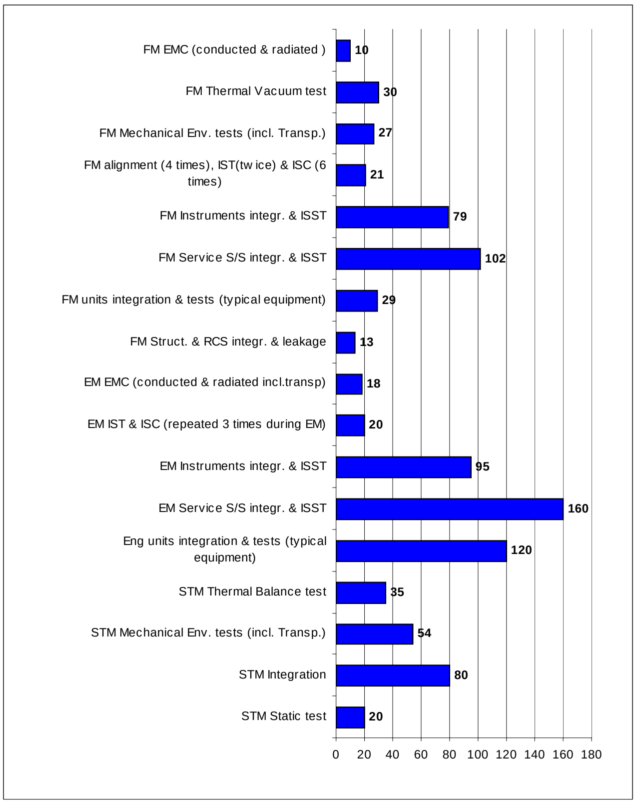

Fig. 3.2-1 – AIV ACTIVITIES DURATION

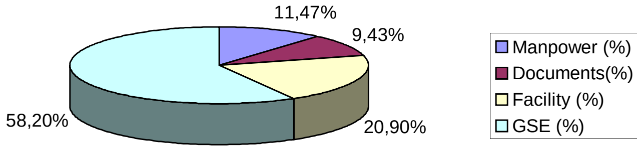

Fig. 3.2-2 – DISTRIBUTION OF COSTS IN THE TOTAL AIV PROCESS

In the questionnaire to the managers of the ESA project groups the following aspects have been covered with the indicated main results in terms of expected trends in Model and Test Philosophies.

- Effective Model Philosophy and associated Models (for one-of-a-kind spacecraft: hybrid approach, EM substituted by test bench, SM only with possibility to re-use the structure, EMC/RFC qualification by analysis; for series production: prototype philosophy or protoflight in case of recurrent platform)
- Effectiveness of qualification and acceptance tests (in qualification: use of transient, deletion of thermal balance, reduction of EMC/RFC; in acceptance: acoustic and thermal vacuum most effective, sine vibration effectiveness controversial)
- On-orbit critical subsystems and equipment (more critical: AOCS, Mechanism, instruments of new development, TWA's and RF switches in communication payloads, propulsion, software; less critical: electrical boxes for mechanical aspects)
- Cost/time drivers in the AIV process (test activities: TB/TV, Sine Vibration, EMC, Acoustic, system functional test, mechanism test, RFC and S/W Test; EGSE; Re-configuration of test items among different tests; certain non-test activities: combination of analysis and test, AIV team organization, Test preparation, transportation, trouble-shooting)
- Expected trends in AIV process (general: reduction of budgets, different contractual relationship i.e. fixed prices, industry to share risks; particular: more analysis with reliable analytical models, new test methodologies i.e. shogun/multi-axis/transient, more automation and commonality test vs operations, more standardization and design to test)

Specific factors for AIV improvements (see the table of Fig. 3.2-3).

– **Verification by test and/or analysis**	**= + analysis**
– **Modular testing**	**= OK depending on size**
– **Combined test methods**	**= no experience in Europe**
– **Deletion of sine vibration**	**= controversial**
– **Reduction of thermal cycles**	**= controversial at equipment level OK at system level**
– **Influence of Delta T in TV**	**= important**
– **Thermal Vacuum Vs Thermal Test in air**	**= to be investigated, but satellite (and its part) should be exposed at least once to TV**
– **Optimum functional verification in TV**	**= controversial**
– **Optimum Modal survey test Methods**	**= to be investigated (on shaker)**
– **Transient test**	**= to be investigated**
– **Centrifuge Test**	**= limited by size and configuration**
– **Force Control Test**	**= to be investigated**
– **Optimum Equipment Test sequence**	**= suggested with a certain logic**
– **Deletion of third axis in vibration**	**= OK in acceptance**
– **Optimum test margins**	**= actual std is OK**
– **Reduction of STM**	**= OK for thermal Balance**
– **Optimum Integration Sequence**	**= suggested with a certain logic**
– **Optimum EMC Test approach**	**= conducted in clean room, radiated to be substitutes by analysis in future**
– **Infant mortality theory**	**= no specific opinion**
– **Other suggestions for optimization**	**= in-orbit verification, test instrumentation as part of on-board design, organization of project team, independent verification approach, verification data base, commonality with ground segment, reduction of failures due to operation errors, flight S/W verification**

Fig. 3.2-3 – SPECIFIC FACTORS FOR AIV IMPROVEMENTS

Considering the AIV trends for the industry, the industrial perspective has been evaluated in terms of tendencies, factors and impact on the AIV process in several areas (see Fig. 3.2-4).

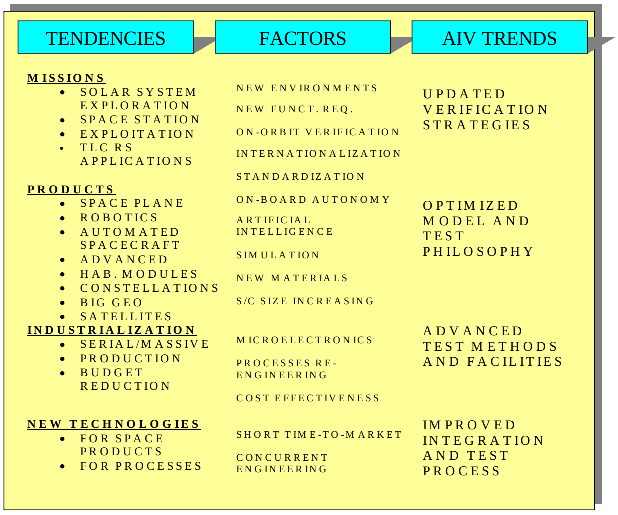

Figure 3.2-4, AIV TRENDS FOR INDUSTRY

In general the results are coherent with the ESA project groups ones, although more innovative for certain aspects due to the commercial pressure.

In particular the following trends have been identified:

- Increased role of simulation in the verification strategies
- In the model and test philosophies, increased application of rapid prototyping concept, utilization of off-the-shelf H/W and S/W, stressing of modularity (plug-in concept), emphasis on design to test/integration (built-in testing), divergence in the approach for one-of-a-kind (protoflight with minimum qualification model activities) and series production (full qualification prototype model with minimum acceptance on FM)
- In the advanced test methods and facilities, reduction of test condition conservatism's, new facilities for MARS simulation and aero-thermal verification, increased use of combined test approach, application of accelerated testing technique
- In the improved integration and test process, maximum automation of integration and test activities, use of digital mock-up, increased commonality between GSE and Mission Control System, application of tele-testing.

3.3 Recommendation of Analysis methodologies

The activities carried-out in the **step 1C "Recommendation of Analysis Methodologies"** included the summary of the Test effectiveness investigations, the preliminary identification of MAT€D data and of the recommended analysis methodologies.

Concerning the **summary of Test effectiveness investigations** it has been based on the MAT€ state-of-the-art of step 1A. A total of 37 different types of analysis have been listed in terms of description of the method, utilized data, results with examples, references to the MAT€S survey and status of the activity.

Concerning the **preliminary identification of MAT€D data** the following categories of data have been identified; Project Data, AIV Process Data, NCR data and Flight Anomaly Data, as shown in Fig. 3.3-1.

Concerning the **recommended analysis methodologies**, the output was the following: four different levels of analysis, pre-definable and customizable (i.e. including three parameters) involving all the data or a subset of them, each level of analysis could in principle use actual or theoretical data, each level of analysis could generate "lessons learned" to improve ECSS standards.

The schematic of Fig. 3.3-2 shows the concept of MAT€D recommended analysis methodologies.

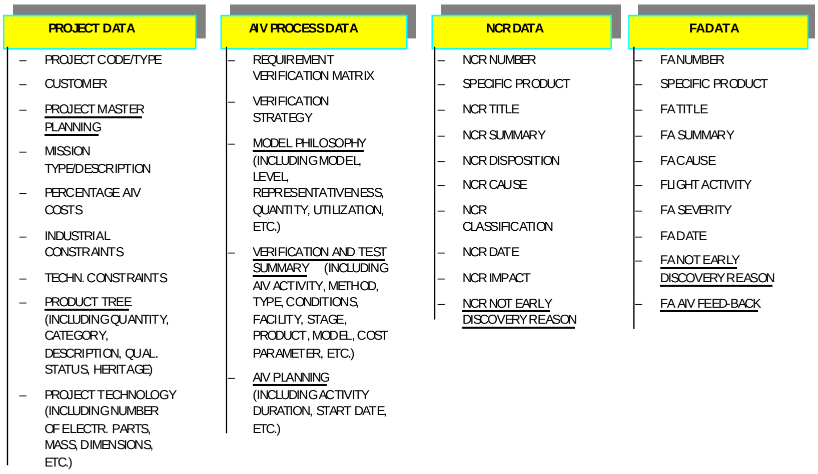

Fig. 3.3-1 – MAT€D DATA

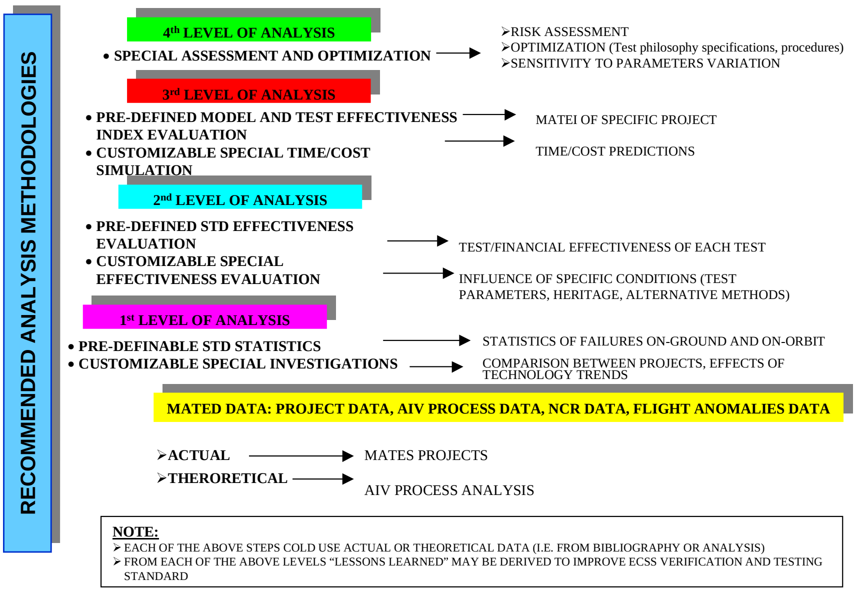

Fig. 3.3-2 – RECOMMENDED ANALYSIS METHODOLOGIES

3.4 MAT€D Prototype Development

The activities carried-out in the **steps 1D "Requirements Definition", 2A "Data Identification", 2B "Software Requirements" and 2C "Prototype Realization"** included the MAT€D software life cycle from the user requirement up to the coding and testing of the prototype.

In particular a spiral implementation approach (in line with ESA PSS-05 for not critical ground software) has been selected for MAT€D software development. It sees the completion of a Version 1 (V1) by the end of MAT€S and the preparation of a Version 2 (V2) in the subsequent pre-operative phase not covered by the actual contract. A "MAT€D User Requirement Document (URD)" has been prepared and agreed between ESA and the Industrial Consortium. It contains MAT€D functional, implementation, operational and interfaces requirements together with the associated implementation planning. A "MAT€D Software Requirement Document (SRD)" has been derived together with the "MAT€D Architectural Design Document (ADD) / Detailed Design Document (DDD)", the "MAT€D Interface Control Document (ICD)" and the "MAT€D Software User Manual (SUM)" which included the Acceptance Test Procedure.

The MAT€D general functions are the following:

- Archive actual data on the anomalies of different spacecraft's occurred during on-ground testing and flight operations;
- Archive data on the AIV process of different spacecraft's with particular emphasis on the cost drivers activities;
- Provide data analysis functions which supports identified methodologies for test effectiveness evaluation and AIV program optimization purposes;
- Ensure security of data, remote and multiple access, flexibility in installation and utilization.

The MAT€D architecture is based on a commercial RDMS with a client/sever approach compatible with the WEB. Its logical design is shown in fig. 3.4-1.

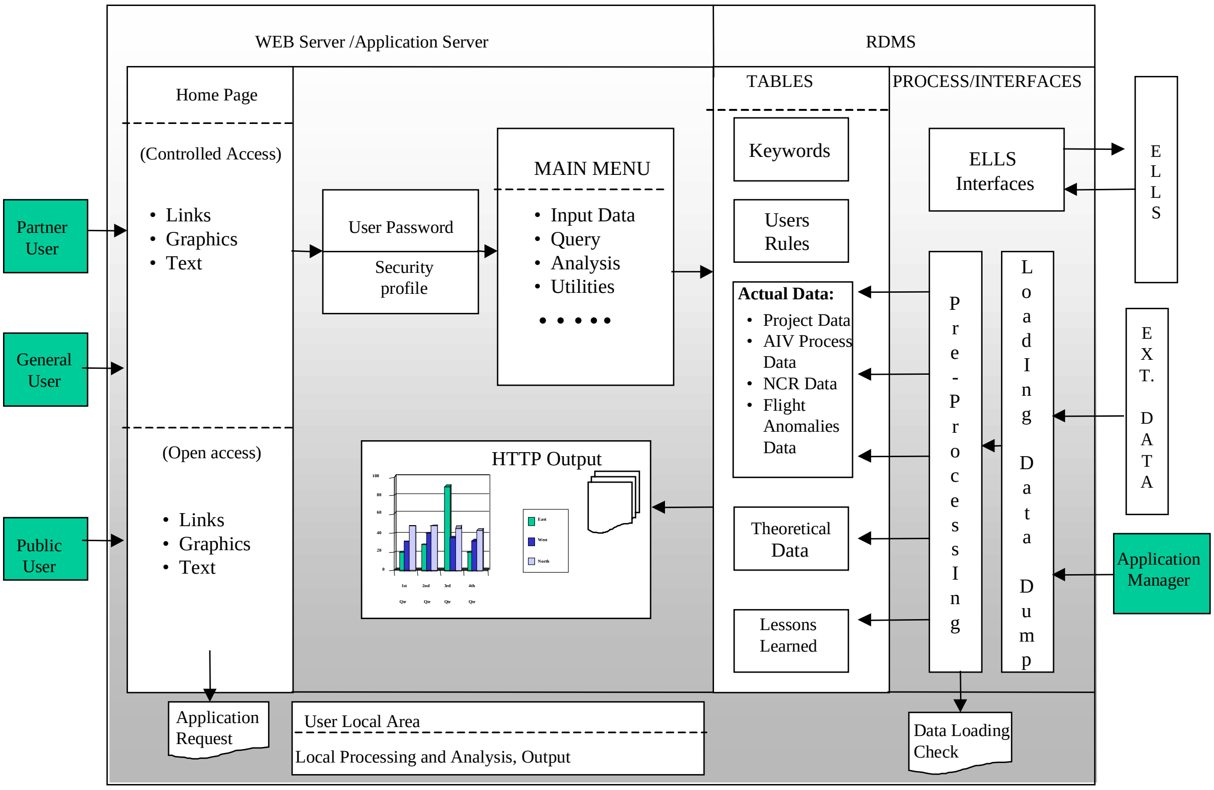

Fig. 3.4-1 - MAT€D LOGICAL DESIGN

3.5 Collection of User Data

The activities carried-out in the **step 3A "Collection of User Data"** included the population of the MAT€D with the data of the selected pilot projects and the validation of the MAT€D and its SUM for their functions, especially for the import of the data.

Concerning the **MAT€D population**, the Project Data, AIV Process Data, NCR Data and Flight Anomalies Data of 7 pilot projects (4 scientific and 3 application, 5 ESA and 2 non ESA, 5 in Operation and 2 in development) have

been collected by the Industrial Consortium with the support of ESA for the flight anomalies, through a stage in ESOC.
The MAT€D batch loading functions have been utilized, in the operational scenario shown in Fig. 3.5-1, to import the data using the standard I/F ASCII file. The file has been originated by filling an EXCEL table in line with the instructions of MAT€D ICD filtering existing company data bases or using an “ad hoc” MAT€D “Database Loader”. Refinement of data has been executed by means of MAT€D on line interface capabilities.
With reference to the mentioned 7 projects of ALS Turin, ALS Rome and Astrium Friedrichshafen the populated MAT€D presents the following statistics:

- 14(P) FM’s, 5 E(Q)M’s, 5 S(T)M in the Model Philosophies
- about 800 products in the Project Data
- more than 300 AIV activities in the AIV Process Data
- about 400 NCR’s collected among more than 10000 reviewed
- about 50 FA’s collected among more than 1000 reviewed

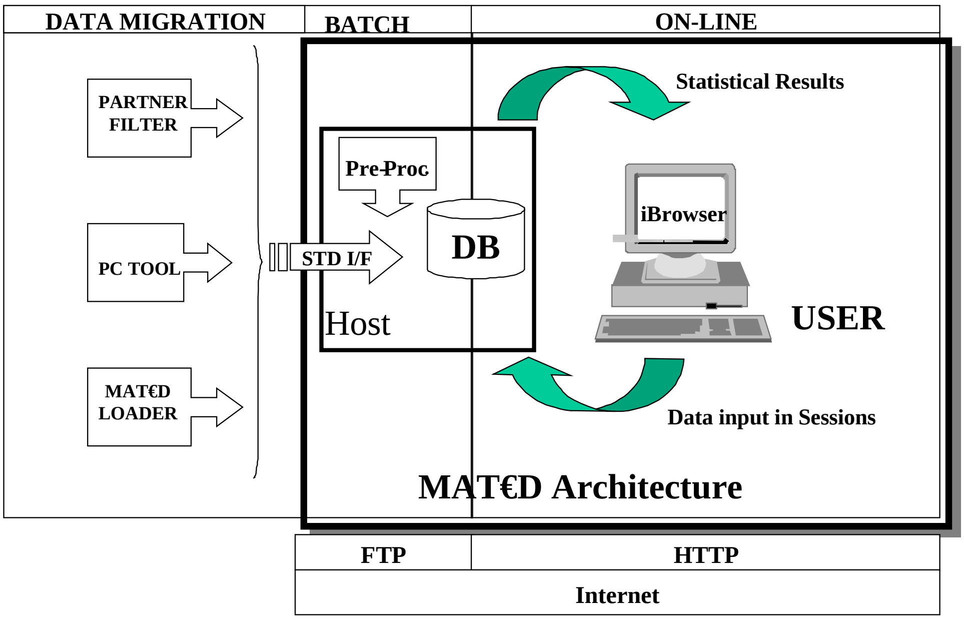

Fig. 3.5-1 - MAT€D OPERATIONAL SCENARIO

The following major difficulties have been experienced in the population of MAT€D through the collection of pilot projects historical data:

- some of the data sources were incomplete and the company expertise’s difficult to be recovered (especially in the lower level data and for schedule/cost aspects)
- due to the splitting of responsibility among industry, customer and scientific organizations some of the FA data and/or their interpretation were difficult to be collected (especially for the payloads)
- some of the oldest projects (started more than 10 years ago) didn’t have data base of NCR’s, therefore it was difficult to recover the paper forms
- in spite of the existing good level of standardization of the NCR format (through projects, companies and customers), its actual filling and in particular the anomalies classification in far to be standard, this fact originated the need to practically review each NCR classification.

On the light of the above identified difficulties, the pilot projects system level AIV and NCR data have been completely collected while the lower level data will be subject to an additional effort in the following pre-operational phase. The Flight Anomalies data have been substantially collected with the exception of some of the anomalies relevant to the payloads, which are in principle less important for the MAT€S objectives, being the payloads not the primary focus of the MAT€ analyses (i.e. not standard, not recurring).

Concerning the **validation of the MAT€D functions and its SUM** the activities has been completely carried-out for the part involved in the step 3A. In particular the Verification Matrix of the URD has been filled on the basis of the verification close-out activities with Review of Design and Test. Requirement traceability with SRD has been also provided.

3.6 Data Analysis

The activities carried-out in the **step 3B "Data analysis"** included the MAT€D preliminary analysis results, the recommendations for the standard adaptation and the recommendations for the MAT€D operative phase.
Concerning the **MAT€D preliminary analysis results** a total of more than 150 analyses have been carried-out and its content commented on the light of the MAT€S objectives. Preliminary lessons learned have been derived.

In terms of L1 Ground Failures Statistics, a set of analyses have been executed deriving the distribution of NCR's for the projects having a consolidated set of these NCR's (i.e. project completely developed) as a function of several parameters like:

- Type of Test (or AIV activity)
- Type of Test Environment (or requirement, e.g.. Functional, Mechanical, Thermal)
- Model Type (e.g. EM, STM, PFM, FM)
- Detailed Model (i.e. in case of family of S/C: FM1, FM2, etc.)
- Type of Verification Stage (e.g. Qualification, Proto-qualification, Acceptance)
- Type of Equipment
- Type of Subsystem
- Type of Cause (i.e. Design, Part and Material, Workmanship, Operations)
- Cause Category (e.g. Software, Electrical, Mechanical)
- Type of Classification (i.e. Critical, Major, Minor)
- Time into Test (i.e. operating days from the beginning of the activity on that specific Product and Model).

The distributions have been measured in absolute or in relative values (i.e. percentage of NCR's) and normalized in number of electronic parts when necessary (to take into account the project complexity).
Customizable statistics have been carried-out too, selecting a third parameter among the different possibilities available in the dedicated customization pop-up menu.

Examples of the analysis results are shown in the MAT€D print screens of the following figures:

- Fig. 3.6-1 reports the distribution of NCR's vs the Type of Test, where the ranking of the different tests is highlighted (i.e. Funct. & Perf., Integration, Thermal Vacuum, etc.)
- Fig. 3.6-2 reports the customization of the above distribution wrto the Verification Stage parameter, where, limiting the investigation to the NCR's classified as CR, the effectiveness of Funct. &Perf., EMC, Shock and Sinusoidal Vibration Testing in Qualification and of Funct. & Perf., Integration, Thermal Vacuum and Acoustic in Acceptance or Proto-qualification are highlighted
- Fig. 3.6-3 reports the distribution of NCR's vs the Type of Cause, where the importance of the Design cause wrto the Workmanship is highlighted for the considered projects
- Fig. 3.6-4 reports the customization of the above distribution for the different projects, where it is confirmed that new development projects (as A001 and B001) present an higher incidence of Design problems, while basically recurrent projects (as A003 or B003) show an higher incidence of Part and Material problems

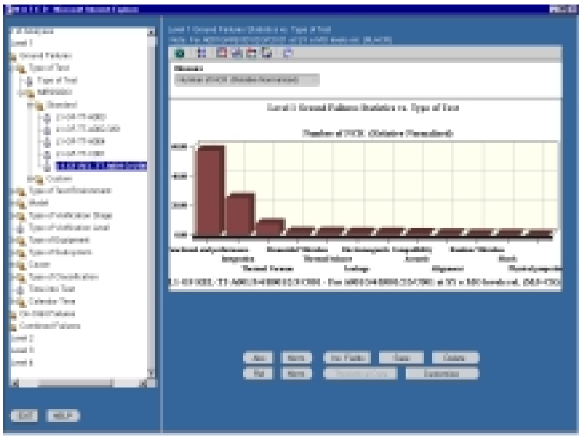

Fig. 3.6-1

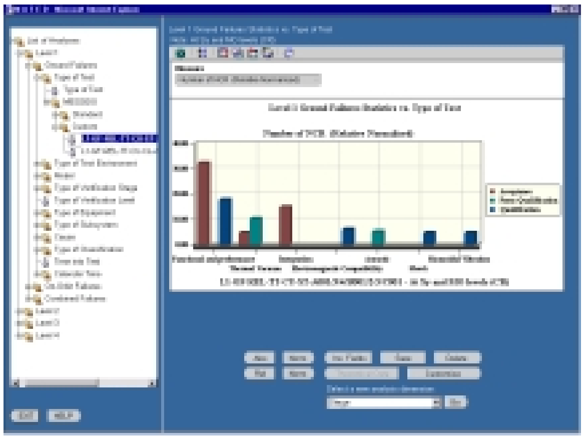

Fig. 3.6-2

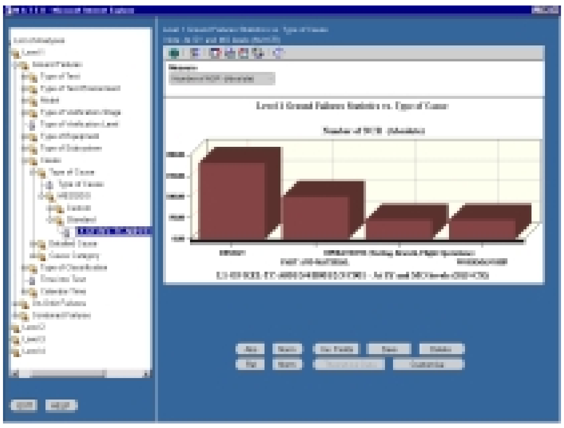

Fig. 3.6-3

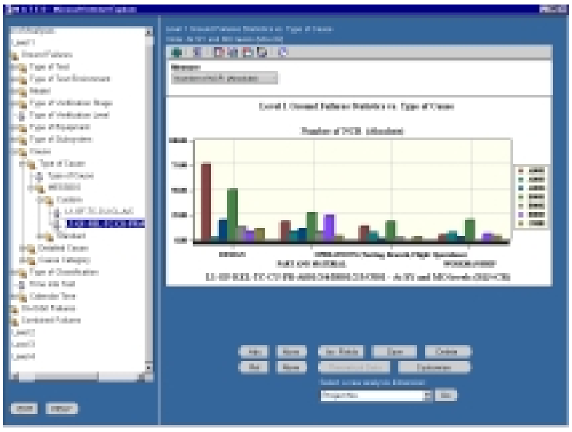

Fig. 3.6-4

In terms of L1 On-Orbit Failures Statistics, a set of analyses have been carried-out showing the distribution of Flight Anomalies for the projects having a consolidated set of these anomalies (i.e. actually in operations or at the end-of-life) as a function of several parameters like:

- Model Type (e.g. FM or PFM)
- Type of Equipment
- Type of Subsystem
- Type of Cause (i.e. Design, Part and Material, Workmanship, Operations)
- Cause Category(e.g. Software, Mechanical, Electrical)
- Type of Severity (e.g. Loss of partial functionality, Switch to redundancy, Delay to operations)
- Time into operations (i.e. days from the launch).

The distributions have been measured in relative values (i.e. percentage of anomalies) and normalized in the number of electronic parts (to consider the project complexity). Customizable statistics have been carried-out too, selecting a third parameter among the different possibilities available in the dedicated customization pop-up menu.

Examples of the analysis results are shown in the MAT€D print screens of the following figures:

- Fig. 3.6-5 reports the distribution of Flight Anomalies vs the type of Subsystems, where the criticality of the different subsystems is highlighted (AOCS, Data Management, Payload, Power)
- Fig. 3.6-6 reports the distribution of FA vs the Type of Cause, where the importance of the Design cause is highlighted wrto the Workmanship one, for these type of projects

- Fig. 3.6-7 reports the cumulative distribution of FA vs Time into operations, where the typical failure investigation curve (the so called "bath curve") is confirmed (i.e. after the early flight period, the slope is stabilized and increases only at the end-of-life for aging effects); the early flight period is resulting in about 120 days, higher than the typical US value.

In terms of <u>L1 Combined Failures Statistics, </u>a set of analyses has been carried-out, showing the combined distribution of NCR's and FA as a function of the operating time in days, for the projects having a consolidated set of both ground and flight anomalies (i.e. fully developed and actually in operations), in order to verify the classical Infant Mortality Theory (i.e. continuity between the ground and early flight failures).
The distribution have been measured in absolute terms cumulative in time.
Fig. 3.6-8 shows an example of the Infant Mortality distribution for the A001 project, where the theory is confirmed being the launch at 850 days from the beginning of the flight hardware operating life.

In terms of <u>L2 Test Effectiveness Evaluations </u>a set of analyses has been executed deriving the Technical and Financial Test Effectiveness (i.e. TTE and FTE) in the following conditions:

- projects with a consolidated set of AIV Process Data, NCR Data and FA Data (at least up to 120 days corresponding to the early flight failures of the Test Effectiveness formula)
- NCR classification and FA severity as MJ and CR
- System and Modules levels (presently MAT€D doesn't include yet the lower level data)
- all models (i.e. EM, STM, PFM and several FM's) and stages (i.e. Qualification, Proto-qualification and Acceptance)

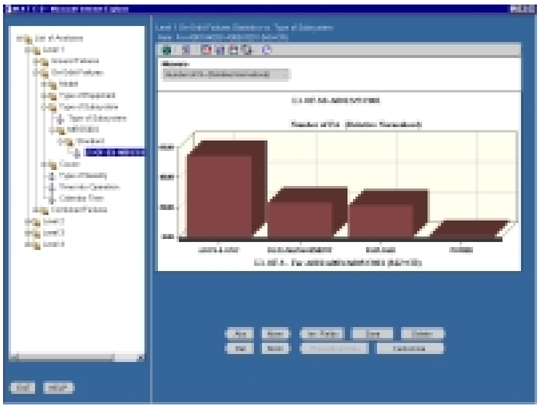

Fig. 3.6-5

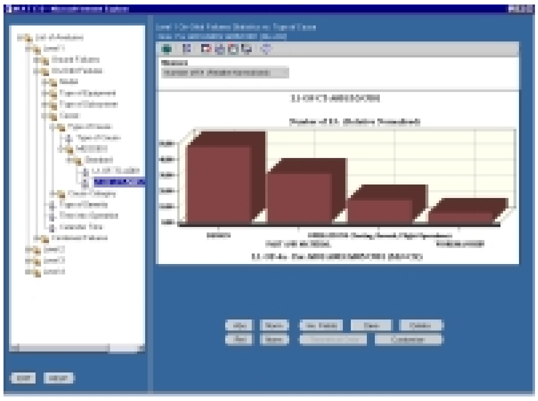

Fig. 3.6-6

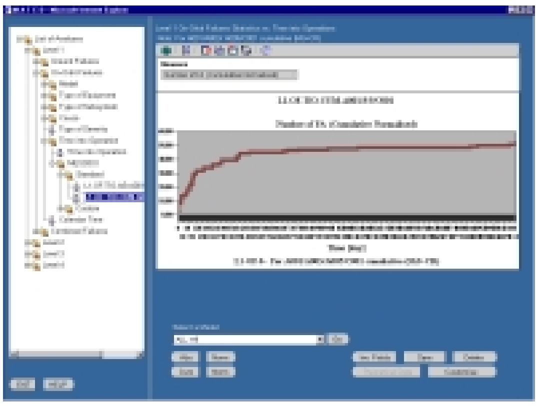

Fig. 3.6.7

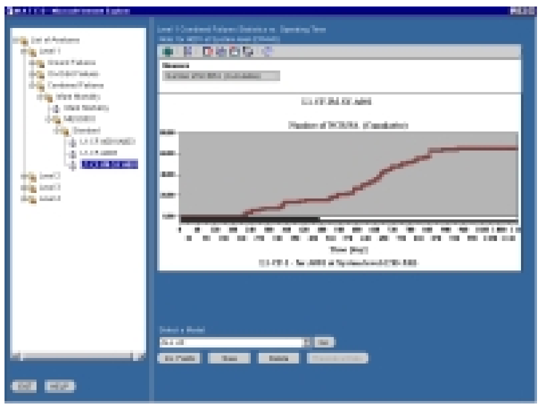

Fig. 3.6-8

The results have been measured in percentage for each single test or AIV activity.
For the Technical Test Effectiveness (TTE) it corresponds to the number of NCR's in the test in interest, divided by the sum of the total number of NCR's in the investigation field plus the relevant number of FA's.
For the Financial Test Effectiveness (FTE) it corresponds to the TTE multiplied by the cost of the mission and divided by the cost of the test in interest (which is equivalent of dividing the TTE by the percentage of the test cost wrto the overall AIV cost and by the percentage of the AIV cost wrto the overall mission cost). With the increasing of the cost of the test, the FTE decreases, while with the increasing of the TTE of the test, FTE increases.
Fig. 3.6-9 shows the print screen of the typical TTE and FTE analysis result for the Acoustic Test in all stages.

From the analysis results the following preliminary considerations can be originated:
- among the different tests and AIV activities it is confirmed that Funct. & Perf., Integration, Thermal Vacuum and Acoustic are in general the most effective tests
- their contribution to the different stages sees respectively Funct. & Perf., Integration and Leakage for Qualification; Funt. & Perf., Integration and Thermal Vacuum for Acceptance; Thermal Vacuum, EMC and Acoustic for Proto-qualification
- financially speaking, while the Funct. & Perf., Integration and Thermal Vacuum maintain their technical effectiveness ranking, EMC test seems more attractive than Acoustic test.

In terms of <u>L3 MAT€I and Time/Cost Parameters Evaluations</u> a set of analyses has been executed to derive the MAT€I and TIME/COST Parameters using the following conditions:
- for MAT€I the same as per the L2 Test Effectiveness Evaluation
- for TIMEP and COSTP limited to system and Module levels of the already launched projects

The MAT€I methodology, which is still preliminary, implied that the Test Effectiveness values of the MAT€D have been utilized as input for the filling of the reference values in the MAT€I ECSS data Test Philosophy table.

Subsequently the MAT€I of each considered project has been calculated automatically by the same table, on the basis of the contributions estimated for each specific identified test (the "other tests" line includes other tests than those listed). The estimate will be derived by comparing the actual project philosophy details (as they are collected in the MAT€D AIV Process data) with the ECSS "Testing" standard parameters.
The MAT€I analysis preliminary result wrto the ECSS for the project A001 is shown in the print-screen of Fig. 3.6-10.
A similar approach has been followed to compare the Test Philosophy with the selected Theoretical Data (presently those elaborated by the TAC in comparison with the MIL-STD-1540C) using a different set of reference data.

The MAT€I analysis results for the different projects, both wrto the ECSS or the Theoretical Data, can be included in a diagram which allows the comparison between them and the estimate of the possible Early Flight Failures for a new project still to be carried-out.
Fig. 3.6-11 shows the print-screen of the preliminary diagram of MAT€I Early Flight Failures. The MAT€D project A001 for instance fits quite well with the TAC curve.

The TIMEP methodology, which is still preliminary, implied that the results of the AIV Process analysis of the MAT€S step 1B and in particular the maximum duration's identified in the synthesis table, have been utilized, together with the actual average content of the MAT€D, to fill the reference values in the TIMEP simulation table. These values will be additionally refined with the growing of the database.
The TIMEP analysis has been carried-out automatically for each selected project, showing the starting date and the duration of the AIV activities of each specific model and calculating the overall calendar duration on the basis of the model respective duration and the associated starting date. The TIMEP analysis for the A001 project is shown in the print-screen of Fig. 3.6-12. The TIMEP analysis results for the different projects can be included in a plot, which shows the TIMEP vs the project average launch date. The corresponding MAT€I is also associated.
The results show a reduced TIMEP for the recurrent projects wrto the new developments. It seems that a big difference doesn't not exist wrto the type of mission at least for the considered projects and customers. The TIMEP analysis can be utilized also to estimate a new project duration, on the basis of the MAT€D average or of an already existing project suitably modified taking into account the foreseen Model and Test Philosophy and associated AIV activities.

The COSTP methodology, which is still preliminary, implied that the results of the AIV Process Analysis of the MAT€S step 1B and in particular the average cost's identified in the synthesis table, have been utilized, together with the actual average content of the MAT€D, to fill the reference values in the COSTP simulation. These values will be additionally refined with the growing of the database. The COSTP analysis has been carried-out automatically for each selected project, showing the contribution of each specific model in terms of percentage of the overall project cost and calculating the total cost (i.e. percentage of the project cost due to the overall considered AIV activity).
The COSTP analysis for the A001 project is shown in the print-screen of Fig. 3.6-13.
The COSTP analysis results for the different projects can be included in a plot, which shows the COSTP vs the project average launch date. The corresponding MAT€I is also associated.
It has to be highlighted that the maximum value is shown for recurrent project (i.e. the cost is mainly due to manufacturing, AIV and operations) while the minimum value is for complex and new development project (i.e. high design costs). It seems that the variation wrto the type of mission is minimum, at least for the considered projects and customers. The COSTP analysis can be utilized also to estimate a new project AIV costs, on the basis of the MAT€I average or of an already existing project, suitably modified taking into account the foreseen Model and Test Philosophy and associated AIV activities.

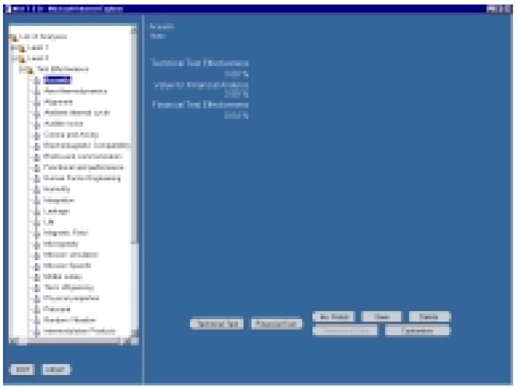

Fig. 3.6-9 - TYPICAL TTE AND FTE ANALYSIS RESULT

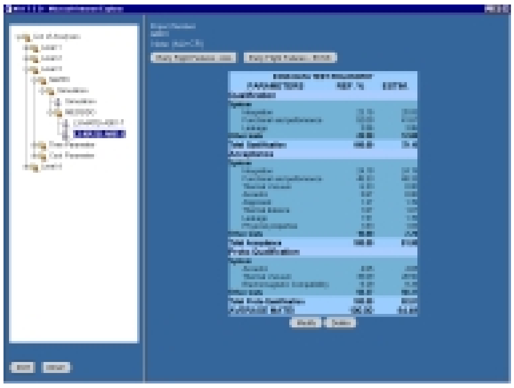

Fig. 3.6-10 - PRELIMINARY MAT€I ECSS ANALYSIS FOR THE PROJECT A001

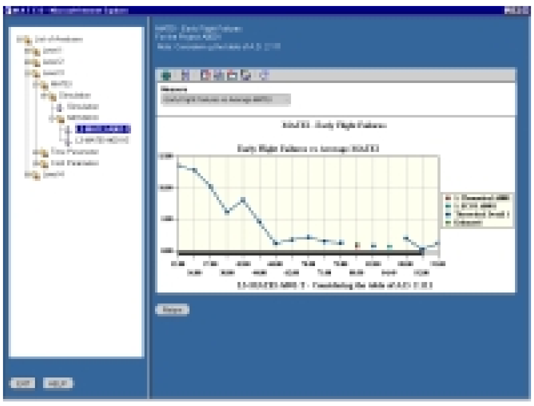

Fig. 3.6-11 - EARLY FLIGHT FAILURES DIAGRAM vs MAT€I

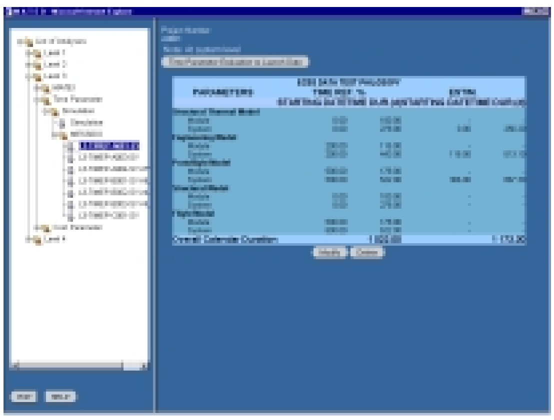

Fig. 3.6-12 -TIMEP RESULTS OF A001

In terms of <u>L4 Sensitivity Analyses and Optimizations</u> no specific analyses have been executed, only the methodology has been defined. The L4 Analyses are theoretical, in the sense that they support the user to carry-out Risk Assessment, Risk/Cost Comparison, Sensitivity Analysis and Optimization of existing and new projects.

The analysis is usually supported by a suitable set of L3 and sometime L2 analyses, which furnish the input for the L4 assessment. Additional off-line investigations are also necessary (e.g. Risk Assessment). The analysis starts from a baseline project (for instance a new project, which has an assigned project code- we suppose the A001 one). To this project it corresponds a Model and Test Philosophy defined on the basis of the technical requirements and constraints.
Using a L3 MAT€I analysis the MAT€I of the project is estimated (for instance the one already estimated for A001, i.e. 84.49). Considering the project design, configuration, mission, etc. by using specific risk models, a risk level associated to the baseline conditions is evaluated (for instance 17%, which is basically the complement to 100 of the satellite reliability).
Through proper L3 analyses on the same project baseline the associated TIMEP and COSTP are evaluated (in the same example of A001 TIMEP=1173 days and COSTP=5.76 % of project costs). Now , considering a baseline variation, for example the deletion of the Thermal Vacuum test in Proto-qualification on the PFM (which seems promising under the cost and time point of view), it is possible to evaluate new corresponding values of MAT€I, TIMEP and COSTP running suitable L3 analyses (the results are respectively 74.99%, 1150 days and 5.54% of the project cost). To the new MAT€I value corresponds an estimated variation of the early flight failures of about 1 unit per 10to5 electronic parts (using the MAT€I curve of L3 analysis) which means about 9 possible additional anomalies related to the missing thermal vacuum screening. Running the risk models this corresponds to an increasing of the risk level up to 27%. Considering then a second baseline variation, for instance the deletion of the Acoustic test in Proto-qualification on the PFM, the new values are MAT€I=82.94 , TIMEP=1152 and COSTP=5.72. To the new MAT€I value corresponds an increasing of early flight failures of 1.3 and consequently of risk level up to 18%. Fig . 3.6-14 shows the Risk Assessment vs MAT€I, graph. Fig. 3.6-15 shows the Risk/Cost Comparison VS MAT€I, graph. It is evident from the example that the deletion of the Acoustic test may be considered, while the deletion of Thermal Vacuum test is producing a risk level clearly unacceptable in spite of the reduction of cost. Fig. 3.6-16 shows the Sensitivity Analysis and Optimization, graph. The deletion of Acoustic test seems more attractive considering the equivalent reduction of TIMEP in front of a much lower reduction of MAT€I (i.e. lower increasing of Risk).

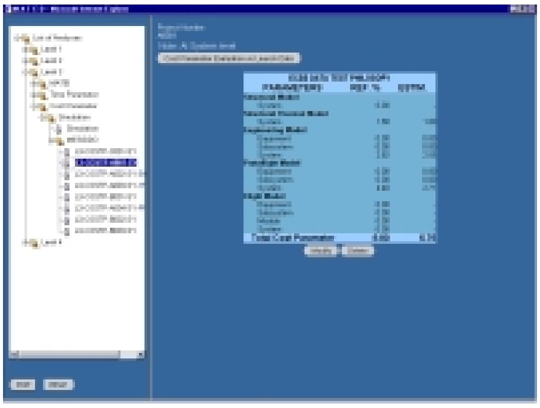

Fig. 3.6-13 - COSTP RESULTS OF A001

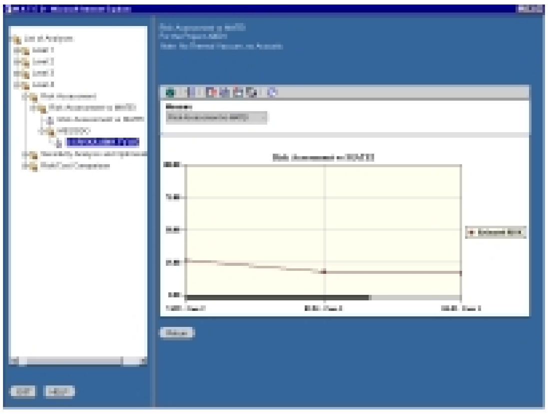

Fig. 3.6-14 - RISK ASSESSMENT VS MAT€I GRAPH

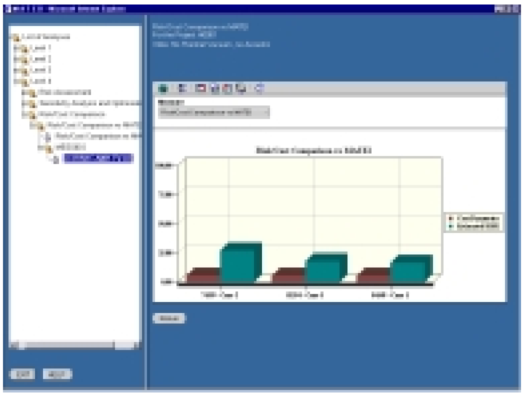

Fig. 3.6-15 - RISK/COST COMPARISON VS MAT€I GRAPH

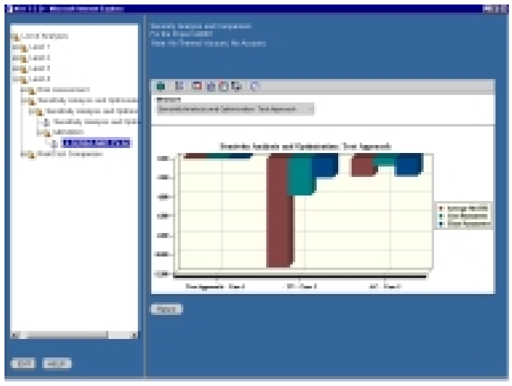

Fig. 3.6-16 - SENSITIVITY AN. AND OPTIMIZATION GRAPH

Concerning the **preliminary Lessons Learned** derived from the analysis results, a list of 10 Lessons has been proposed. The list has to be additionally verified and improved in the next MAT€S phases.
Basically the following major suggestions have been derived:

- The list of the most effective tests in the different stages also under financial point of view
- The possible deletion of the Sinusoidal Vibration test in Acceptance
- The irrelevance of the EMC environment in the Acceptance Campaign
- The reduction of acceptance tests after few units in case of recurrent S/C family
- The increasing of effort in testing AOCS and Optical Equipment
- The usage of 120 days as early period in the confirmed Infant Mortality Theory
- The usage of the so called “Hybrid Approach” (per ECSS standards) as the most effective Model Philosophy

Concerning the **recommendations for standard adaptation** the following methodology has been proposed to ESA to derive MAT€D Lessons Learned for improving the ECSS Verification and Testing Standard :

- Establish a MAT€D Board chaired by ESA with the participation of the MAT€D Partners
- Run periodical analyses using MAT€D and derive suitable Lessons Learned
- Approve through the MAT€D Board the proposed Lessons Learned and write proper report or, in case of Standard Modification, proper Change Request to the ECSS Organization following the applicable rules
- Archive the approved Lessons Learned in the MAT€D and insert them in the ESA Lessons Learned System

Concerning the **recommendations for the MAT€D Operative phase** the following operative scenario has been proposed and the relevant cost estimate per year for ESA and the other involved parties has been derived.:

- The master copy of MAT€D would reside in ESA which will provide the Oracle Standard Data Base Administration
- ESA would manage the MAT€D through the MAT€S Industrial consortium in which ALS would act as Application Manager ensuring data loading and validation
- ESA would act also as Partner User providing data from the running projects and its internal Departments would have controlled remote access to MAT€D as General Users
- The MAT€S Industrial Consortium would be in support to ESA for MAT€D technical upgrading (if necessary), maintenance and performance of special analyses and feed back on standards
- Other European and world wide Companies, Organizations and Agencies would become MAT€D Partners Users providing data or statistics and receiving back suitable access to MAT€S functionality’s.

The MAT€D Operative Scenario is shown in Fig. 3.6-17.

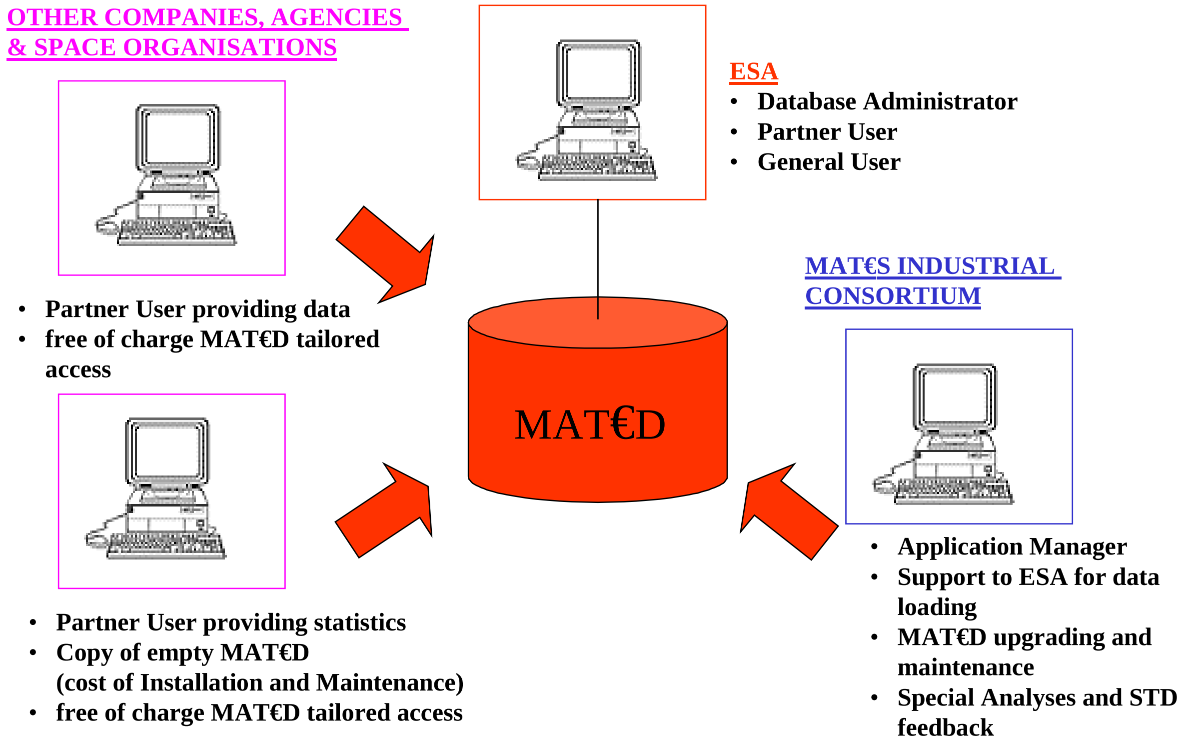

Fig. 3.6-17 – MAT€D Operative Scenario

4. CONCLUSIONS AND PERSPECTIVES

The MAT€S objectives have been satisfactorily met. In particular:

- the MAT€ state-of-the-art has been analized
- the typical ESA AIV process has been investigated
- the necessary AIV data have been identified and the analysis methodologies proposed
- a prototype of the MAT€D has been developed and populated with data from pilot projects
- a set of analyses has been carried-out to demonstrate the validity of the concept
- a list of preliminary lessons learned has been originated
- recommendations for continuous standard improvements and for the future operative scenario has been proposed

The methodology seems valid and promising. The next steps would be to enter in a pre-operational phase, which will complete the collection of data for additional new projects and will update the prototype in line with the expected operative scenario. Contacts with possible partners will be pursued in order to enlarge the MAT€D community in line with the final operative phase objectives.