Systems engineering plan for the construction phase of the E-ELT

J. C. Gonzalez*, H. Kurlandczyk, D. Schneller

European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748-Garching b. München, Germany

ABSTRACT

After having completed the phase B (front-end design) of the several subsystems, the E-ELT project is entering into the construction phase. The subsystems specifications, interface control documents and accompanying technical documentation resulting from the said design activities are being drafted along with the statements of work needed for the tendering processes.

This paper presents an overview of the Systems Engineering Plan for the construction phase focusing on the specific systems engineering processes. The goal is to ensure that this phase is developed following an efficient systems engineering approach based on the lessons learned during phase B. The ultimate objective is that the E-ELT meets the science requirements defined by the users while the risk of overruns in cost or schedule, which might otherwise originate from the lack of a system perspective, is minimized.

Keywords: systems engineering, processes, configuration, interfaces, requirements, verification, documentation

1. INTRODUCTION

The European Extremely Large Telescope (E-ELT) is entering into the construction phase. Actually, the call for tender for the detail design, manufacturing, assembly and test of the dome, buildings, telescope structure and mechanisms has just been released.

The E-ELT construction is managed as a programme composed by a number of projects. In this organization, Systems Engineering (SE) is responsible for ensuring that the several subsystems of the E-ELT, which are specified, designed and built by different entities (programme members and external companies or institutes) and at different timescales, smoothly match all together as a single system meeting the top-level science requirements. At the same time, minimizing the risk of overruns in cost or schedule, which might originate from the lack of a system perspective and proper configuration control, is a must for SE.

To achieve that goal, SE is responsible for defining and continuously improving a number of key processes as well as taking a lead role on them. These processes are:

- Requirements Management
- Interfaces Management
- Configuration Management
- Verification Management
- Documentation Management

In addition, SE is also responsible for defining and improving the tools to support the processes. In this sense, a fundamental principle is to define first the process and then to define the needed tool. It is a common mistake in many organizations to proceed the other way around, the result being that the processes are trapped by the tools, which in turns negatively impacts the efficiency.

Finally, SE is in charge of coordinating the requirements on the Interlock and Safety System (ILS) of the E-ELT after performing a hazard analysis at system level.

*jcgonzal@eso.org; phone +49 89 32006641

In some organizations systems engineering is responsible for ensuring that the processes are properly and effectively being followed in the normal workflow. In the case of the E-ELT Programme, this is a charge on Quality Assurance, which reports directly to the Programme Manager. Risk management is performed at programme level.

E-ELT Systems Engineering is led by a Lead Systems Engineer who manages a group of two full-time systems engineers (one of them acts as Configuration Manager) plus a number of partial-time engineers who are specialist in different subjects (optics, optomechanics, analysis, electrical, electronics, software, instruments). All this effort is supported by the ESO Directorate of Engineering and consistent with the overall ESO systems engineering approach. Also, the E-ELT Archivist works in this group. The Lead Systems Engineer reports to the E-ELT Programme Engineer.

The following sections describe the processes enumerated above as well as the chosen tools. The very valuable experience and lessons learned accumulated during the several years spent in the E-ELT phase B have obviously been taking into consideration when preparing the SE Plan for the construction phase.

2. REQUIREMENTS MANAGEMENT

The top-level science requirements of the E-ELT have been defined in discussion with the community of users and are owned by the Project Scientist. These requirements have to be flown down to the contracted items following a requirements management process consistently across the whole programme. This process starts with the translation of the said science requirements into system-level engineering requirements (called level-one requirements). From there, subsystems, units and subunits requirements are derived down to the contracted elements.

The process of preparing a specification of requirements starts with the discussion and agreement on the required contents as well as the style of the document as recommended by the expected type of bidders and the strategy for procurement. This can be actually seen as the Data Item Description (DID) for the concerned specification.

Then, the engineering work proceeds involving the following activities:

- Splitting higher level requirements and allocating contributions into lower level requirements: this activity is mainly supported by a combination of analysis, past experience and best engineering judgment. Engineering budgets have been set up and are being populated as the fundamental tool for requirements allocation. Around 30 budgets are being worked out at the moment; typical examples are optical performance, pointing accuracy, preset time or power consumption. The Programme Engineer, assisted by SE, leads the engineering trade-offs supporting the allocations down to contracted items. SE is responsible for keeping the budgets under configuration control and for making sure that the budget items are reflected in requirements as appropriate. Each engineering budget is implemented as a simple table in which every item is uniquely labeled and the data supporting the allocation (e.g., analysis, design report, etc.) clearly identified.

- Defining lower-level requirements which are directly derived from higher-level ones.

- Determining the applicable environmental conditions.

- Identifying any special condition (e.g., transport, storage, maintenance, etc.) that will apply to the concerned item.

- Defining the applicable safety conditions as derived from the overall safety assessment.

- Determining the applicable E-ELT standards, which in many cases are just taken in from the ESO-wide standards. Typical examples of E-ELT standards are ESO Mechanical Standards, E-ELT Standard Coordinate Systems and Basic Conventions, Electrical and Electronic Design Technical Specification, etc. SE is responsible for keeping under control the complete set of E-ELT standards.

The outcome of the above activities is a list of requirements on the concerned item. In parallel, the following tasks are also performed:

- Ensuring that the requirements are properly identified by means of a unique identifier.

- Providing the rationale behind every requirement.

- Wherever possible, identifying the parent requirement, i.e., the requirement to which the concerned one has to be linked. This is called linking information because it allows connecting requirements each other.

- Defining the method(s) by which the requirements should be verified.

All this information, which consists actually of attributes of the requirements, alongside with the requirements themselves, is recorded in a DOORS® database maintained by SE. This database contains all the requirements on the E-ELT elements and is used as the unique repository for managing them. They are linked to each other, which facilitates the analysis of the changes requests impacts. Engineering budgets are also kept in DOORS®; that way the requirements can be linked to the specific budgets items from which they are derived. The database is accessible to all the programme members. Access rights are properly defined.

2.1 Review of requirements

Before releasing a specification of requirements a formal review is performed by E-ELT Programme members and (in some cases) external reviewers aiming to ensure that the requirements applicable to a given procurement are complete and are correctly defined. This review is organized and led by SE. Documents under review, i.e., the specification itself, its applicable documents and drawings and, for the sake of completeness, the Statement of Work (SOW), are submitted for review. The reviewers raise the issues (RIXes) classified as critical, major and minor. RIXes are replied by the data owners and then rejoinded by the reviewers, who state whether any of their critical and major RIXes can be closed or remain open for further discussion. The open RIXes are discussed in a close-out meeting where a decision is made by the relevant authority (usually the E-ELT Programme Engineer).

Finally, the conclusions of the review are implemented in the relevant documentation items that are then released. Once the work is completed, the specification contents are exported from DOORS® into a MS Word® file and a pdf file, the latter being the one that goes to the tendering process.

Changes to the requirements are managed through the change request process as explained below.

For more details on how requirements are managed see [1].

3. INTERFACES MANAGEMENT

As already said in section 1, SE is responsible for ensuring that the several subsystems match all together as a single system. To this extent a proper management of the interfaces between subsystems developed by different entities and at different time scales is mandatory.

Interfaces management process involves the identification, definition and control of the interfaces. Starting from the Product Breakdown Structure (PBS) and taking into consideration the strategy for procurement (i.e., which products are procured under which tendering processes) a classical N^2 interface diagram is developed and made available to all the Programme members.

Every interface identified in the N^2 diagram is developed and documented in an Interface Control Document (ICD). SE owns all the ICDs and is responsible for managing them and importing under DOORS® as it is the case of all the requirements documents (ICDs are actually documents stating the interface requirements). The ICDs are in general written by technical experts on one or the two sides of the interface.

ICDs in general apply to both sides of the interface. However, in some cases, in particular when the development cycles of the two sides are very different with an inevitable mismatch of the level of technical details and defined interfaces which can be specified, elaborating an ICD for each side is a better solution. Although this approach implies keeping two ICDs under control, it optimizes the flexibility in adapting the applicable technical documentation to the every procurement. The aim is to focus in the interface information that is needed in each case avoiding confusing the bidders with data that only applies to the other side of the interface. This approach also allows specifying the interface requirements for the side to be procured first and then, once this has been further developed, specifying a more detail set of interfaces requirements to the other side. Both ICDs are in the DOORS® database and linked to each other, which allows keeping control on the needed changes on one side as soon as a change in the other side arises.

A typical example of the above approach is the interface between the telescope structure and the Nasmyth instruments. At the time of preparing the tendering documentation for the former, interfaces requirements with the set of instruments to be installed in the Nasmyth platforms were compiled in an ICD; for instance, the total mass to be supported by each platform, the volume reserved for the set of instruments or the envelope of allowed positions to install the services connections (power, coolant, etc.). However, in the other side of the interface, individual instruments are not interested

in knowing the total mass to be supported by each platform but instead they need to know the maximum mass allocated to every instrument. Also, instruments need to know the exact location of the services connections. This information, which will be needed when detail design of the instrument starts, will only be available in a couple of years after awarding the telescope structure contract. The ICD applicable to the instruments side will therefore contain more detailed information than the one applicable to the telescope structure, will also be produced later and will be tailored to the instruments needs.

4. CONFIGURATION MANAGEMENT

E-ELT configuration is defined as the complete set of physical, functional and performance characteristics of the whole system. At any point in time, this set defines the system baseline. The data (documents, drawings, computer models, software code …) describing the system baseline are by definition the configuration data. In other words, the system baseline at any moment in time is represented by a snapshot of the configuration data in this moment. The system baseline evolves in time; therefore, keeping the configuration data under control and aligned to the actual baseline along the E-ELT Programme lifecycle is the objective of configuration management.

Configuration management in the E-ELT Programme involves configuration identification, configuration control, configuration communication and configuration audits. These activities are described following. Specific configuration management requirements on contractors are defined and made applicable to the SOW.

4.1 Configuration identification

Configuration identification refers both to the products (i.e., the system elements) and to the data representing the configuration of the products.

The products are identified by means of a structured breaking down of the system based primarily on functional criteria; a functional decomposition is done resulting in functions which define the products to be implemented. This is not always possible or practical. Hence, in some cases, in particular at lower levels of decomposition, anticipated physical location or procurement considerations may prevail. Performing this activity, which strongly involves the Programme Engineer and the subsystems responsible, actually means building the system architecture.

The products are represented in the Product Breakdown Structure (PBS), which is a fundamental tool for configuration and requirements management. Figure 1 shows a partial view of the E-ELT PBS:
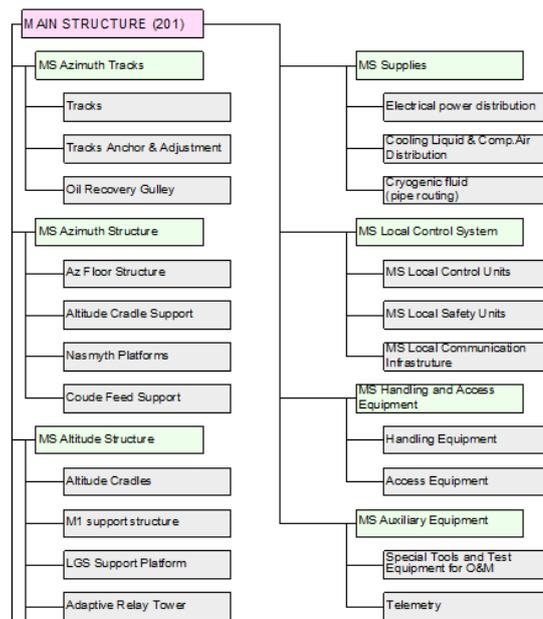

Figure 1. Partial view of the E-ELT Product Breakdown Structure.

The PBS is frozen down to procured items; however, contractors may propose changes on the structure belonging to their scope of delivery.

The products in the PBS get acronyms that are used in the requirements identifiers (see section 2). Therefore knowing which product a given requirement applies to is straightforward.

For obvious practical reasons the decomposition represented in the PBS does not reach the part level but stops at sub-assembly level. Nevertheless, certain requirements are set on the SOW in order to make sure that products within the scope of delivery, down to the part level, are properly and uniquely identified.

Apart from the products, the data representing the configuration of the products are also identified. Some of data items are produced by E-ELT Programme (typical examples are requirements documents or ICDs) while others are delivered by contractors (e.g., as-built drawings or tests reports). Specified E-ELT standards apply in both cases to guarantee that configuration data are correctly and uniquely identified.

4.2 Configuration control

Configuration control refers essentially to:

- Keep the data that represents the system baseline, i.e., the configuration data, fully aligned to the actual configuration of the system. This is done through strict control of versions of the configuration data items. In particular, data applicable to all the procurements are recorded in the corresponding Configuration Items Data List (CIDL) that is kept up to date. Similarly, data delivered by contractors are also controlled by means of the concerned CIDL, which is also requested to be kept updated by the contractor.

- Ensure that proposed changes to the baseline are properly managed. This involves the following steps:

   o Checking that enough information has been provided to sufficiently define the proposed change.

   o Understanding the impact on the system configuration, the schedule and the cost.

   o Making a decision on approval or rejection.

   o Communicating the conclusion.

   o If the change is approved, implementing the change in the affected configuration data and when needed, in the affected product(s).

A Change Request (CRE) may be submitted by any member of the E-ELT Programme but also by contractors. When a CRE is submitted it is classified by SE (after discussion with the Programme Engineer) as major or minor after checking that the necessary information to start processing the CRE has been provided by the originator.

Major CREs usually involves an ad-hoc Change Request Board (CRB) which provides an in-depth analysis of the change impacts as well as a recommendation to the Change Control Board (CCB). The latter is a standing committee, composed by the Programme Manager (chair), the Programme Scientist, the Programme Engineer, the Lead Systems Engineer and the Configuration Manager (secretary). The CCB has the authority for making the final decision. Minor CREs are normally handled by SE by conducting a simplified procedure. In any case, the decision is communicated to the CRE originator and to all the E-ELT Programme members.

If the CRE is approved, implementing the changes to the baseline, that is, to the data representing the baseline, and to the products if needed is the final step. A responsible person is designated by the CCB and a schedule defined.

As part of the change impact analysis, DOORS® database is used as a tool to identify which parent and child requirements are potentially affected by changing a given requirement. The affected items of the engineering budgets are also identified, which facilitates assessing the impact on the overall system performance.

A tool based on JIRA® issues tracking system has been developed as the basis for helping in the workflow involved in a CRE. It is at the moment under test but the results a very promising. The aim is streamlining the process and reducing the time needed to manage a CRE.

4.3 Configuration communication

The data describing the system baseline, i.e., the configuration data, are maintained in a Product Data Management (PDM) tool that has been customized to the E-ELT Programme needs (see section 6). The PDM is organized following a hierarchical folder structure that exactly matches the PBS, which facilitates searching for information (see next figure).
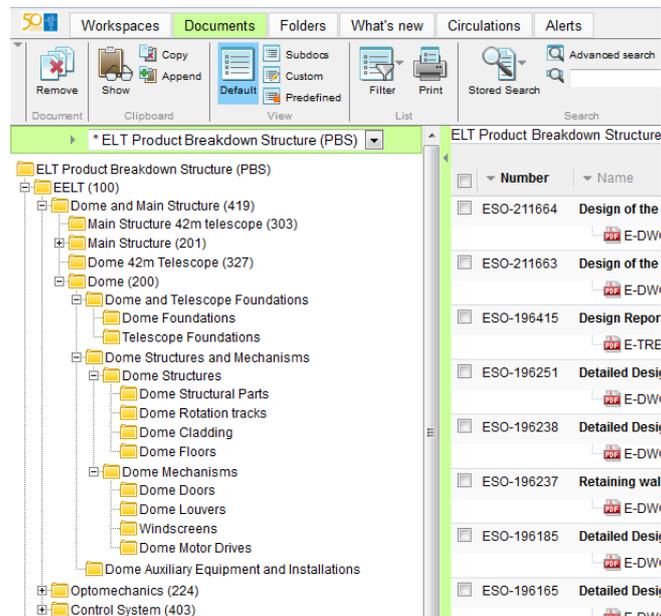

Figure 2. Partial view of the Product Breakdown Structure of the E-ELT PDM.

Only released configuration data are uploaded to the PDM by the Configuration Manager, who is the only member with write access. This ensures strict control of the data. The rest of the E-ELT Programme members have read access to the entire structure.

In summary, the data archived in the PDM represent the actual system baseline at any moment in time. It is the unique repository for making these data available to the E-ELT members.

4.4 Configuration audits

Configuration audits are conducted under the responsibility of E-ELT Quality Assurance, who reports directly to the Programme Manager. The goal is checking that the internal configuration management processes as well as the requirements on configuration management set on the contractors are properly followed. Corrective measures are identified and put in place when needed.

5. VERIFICATION MANAGEMENT

One of the main roles of the E-ELT Programme is splitting the system into elements to be contracted separately, defining the right requirements applicable to each contract and making sure that these requirements are met. Ensuring that the right requirements are defined is the objective of review of requirements (see section 2.1) while checking that the requirements applicable to a given procurement are met by the contractors is the goal of the verification management process.

This process, led by SE, has three phases: planning, execution and reporting, and control and closeout. Specific verification management requirements on contractors are defined and made applicable to the SOW.

5.1 Planning

As part of the technical specification and its applicable documents E-ELT Programme defines the following:

- The suggested verification methods for each requirement (Design, Analysis, Inspection, Test). Each requirement includes a verification tag D/A/I/T which indicates the suggested method(s). This information is non-binding and is to be understood as a guideline for the contractor.

- A set of specific verification requirements. These are verification activities to be conducted by the contractor for a set of specific requirements. As opposed to the verification tags which suggest the verification methods, the specific verification requirements are binding. In case the contractor requests a change in them, this must be achieved through a formal change request.

Based on that, the contractor goes through a planning phase in which all the verification efforts for the complete scope of work are carefully assessed and summarized in a verification plan, which has to be approved by the E-ELT Programme. This plan defines which requirements are verified by which methods and at what temporal milestones. To this end, inspection and tests plans are delivered by the contractor. Other aspects of the verification such as the selection of the appropriate models or clustering of several requirements to be verified in "one-shot" are also included in the plans.

Figure 3 shows the logical flow of the document creation.

5.2 Execution and reporting

In this phase the verification by Review-of-Design, Analysis, Inspection and Tests are performed at certain milestones according to the agreed plans, following the corresponding procedures and recording the results in the relevant reports.

Reviews of design are conducted by E-ELT Programme following a standard ESO procedure normally at PDR and FDR milestones. Analysis results are provided by PDR and FDR but also later. Inspection and test reports are delivered by Shipment Readiness Review (SRR) and Provisional Acceptance.

5.3 Control and closeout

Control and closeout phase ensures that verification is performed as planned and specified, that the end data are compliant, documented in the agreed manner, and traceable to the original requirements, or that deviations are understood and controlled. The final results are compiled in a compliance matrix, which is an essential tool in the process.

Actually, control of verification overlaps with the previous phase (executing and reporting), since it is performed through the contractual milestone reviews as defined in the SOW (PDR, FDR, SRR, Provisional Acceptance …).

6. DOCUMENTATION MANAGEMENT

Documentation management deals with the process of producing, releasing and archiving documents and drawings (unless otherwise stated, the term 'documents' refers in this section also to drawings). The entire lifecycle of a document is therefore addressed.

Depending on the type of document, there are some differences in the process. Specifications of requirements, SOWs, plans and procedures are subject to a more formal process than the remaining documents. At least in these cases (may also be done for other documents), a Data Item Description (DID) has to be prepared by the document owner before starting to work on it and agreed by the E-ELT members who have to approve and release the document (approvers). This is a key step to beforehand reach a common understanding on the contents and style of the document and therefore to maximize the effiency of the process.

Documents are created following standard templates that are chosen depending on the type of document. Once ready, a document is usually reviewed by experts that have not been directly involved in drafting it. Issues from this review are iterated with the owner and, when needed, are escalated to the approvers. Requirements documents and SOWs are reviewed following a specific procedure as described in section 2.1.

The next step in the lifecycle is releasing the document after signatures from the owner, approvers and releasing authority have been collected. Then, the document enters into the E-ELT archive where is kept under control.

Specific documentation management requirements on documents delivered by contractors are defined and made applicable to the SOW.
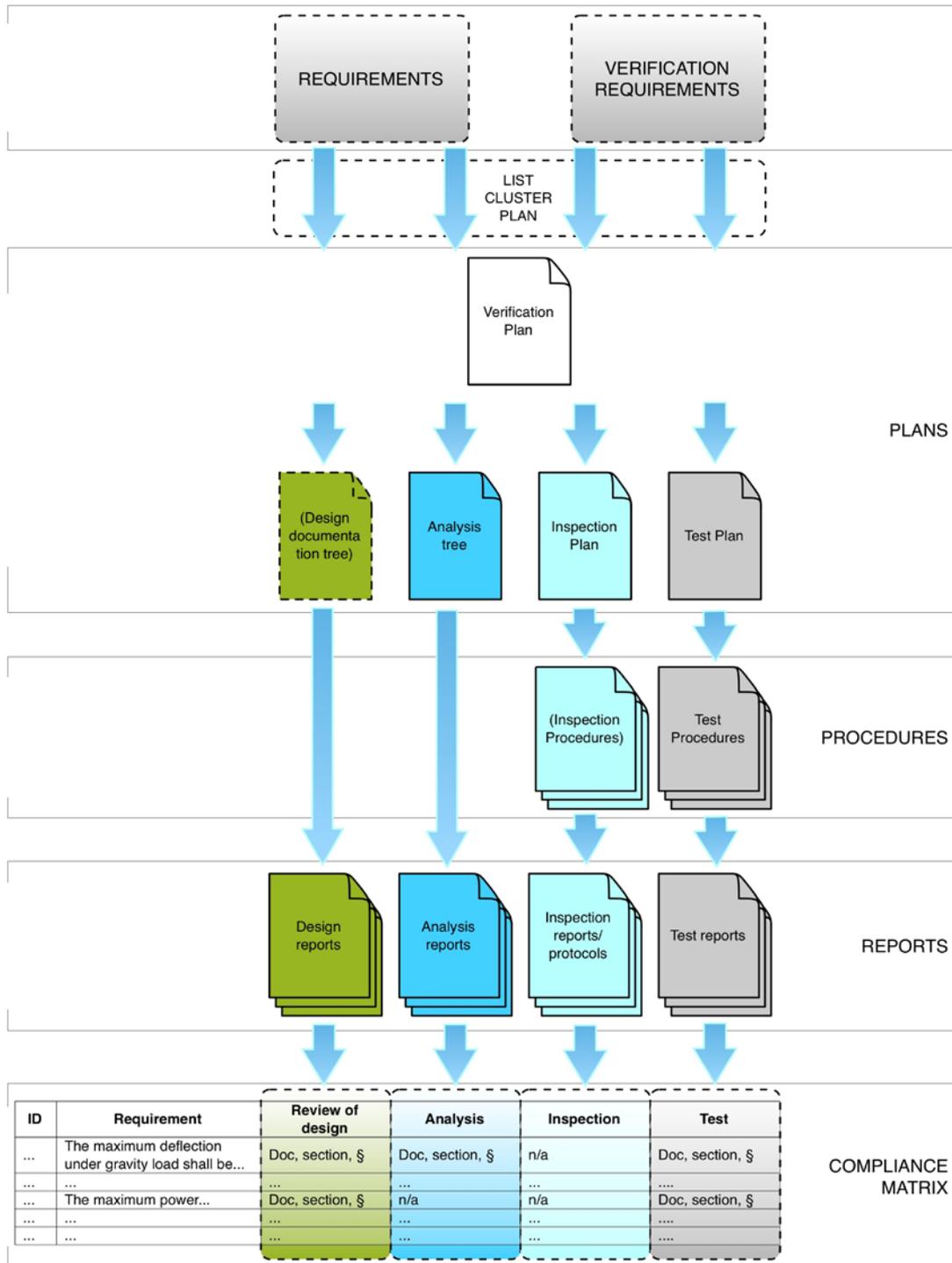
Figure 3: Verification documentation.

The complete process depicted above is assisted by the PDM tool that has already been mentioned in section 4.3. To create a new document the applicable template has to be chosen; a new document entry is then automatically created in the PDM and a unique identifier automatically assigned (as well as other relevant metadata useful to characterize and search for the document). The PDM also incorporates functions that allow circulating the document for online review.

Once it is ready, signatures can be done electronically within the tool. Finally, the document is archived in the proper folder.

The PDM is organized in three separated areas:

1. A Formal Area to archive relevant documents which are binding for the E-ELT Programme (e.g., SOWs, minutes of meetings with external partners, contracts deliverables …). This area is organized in a folders structure that follows the Work Breakdown Structure (WBS). It is under strict control by the Archivist, meaning that only (s)he has write access. Read access may be restricted to some folders according to the ESO confidentiality policy.

2. A Product Area to archive the configuration data. As already explained in section 4.3 this area is organized following the PBS. It is under strict control by the Configuration Manager, so only (s)he has write access.

3. A Collaborative Working Area, intended to provide a common workspace to E-ELT Programme members. It is organized according to the WBS. Write access is normally granted to all the E-ELT members.

Figure 4 shows a view of the Formal Area and the Collaborative Area. The PBS area is shown in Figure 2 above.

Obsolete and superseded versions of documents are clearly identified in the PDM in a way such as the user always knows what the latest, valid version of a document is.

An additional tool used to help in documentation management is a documentation tree. Critical documents such as specifications of requirements, ICDs, design reports or E-ELT standards are represented in a hierarchical structure that shows the relation between them. This tool provides a very good overview of the entire documentation structure and facilitates scheduling the elaboration of the documents.
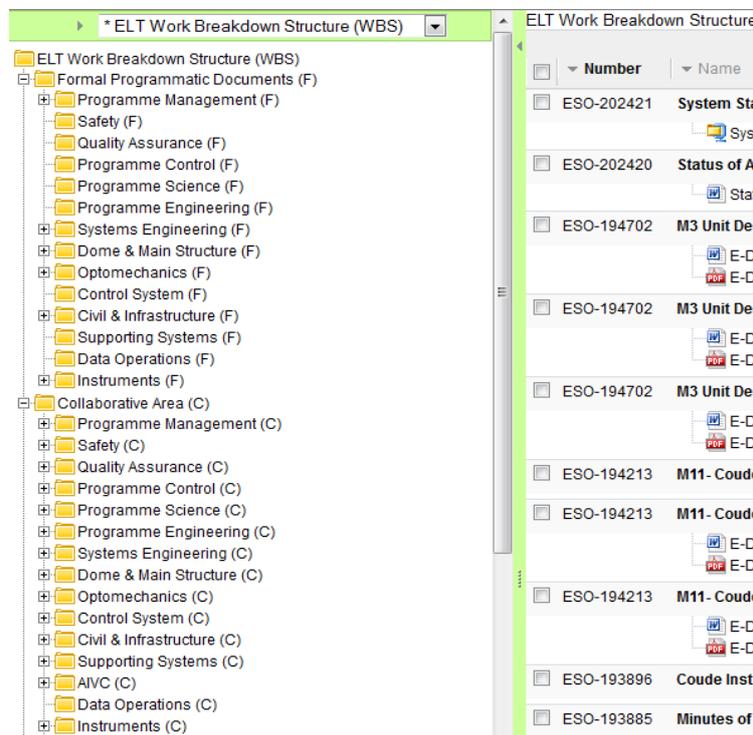

Figure 4. Partial view of the level 1 folder structure of the Formal Area and the Collaborative Area of the E-ELT PDM.

REFERENCES

[1] Schneller, D., "E-ELT Requirements Management," Proc. SPIE, (in press) (2014).