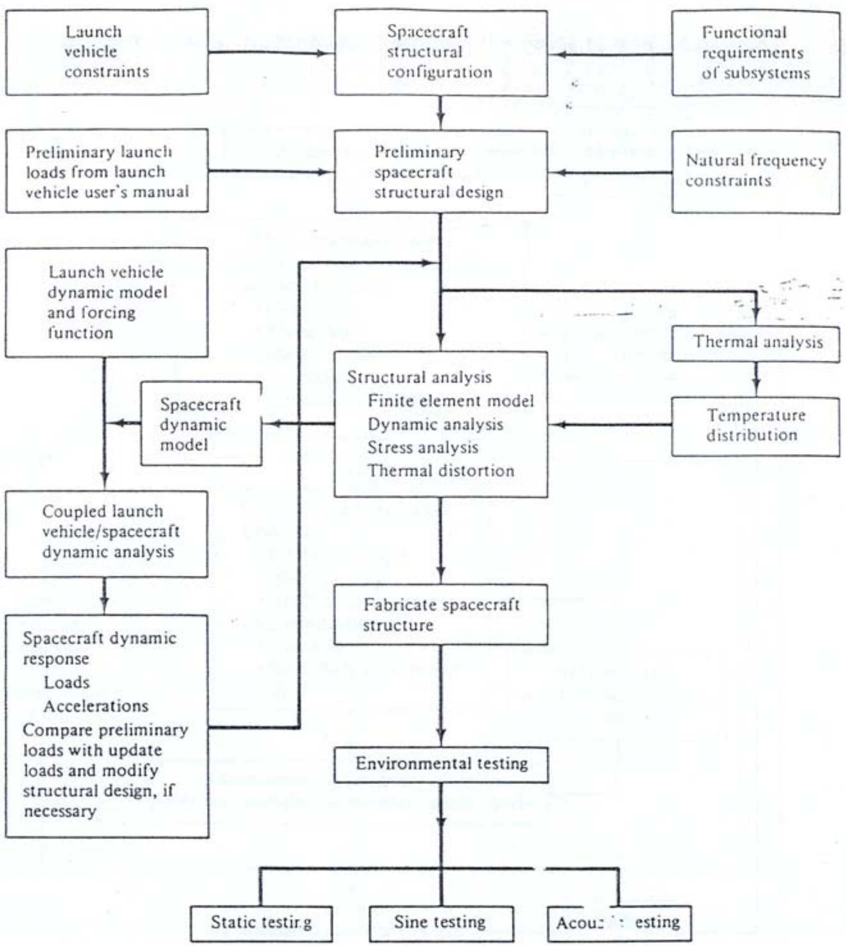
7. Design criteria and procedures of space structures

Prof. P. Gaudenzi

Università di Roma La Sapienza, Rome Italy

paolo.gaudenzi@uniroma1.it

THE STRUCTURAL DESIGN PROCESS



Many factors influence the definition and selection of the structural design concept (e.g. strength, stiffness, mass, resilience, resistance to corrosion and the environment, fatigue, thermal properties, manufacturing, availability and cost).

Structural design is an iterative process.

The process starts with the conceptual design of possible alternatives which could be considered to satisfy the general performance requirements and are likely to meet the main mission constraints (e.g. mass, interfaces, operation and cost).

From ECSS

THE STRUCTURAL DESIGN PROCESS (2)

The various concepts are then evaluated according to a set of prioritized criteria in order to select the one or more designs to be developed further in detail. The main purpose of the evaluation is to identify the main mission requirements and to establish whether the selected concepts meet the requirements.

The selected concepts are evolved and evaluated inmore detail against a comprehensive set of mechanical requirements and interface constraints which are “flowed down” from the main mission and functional requirements.

DESIGN CONCEPT (ECSS 4.6.5)

a.The following structural design aspects shall be covered:

1.The structural design shall lead to an item that is proven to be strong and stiff enough for the intended purpose throughout its intended lifetime;

2. Practices used in structural design shall be in accordance with those stipulated or agreed by the controlling bodies to permit certification and qualification of structures;

3. All structural design concepts shall include provision for verification of the structural integrity during design, manufacture and once in service;

4. The structural materials used shall have known, reliable and reproducible properties and shall have proven resistance to the environmental factors envisaged.

5. The structural materials shall not be hazardous to the operators, crew or mission;

DESIGN CONCEPT (2)

6. The structure mass shall be minimized;

7. The design shall include balancing mass fixations;

8. The structure shall be cost effectively manufactured, by methods that do not alter the designed characteristics (mechanical or environmental resistance) in an unknown way, and by methods proven to be reliable and repeatable;

9. The generation of space debris by structural breakup shall be minimized.

b. Redundancy concepts (fail-safe) shall be considered whenever possible to minimize single-point failures.Where a single-point failuremode is identified and redundancy cannot be provided the required strength and lifetime shall be demonstrated (safe-life).

AREAS OF INTEREST OF STRUCTURAL DESIGN

The mechanical engineering requirements for structural engineering are to be considered in all engineering aspects of structures: requirement definition and specification, design, development, verification, production, in-service and eventual disposal.

All general structural subsystem aspects of space products are to be considered and in particular: launch vehicles, transfer vehicles, re-entry vehicles, spacecraft, landing probes and rovers, sounding rockets, payloads and instruments, structural parts of all subsytems and of payloads.

GENERAL CRITERIA

Structural design shall aim for simple load paths, maximize the use of conventional materials, simplify interfaces and easy integration.

All structural assemblies and components shall be designed to withstand applied loads due to the natural and induced environments to which they are exposed during the service-life and shall be able, in operation, to fulfil the mission objectives for the specified duration.

From ECSS Standards

IDEAL STRUCTURE

The best structure is stressed to its max allowable stress everywhere, i.e. the best effective use of the material is obtained. To pursue this effort and reduce the structural mass, the geometry of the structure has to be conceived in such a way to reduce the load paths and make the loads equilibrate each other in every possible location.

In fact structures has to materialize the load path to enable the forces acting on a body to find each other and vanish. Along this path, stress fields are created in the structure.

The load path has to be materialized in such a way by an appropriate structural geometry that the material is used in the most uniform way (membrane behaviour). Compression should be avoided whenever possible to prevent buckling problems.

MATERIALS ALLOWABLES

a. For all structural materials allowable stresses shall be statistically derived, considering all operational environments. The scatter bands of the data shall be derived and allowable stresses defined in terms of fractions of their statistical distribution with prescribed levels of reliability and confidence.

b. For each type of test the minimum number of test specimens shall be ten to establish A-values, and five to establish B-values.

A value
mechanical property value above which at least 99% (90 % for B value) of the population of values is expected to fall, with a confidence level of 95 %

c. If thematerial is delivered in several batches, the allowables test programme shall consider the probability of variations frombatch to batch. In such cases, preliminary allowable stresses may be based on the initially small sample size, and upgraded as the sample size increases by tests of newly arriving batches.

MARGIN OF SAFETY (MOS) ECSS 4.6.14

margin of safety (MOS): margin of the applied loadmultiplied by a factor of safety against the allowed load

a. Margins of safety shall be calculated by the following formula:

MOS =(*allowable load*)/ ((*applied load*)×*FOS*)−1

where:
allowable load: allowable load under specified functional conditions (e.g. yield, buckling, ultimate)
applied load: computed or measured load under defined load condition (design loads)

MARGIN OF SAFETY (MOS) ECSS 4.6.14 (2)

FOS: Factor of safety applicable to the specified functional conditions including the Specified load conditions (e.g. yield, ultimate, buckling)

NOTE Margins of safety express the margin of the applied load multiplied by a factor of safety against the allowed load. Loads can be replaced by stresses if the load-stress relationship is linear.

b. All margins of safety shall be positive.

FACTOR OF SAFETY (FOS) ECSS 4.6.15

factor of safety (FOS): coefficient by which the design loads are multiplied in order to account for uncertainties in the statistical distribution of loads, uncertainties in structural analysis, manufacturing process, material properties and failure criteria

a. The selection of appropriate factors of safety for a specific structural element depends on parameterswhich are related to loads, design, structural verification approach andmanufacturing aspects. Such aspects include the following:

- pressurized structures;
- human presence;
- flight hardware or ground support equipment;
- material type;
- joints, bearings, welds;
- verification by test;

FACTOR OF SAFETY (FOS) ECSS 4.6.15 (2)

- verification by test;
- verification by analysis only;
- thermal loads;
- ageing effects;
- emergency loads;
- fail safe verification;
- dimensional stability.

The consistency of all assumptions regarding the loads, Factors of safety,materials and other factors shall be verified, following the guidelines given in annex D and annex E of ECSS E 30 part 2.

MINIMUM FOS FOR UNMANNED SPACECRAFT

Table 1: Minimum FOS for unmanned spacecraft

Structure type and sizing case	FOSY	FOSU	FOSY for verification by analysis only	FOSU for verification by analysis only	Additional factors [a]
Metallic structures	1.1	1.25	1.25	2.0	
Composite structures, Uniform material, brittle		1.25		2.0	
Sandwich structures: - Face wrinkling - Intracell buckling - Honeycomb shear		 1.25 1.25 1.25		 2.0 2.0 2.0	 1.2 1.2 1.2
Glass structures		2.5		5.0	
Composite structures discontinuities		1.5		2.0	
Joints and Inserts		1.25		2.0	1.2
Global buckling		2.0		2.0	

[a] For application of these factors, [E54]see 4.5.17.2 d)

MINIMUM FOS FOR PRESSURIZED MANNED MODULES

Table 2: Minimum FOS for pressurized manned modules

Structure type / sizing case	FOSY	FOSU	FOSY for verification by analysis only	FOSU for verification by analysis only	Additional factors [a]
Metallic structures: ▪ Launch and landing ▪ In orbit loads	1.0 1.1	1.4 1.5	1.25 1.25	2.0 2.0	
Pressurized manned compartments [b]: ▪ Pressure only ▪ Pressure and inertia	1.65 1.1	2.0 1.5	1.25	2.0	
Composite structures Uniform material, brittle		1.5		2.0	
Composite structures Discontinuities				2.0	
Joints and Inserts				2.0	1.2

[a] For application of these factos, see 4.5.17.2 d)

[b] For application of pressure FOS, see 4.5.17.2 e).

MINIMUM FOS FOR EXPENDABLE LAUNCHERS

Table 3: Minimum FOS for expendable launchers

Structure type / sizing case	FOSY	FOSU
Pressurized tanks for liquid propellants and solid propellant stage boosters	1.1	1.25
Pressurized tanks for small solid propellant boosters: ▪ Pressure ▪ Other loads	 1.5 1.1	 2.0 1.25
Engine feed pipes and main tank pressurization pipes	1.1	1.25
Other pipes: ▪ Pressure ▪ Other loads	 1.5 1.1	 2.5 1.25
Elastomer and elastomer/structure interfaces		2
Other structures	1.1	1.25

SAFE LIFE AND FAIL SAFE STRUCTURES - ECSS DEFINITIONS

safe life structure: structure which has no failure when subject to the cyclic and sustained loads and environments encountered in the service life

fail-safe structure: structure which is designed with sufficient redundancy to ensure that the failure of one structural element does not cause general failure of the entire structure with catastrophic consequences (e.g. loss of launcher, endangerment of human life)
NOTE: Failure may be considered as rupture, collapse, seizure, excessive wear or any other phenomenon resulting in an inability to sustain limit loads, pressures or environments.

PRIMARY AND SECONDARY STRUCTURES - ECSS DEFINITIONS

primary structure
part of the structure that carries the main flight loads and defines the fundamental resonance frequencies

secondary structure
structure attached to the primary structure with negligible participation in the main load transfer and the stiffness of which does not significantly influence the fundamental resonance frequencies

INTERFACES

a. The design of structural assemblies shall be compatiblewith all interfaces, interna
and external, which can affect, or can be affected by adjacent systems,
subsystems or assemblies.

b. Consideration shall be given to the following:

1. Mechanical subsystem internal interfaces which include:
— thermal control;
— mechanisms;
— ECLS;
— propulsion;
— pyrotechnics;
— mechanical parts;
— materials.

INTERFACES (2)

2. Interfaces controlled by system engineering which include:
— system engineering process;
— requirement definition and analysis;
— system verification;
— spacecraft-launcher interface;
— environments;
— human factors and ergonomics;
— configuration definition.

3. Interfaces with the other engineering branches which include:
— electrical or electronic engineering: interfaces with equipment, optics, avionics.
— communication: ground communications, space link.
— control systems: rendezvous and docking, attitude and orbit controland robotics.
— ground system and operations: mission operation requirements, ground system, pre-flight operations, mission control, in-orbit operations, mission data, post-flight operations.

INTERFACES (3)

c. Interfaces shall be explicitly defined with respect to the following:

1. design requirements, i.e. areas, volumes, alignments, surface finishing and properties, tolerances, geometry, flatness, fixations, conductibility, constraints imposed by design concepts (e.g. thermal, optical design), mass and inertia properties;

2. external loads applied to the interfaces, including temperature effects;

3. global and local stiffness of parts interfacing to the structure.

A SYSTEM ENGINEERING VIEW (From M.Klein Esa Estec) (1)

Space Project Engineering

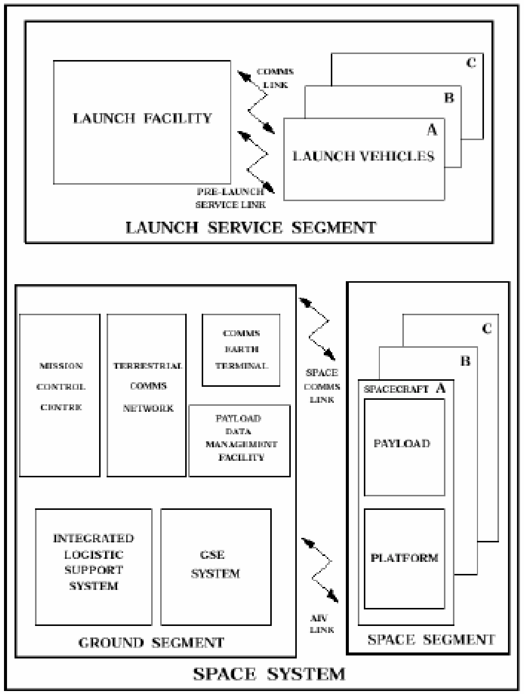
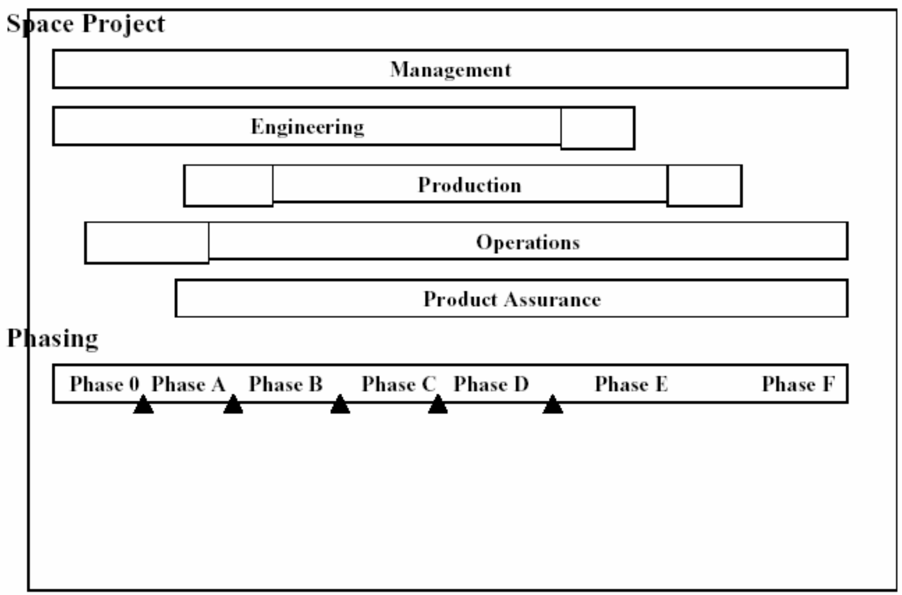


Figure 1: Illustration of the Scope of a Typical Space System

NOTE GSE = Ground Support Equipment
AIV = Assembly, Integration, Verification



The following viewgraphs are taken from M.Klein presentation at the Master course in Satellites of the University of Rome La Sapienza and have the purpose of collocating the space structures activities in the frame of the overall space system design.

A SYSTEM ENGINEERING VIEW (From M.Klein Esa Estec) (2)

- **The activities carried out by the system supplier are conveniently and conventionally categorised into five domains:**

– project management, responsible for achievement of the totality of the project objectives, and specifically for organisation of the project, and its timely and cost–effective execution.

– engineering, responsible for definition of the system, verification that the customer's technical requirements are achieved, and compliance with the applicable project constraints.

– production, responsible for manufacture, assembly and integration of the system, in accordance with the design defined by engineering

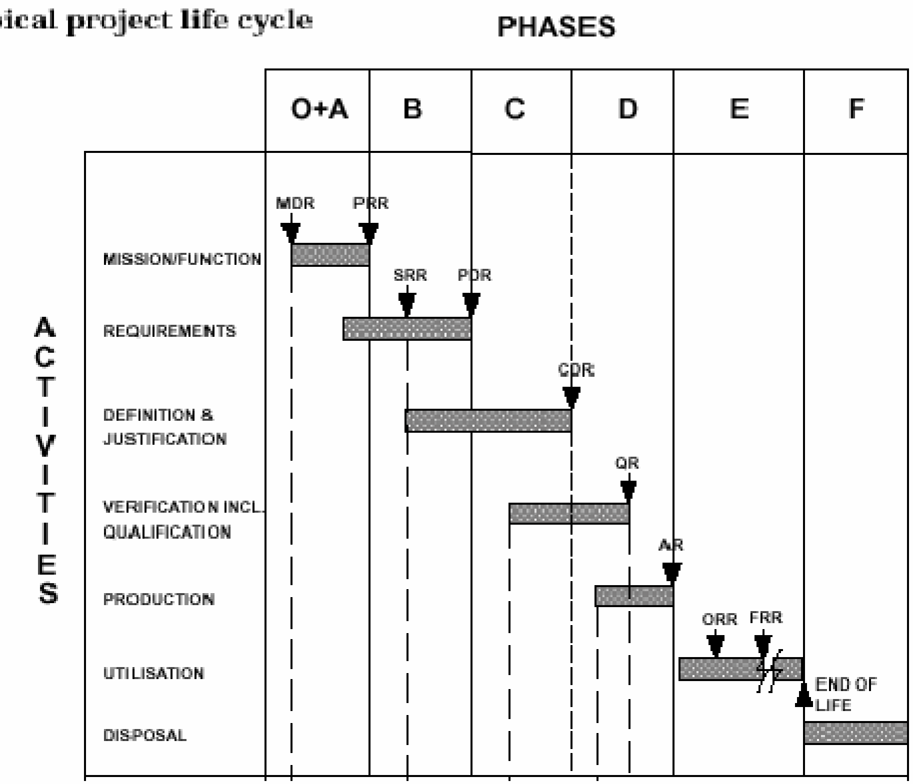
– operations, responsible for exercising and supporting the system in order to achieve the customer's objectives during the operational phases (note; operations may be carried out by the customer, by the supplier or a third party on the customer's behalf, or by a combination of these)

– product assurance, responsible for the implementation of the quality assurance element of the project and also for certain other specialist activities.

A SYSTEM ENGINEERING VIEW (From M.Klein Esa Estec) (3)

Fund. of Project Phasing & Planning

Figure 1: Typical project life cycle



A SYSTEM ENGINEERING VIEW (From M.Klein Esa Estec) (4)

The Engineering Domain

• Introduction to the Engineering Domain

– The project engineering process aims at a satisfactory response to a user's needs by the creation and delivery of a product for the intended mission; it occurs within a domain which can be represented as illustrated in Figure 2.

– Three orthogonal axes can be identified within this domain :

• the "levels of decomposition" axis, which indicates the level (part, assembly, equipment, subsystem, system) at which the engineering process is being exercised.

• the "engineering disciplines" axis which includes those engineering disciplines (systems, electrical, mechanical, software, communications, control and operations engineering) which contribute their expertise to the engineering process.

• the "system engineering process" axis, which includes the functions within the domain which guides and powers the engineering process (called "integration and control"), and those processes which are exercised iteratively through the project in order to design and verify a product which meets the customers requirements.

A SYSTEM ENGINEERING VIEW (From M.Klein Esa Estec) (5)

The Engineering Domain

Introduction to the Engineering Domain

Each cell within the domain in Figure 2 represents a potential project engineering activity.

It can be identified by means of three labels, which indicate :

- the type of system engineering activity
- the engineering discipline concerned
- the level of decomposition

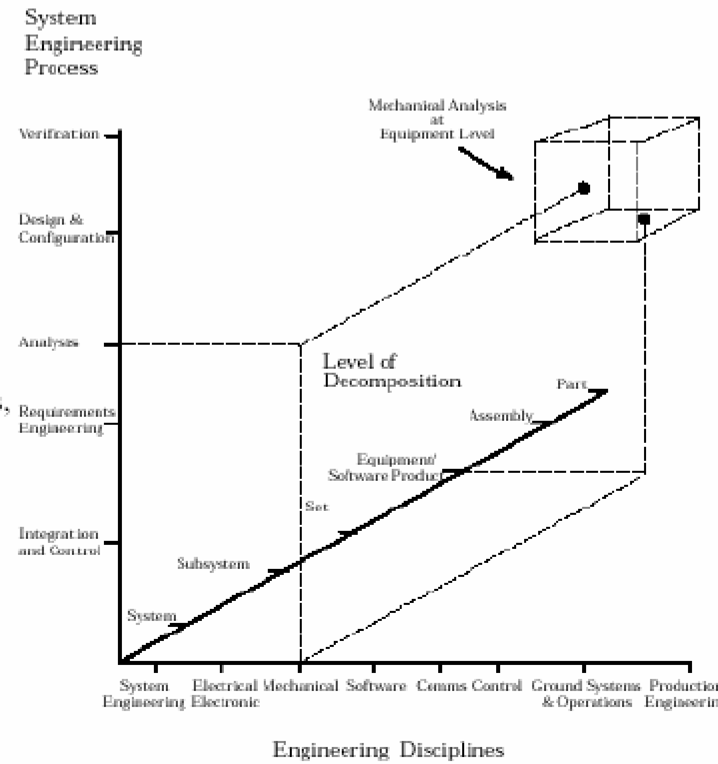


Figure 2: Representation of the Engineering Domain

NOTE The sequence of the items along the axes is not significant.

A SYSTEM ENGINEERING VIEW (From M.Klein Esa Estec) (6)

The Engineering Domain

- **The System Engineering Process**

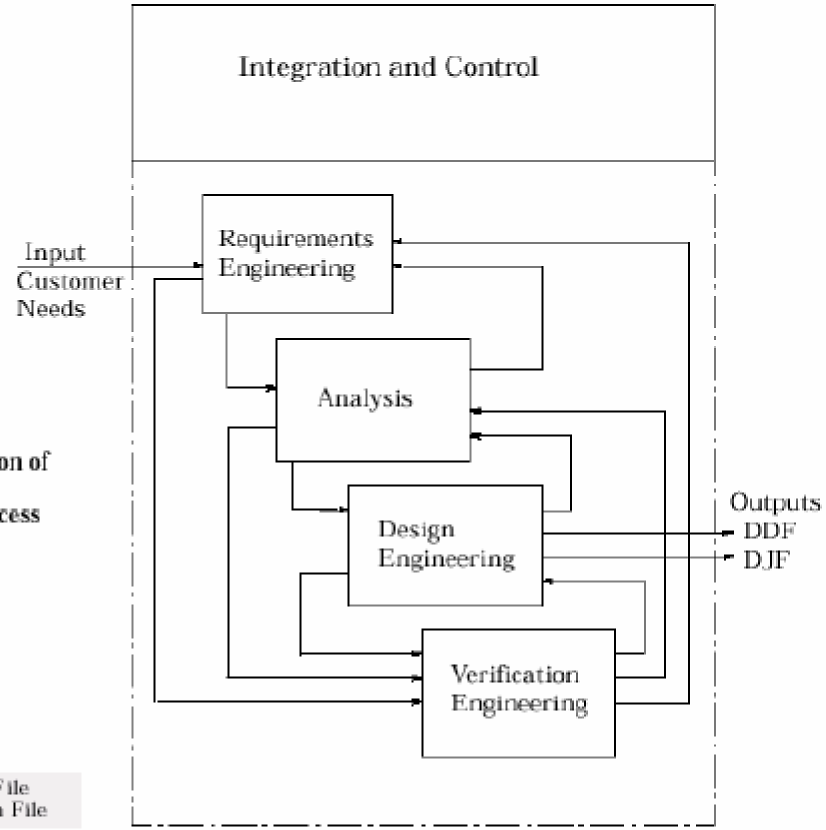


Figure 4: Simplified Representation of the System Engineering Process

NOTE DDF = Design Definition File
DJF = Design Justification File

THE SYSTEM ENGINEERING PROCESS

– A simplified representation of the system engineering process is presented in the previous figure, in which five functions can be identified:

– the integration and control function, which manages the concurrent contributions ofall participating functions, of all disciplines, throughout all project phases, in order to optimise the total system definition and implementation

– the requirements engineering function which ensures that the product requirements are complete, unambiguous, and properly express the customer's need

– the analysis function, which comprises two sub-functions which although related are rather different in nature:

• definition, documentation, modelling and optimisation of a functional representation of the system (functional analysis)

• analytic support to the requirements, design, and verification functions

– the design and configuration function, which generates a physical architecture for theproduct, and defines it in a configured set of documentation which forms an input to the production process

THE SYSTEM ENGINEERING PROCESS (2)

– the **verification engineering** function, which iteratively compares the outputs fromother functions with each other, in order to converge upon satisfactory requirements,functional architecture, and physical configuration, and defines and implements theprocesses by which the finalised product design is proved to be compliant with its requirements.

– The system engineering activities are equally valid and necessary at all levels of decomposition within the space product.

Each responsible designer of a lower item should recognise himself as the system engineer for his product, and ensure that the system engineering process is fully exercised.

STRUCTURAL ENGINEERING AS PART OF ONE ENGINEERING DISCIPLINE

The Engineering Disciplines
– Space project engineering is a multidisciplinary activity employing a wide range of technologies, Consequently, resources from a number of engineering disciplines generally contribute to the engineering process, at least at the higher levels of complexity.

Among those disciplines (system engineering, software engineering communications engineering control engineering, production engineering operations engineering) the mechanical engineering discipline addresses all aspects of the mechanical design of space products, where mechanical in this context includes structural, thermal and material selection aspects, propulsion for spacecraft and launch vehicles, pyrotechnic and environmental control/life support functions, and mechanical parts, interfaces and interconnections.

CONCLUDING REMARKS

The process of structural design

General structural design criteria

Interfaces

Space structures in the frame of the system engineering effort and process