# Method for Controlling Space Transportation System Life Cycle Costs

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**A structured, disciplined methodology is required to control major cost-influencing metrics of space transportation systems during design and continuing through the test and operations phases. This paper proposes controlling key space system design metrics that specifically influence life cycle costs. These are inclusive of flight and ground operations, test, and manufacturing and infrastructure. The proposed technique builds on today's configuration and mass properties control techniques and takes on all the characteristics of a classical control system. While the paper does not lay out a complete math model, key elements of the proposed methodology are explored and explained with both historical and contemporary examples. Finally, the paper encourages modular design approaches and technology investments compatible with the proposed method.**

## Nomenclature

| | | |
|---|---|---|
| $C_{DDT\&E}$ | = | Design, development, test and evaluation (DDT&E) cost contribution |
| $C_{GND}$ | = | Ground operations (launch and recovery) operation and infrastructure cost contribution |
| $C_{lab}$ | = | labor cost contribution |
| $C_{mat}$ | = | material cost contribution |
| $C_{MSN}$ | = | Mission operations and infrastructure cost contributions |
| $C_{oth}$ | = | other direct and indirect cost contributions |
| $C_{PROD}$ | = | Production hardware (recurring expendable elements) cost contribution |
| CONOPS | = | Concept of Operations |
| GSE | = | ground support equipment |
| $LC^3$ | = | life cycle cost control |
| *LCC* | = | life cycle cost |

## I. Introduction

LIFE CYCLE cost characteristics of space flight systems, and in particular human space flight systems, have missed original projections of non-recurring investment, annual recurring sustaining costs, as well as capability shortfalls in system utilization. A structured, disciplined methodology is required to control major cost-influencing metrics of space transportation systems during design and continuing through the test and operations phases. While established techniques have been accepted for managing space vehicle performance by controlling mass properties,[1,2,3] additional techniques are required to bring about the life cycle characteristics demanded by today's stakeholders. A similar methodology is urgently needed for achieving affordability and sustainability objectives in our human space exploration commitments.

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## II. Design Influences on LCC

Many attempts have been made in the past draw relationships between design and the outcome of the design. In Figure XX below, an influence diagram is presented to show primary influences on life cycle cost. This set of relationship draws on an analysis performed by the Space Propulsion Synergy Team used a consensus process to derive a quantified relationship map. The primary finding was that the inherent reliability and the system complexity were the root influences on life cycle cost.[4]

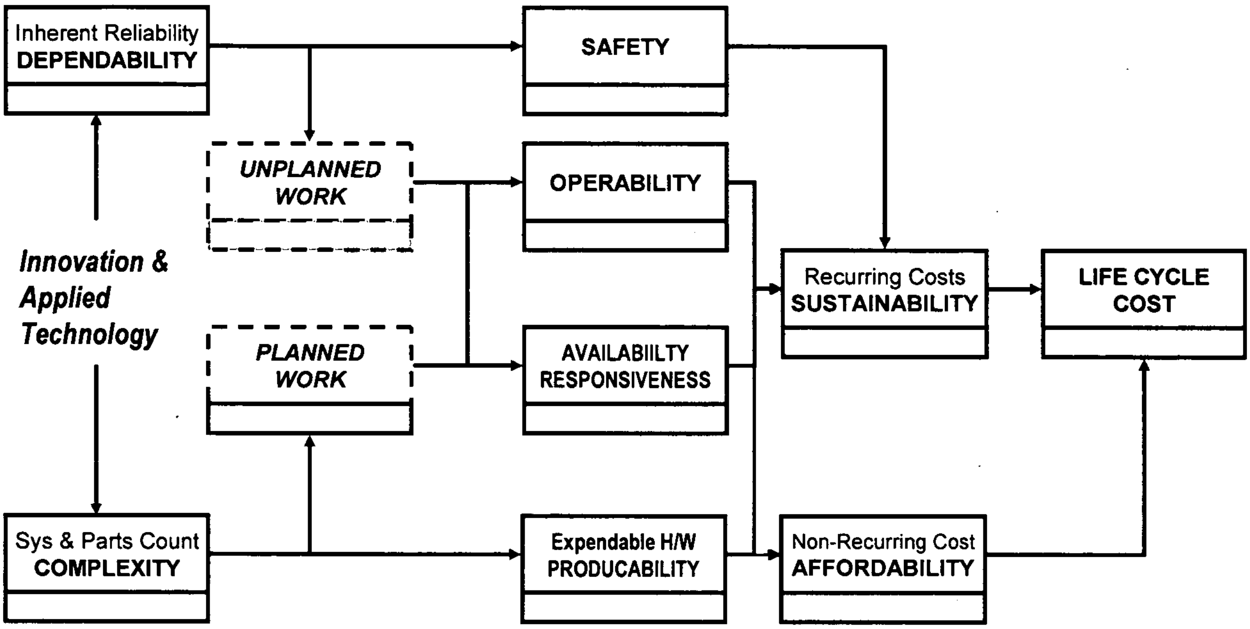


**Figure 1. Life Cycle Cost Influence Diagram**

## III. Life Cycle Cost (LCC) Elements

Having explored the design influences on life cycle cost, what is needed is a quantifiable approach for assessing and measuring a design's LCC. The life cycle cost (LCC) of a space transportation system can be divided into to a hierarchy of cost elements (see Figures 1 and 2).[5]

First, the total life cycle costs during the design phase must include:

(1) Estimating and tracking methods for non-recurring design, development, testing and evaluation costs, $C_{DDT\&E}$, including the costs to acquire and produce first-flight capabilities (flight and ground elements)

(2) Estimating and tracking methods for recurring production costs by manufacturers of flight elements and equipment, $C_{PROD}$.

(3) Estimating and tracking methods for recurring ground operations at launch and recovery sites (both nominal and off-nominal recovery sites), $C_{GND}$.

(4) Estimating and tracking methods for recurring mission operations to support monitoring and managing the space flight, $C_{MSN}$.

Additionally, for each of the life cycle phases described above, and in Figure 1, several common categories should be estimated and tracked during the design phase. These include:

(1) labor costs, $C_{lab}$.

(2) material costs, $C_{mat}$.

(3) other direct and indirect costs, $C_{oth}$.

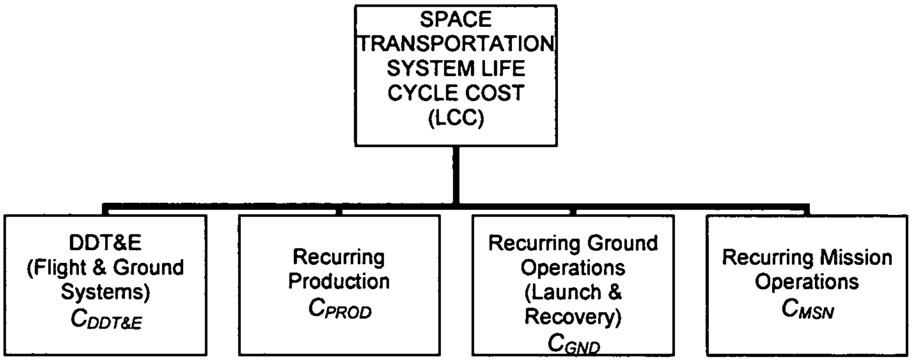


**Figure 2—Top-Level Life Cycle Cost Elements (By Phase)**

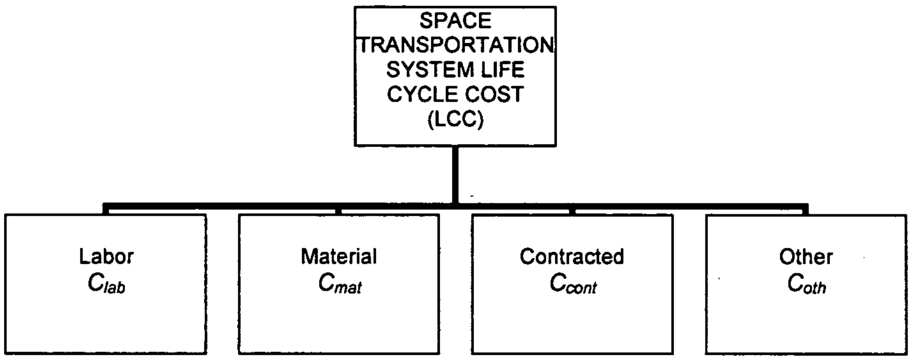


**Figure 3—Life Cycle Cost Elements (By Type)**

Therefore, the basic life cycle cost outcome over time for a space transportation system can be rolled-up per Eq. (1):

$$LCC = \sum_{i,j=1}^{4} C_{i,j}(t) \qquad (1)$$

Where,
$C_{i,j}$ = *life cycle cost element*
$i$ = *index for LCC phase* ($1=C_{DDT\&E}$; $2=C_{PROD}$; $3=C_{GND}$; $4=C_{MSN}$)
$j$ = *index for LCC type* ($1=C_{lab}$; $2=C_{mat}$; $3=C_{cont}$; $4=C_{oth}$)

Graphically, this can be displayed as shown in Figures 3 and 4. In Figure 3, the cumulative life cycle costs are displayed in a *sand chart* (i.e., a stacked area graph, resembling layers of washed-up beach sand) stratified by the various program phases, $C_i$. Alternatively, the same result can be displayed by the cost type, $C_j$, as shown in the sand chart of Figure 4.

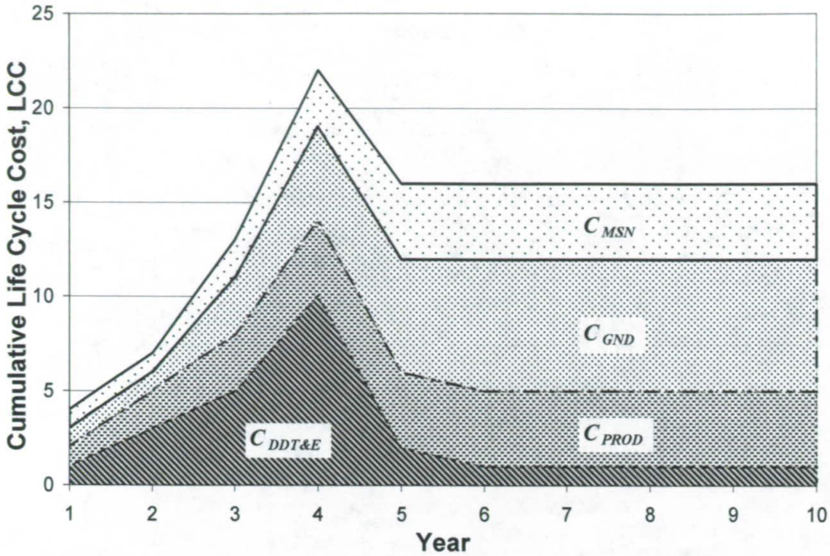


**Figure 4—Simplified LCC *Sand Chart* with Cumulative Cost Elements by Phase, $C_i$**

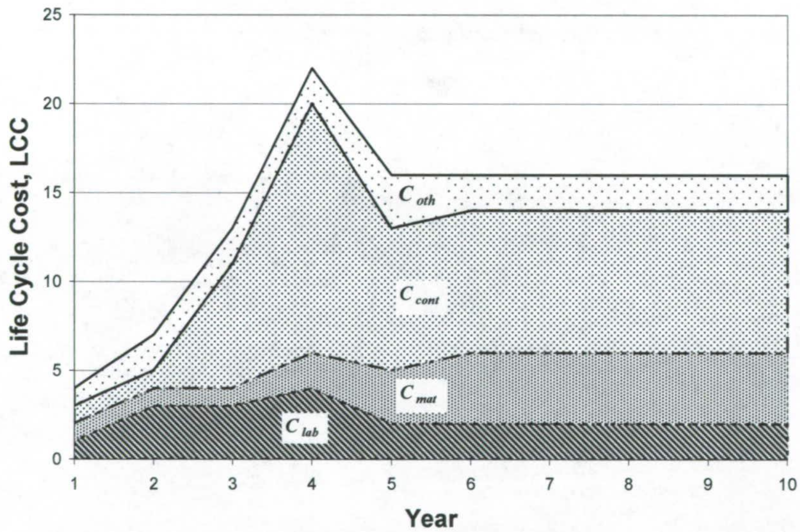


**Figure 5— Simplified LCC *Sand Chart* with Cumulative Cost Elements by Type, $C_j$**

**Table 1—Simplified Life Cycle Cost Table for *Figures 3 & 4***

| | Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $C_i$ | $C_{DDT\&E}$ | 1 | 3 | 5 | 10 | 2 | 1 | 1 | 1 | 1 | 1 | 26 |
| | $C_{PROD}$ | 1 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 34 |
| | $C_{GND}$ | 1 | 1 | 3 | 5 | 6 | 7 | 7 | 7 | 7 | 7 | 51 |
| | $C_{MSN}$ | 1 | 1 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 31 |
| | **Total** | **4** | **7** | **13** | **22** | **16** | **16** | **16** | **16** | **16** | **16** | **142** |
| $C_j$ | $C_{lab}$ | 1 | 3 | 3 | 4 | 2 | 2 | 2 | 2 | 2 | 2 | 23 |
| | $C_{mat}$ | 1 | 1 | 1 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 28 |
| | $C_{cont}$ | 1 | 1 | 7 | 14 | 8 | 8 | 8 | 8 | 8 | 8 | 71 |
| | $C_{oth}$ | 1 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 20 |
| | **Total** | **4** | **7** | **13** | **22** | **16** | **16** | **16** | **16** | **16** | **16** | **142** |

## IV. Life Cycle Cost Control ($LC^3$) Method

The proposed life cycle cost control (LC3) method has the characteristics of a classical control system (see Figure 6). While it is not the purpose of this paper to present a detailed math model, the general methodology can be explored. It has a *reference input signals*, e.g., reference architectural concept, and budget profile guidelines and constraints. It also has a *plant* (existing configuration control, mass properties control, and other performance control processes). The output signal, the item to be controlled, is the of course, the life cycle cost profile, such as displayed in Fig. 7 and Fig. 8. This output signal must be constantly measured during the design process against the constraints on life cycle cost to form an error signal. This error signal must be feedback to the configuration by decomposing and converting the life cycle cost error into the influencing system design characteristics and properly gained and balanced in terms of life cycle cost contribution (it is important to note that this is not necessarily the same influence as the performance contribution). As mentioned in the introduction, traditional configuration control and mass properties management techniques during crucial design phases have successfully used to steer the architectural outcome in terms of mass performance.

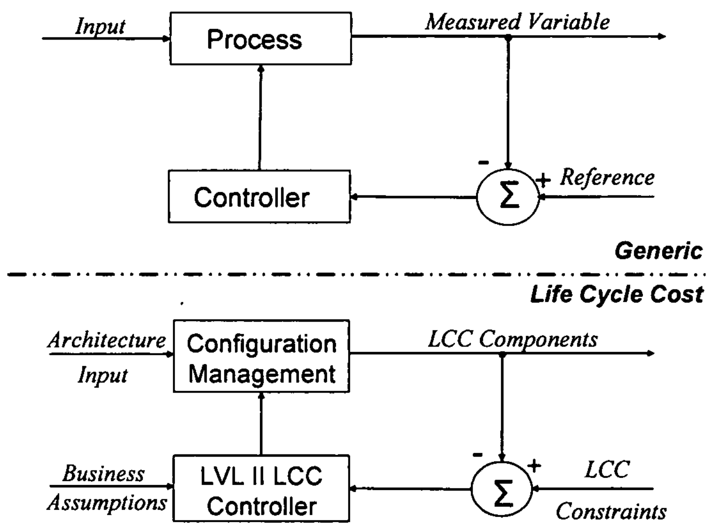


**Figure 6. Control System Analogy.**

## V. Candidate Space System Design Metrics

Transfer functions need to be developed from appropriate statistical data sources to properly apply the proposed technique. Many of these exist and are captured in existing cost models and cost database. These mainly apply to the non-recurring flight h/w development functions. Developing the needed transfer functions for the ground and mission operations functions requires further investment in analyzing existing space operations.

Some preliminary analysis has been performed, however, that indicates that the following should be explored for constructing the missing parametric cost relationships. Some of these include:

(1) Number of separate systems and subsystems
(2) Projected amount of unplanned work
(3) Projected amount of planned work
(4) Number of manual assembly and mechanical mating operations
(5) Number of flight element interfaces
(6) Number of ground interfaces and resultant GSE infrastructure
(7) Number of separate fluids to service, condition, load, and logistically sustain
(8) Number of hazardous systems to operate and sustain
(9) Number of confined spaces and resultant safety-controlled operations

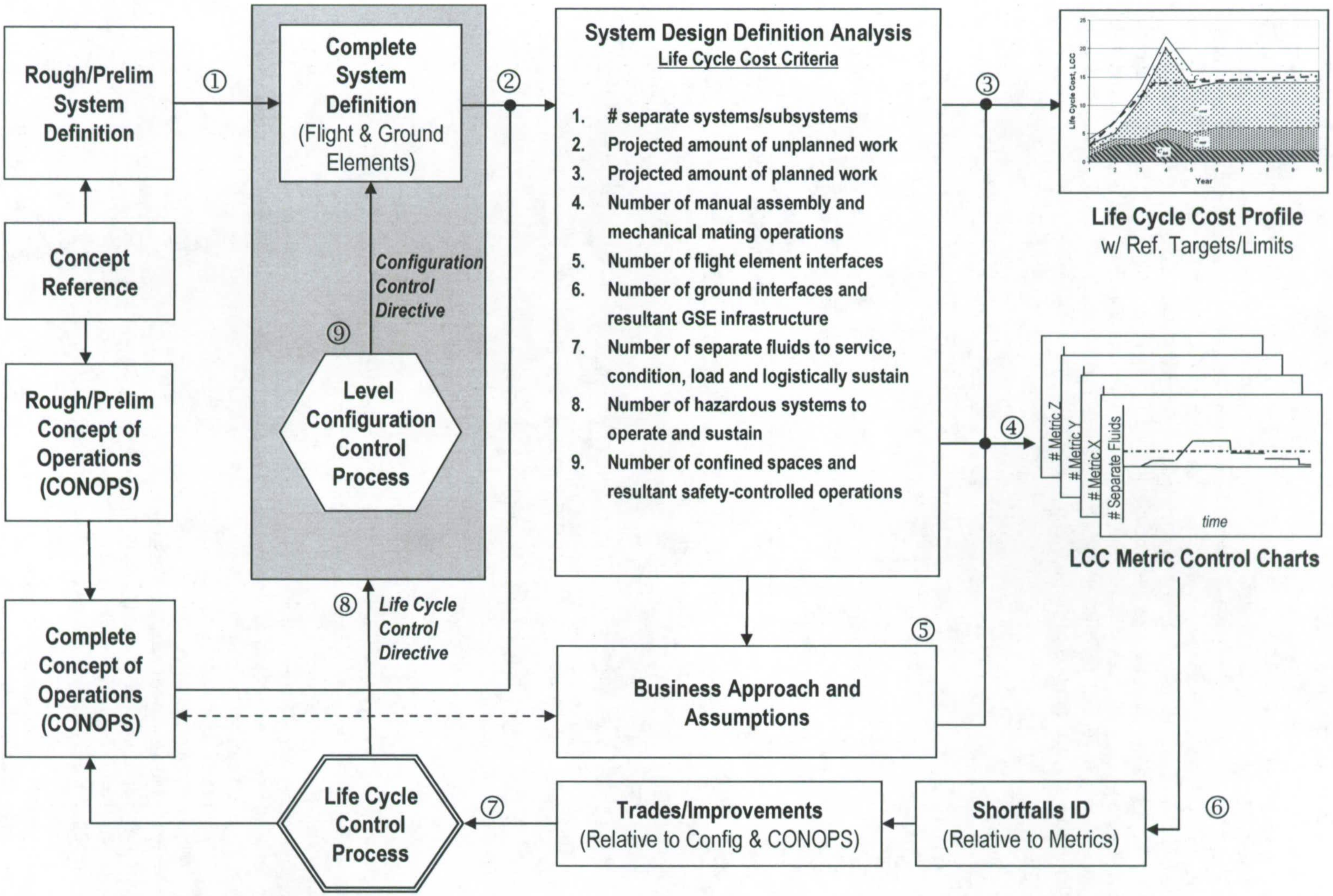


**Figure 7. Life Cycle Cost Control (LC3), 1 of 2**

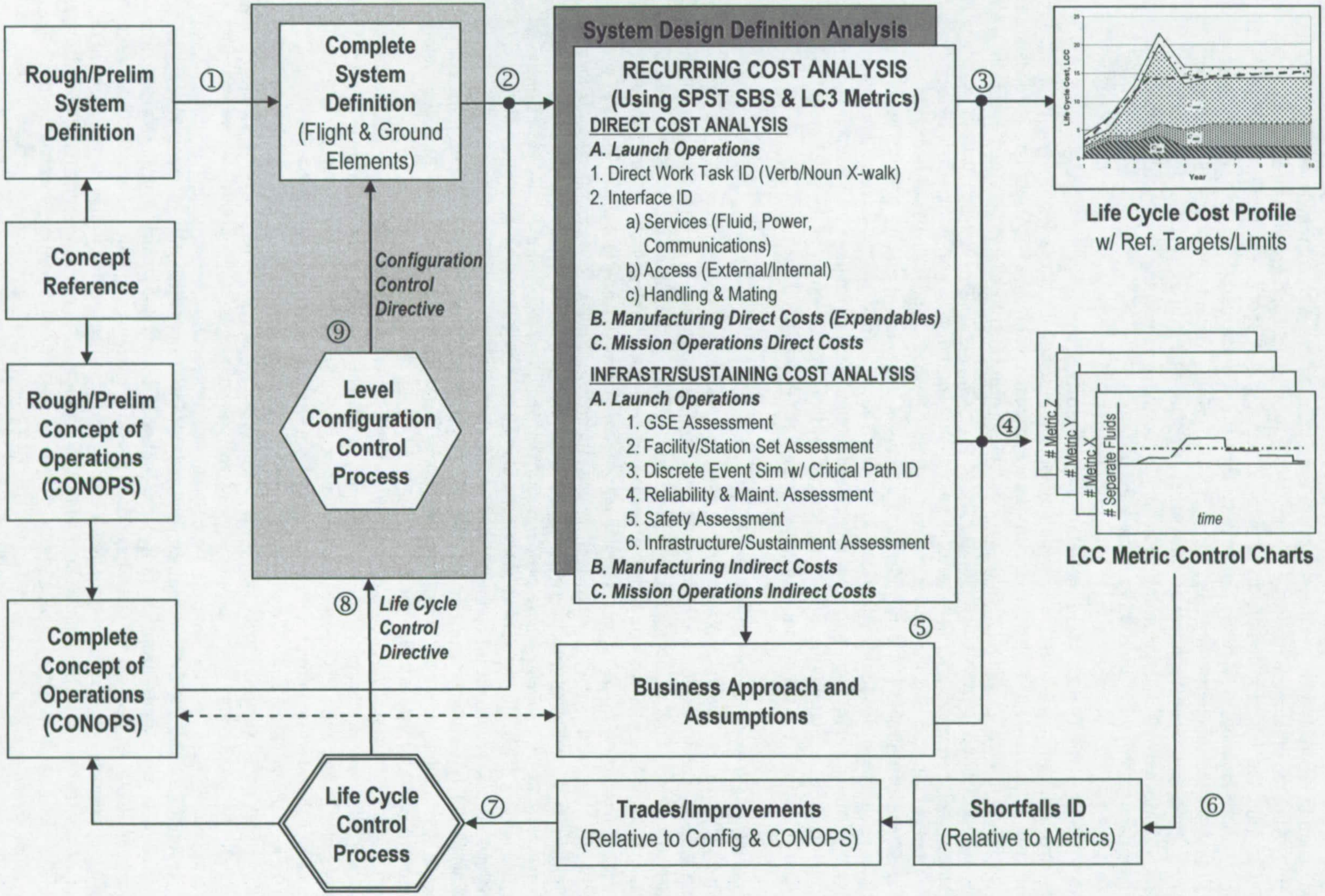


**Figure 8. Life Cycle Cost Control (LC3) Methodology, 2 of 2**

## VI. Example System Design Approaches and Applied Technology

How does one go about correcting a design that is out of balance in terms of life cycle cost? According to the influence diagram in Figure 1, there are three effective approaches (along with combinations of the three):

(1) Alter the inherent reliability, or dependability, of the flight and ground systems

(2) Alter the inherent complexity through better *flight* system integration. This involves performing more functions with fewer hardware systems and subsystems.

(3) Alter the inherent complexity through better *ground* system integration. This involves performing more functions with fewer ground processing stations, facilities, systems, and equipment.

(4) Apply new technology or design techniques that have gained engineering confidence

We will explore each of these approaches in more detail.

### A. Balance Flight Reliability with Maintainability and Supportability

The first approach requires a conscious decision by the design team whether lack of reliability in flight requires: 1) engineering-in a higher degree of dependability in the system components, or 2) adding redundant strings of hardware, or 3) add new safety items, such as crew escape mechanisms, to overcome a bad event. In practice, all approaches will most likely be examined and/or applied on a case by basis. However, certain decisions up-front about avionics fault tolerance and *fail-op/fail safe* vs. *fail-op/fail-op/fail safe* functional redundancy design philosophies, tend to set examples for the design team to follow—whether intended or not intended.

With the advent of reusable spacecraft elements traditional approach of adding systems beyond dual or even beyond triple redundancy for flight safety has come into question due to the adverse impacts of the added maintenance burden, whether it is on terrestrial launch and landing sites, or on permanently deployed facilities, such as the International Space Station. For further exploration of these relationships in the systems definition phase of design—whether for flight system or ground system design—see Adams and Rhodes.[6]

### B. Integrate the Flight Systems and Subsystems for Operability

*1. Element Configuration/Propulsion System Integration Techniques*

The first set of opportunities to *reintegrate* the design concept; i.e., conduct design iterations for the purpose of simplifying the concept, and creating greater inherent operability and supportability, is to look closely at the element, tank, and engine/motor configurations. There are several ground operator design preferences:

- *Preference to load heavy liquid oxygen near the aft of the space vehicle configuration.* This is to enable pressure-fed ground loading, alleviate water hammer effects for emergency off-loading contingencies, as well as propellant geysering complications.
- *Preference to load all launch vehicle propellants from the aft of the vehicle (for vertical take-off configurations).* This allows rise-off umbilicals and avoids critical lift-off service arms or swing arms that need to reconnect following an on-pad launch countdown abort. Often these service arms may unavoidably be attached within the post T-0 flight path creating extra care during the design process and adding life cycle costs for *arm farm* development rigs and precautionary safety equipment, software, and it sustainment.
- *Avoidance of interstage structures and other confined propulsion compartments.* These lead to added system requirements for hazardous gas (or *haz-gas*) monitoring systems, umbilical extensions for the haz-gas monitoring and safety purges (usually air or gaseous nitrogen). Adding elevated umbilicals creates launch towers and directs the design away from simpler launch system approaches.
- *A concept with thrust vector control only—even if it requires more actuation—is preferable to one that requires both thrust vector control and reaction control and/or ullage rocket functions.* The addition of auxiliary propulsion pods creates severe complications to the ground operations and infrastructure. These require separate processing facilities and/or pad servicing equipment and service umbilicals, along extra manufacturing and assembly operations. Often these systems are designed with toxic and hazardous propellant commodities and thus carry a ground safety and infrastructure burden, along with serial hazardous processing delays and reduced availability. Use of single engine stage configurations are often a cause of this problem. While it may appear at the high level of configuration to be simpler, in reality the addition of many active auxiliary propulsion elements detracts from safety and adds to system complexity and life cycle costs during both development and operations.

*2. Propulsion System/Power System Integration*

Another set of opportunities to reintegrate the system design toward improved life cycle costs involves using the available propulsion systems and elements to provide needed power for large mechanical loads, such as flight control actuation, rather using expensive (and often inefficient and hazardous) auxiliary power systems. Tap-offs from the engine hardware or propulsion tank ullage pressure can operate turbine-powered alternators or generators, or directly drive hydraulic/pneumatic pumps for distributed actuation systems, or alternatively, for element/stage electrical distribution. These can be backed-up by other electrically stored power sources or cross-strapped to other systems in case of engine shutdown. In many of these systems the engine is required to be in firing or otherwise operating (such as an engine idle mode). However, stored energy methods that accumulate energy during engine operation, such as momentum flywheels, may also be employed following engine shutdown.

*3. Avionics System Integration Trade-offs*

Placement of launch vehicle and spacecraft on-board command, control, guidance, navigation, and communications hardware can often lead to duplication of function in both the launch vehicle and payload. System integration through careful placement and careful failure mode and contingency mode analysis can lead to a simplified system that is completely controlled by the payload. Isolated capability of the launch vehicle from the payload or spacecraft can also have flight safety advantages, exemplified by the Apollo XII in-flight lightning strike that affected the spacecraft controls, but not the Saturn V launch vehicle's Instrument Unit (IU).

## C. Integrate the Ground Systems and Subsystems for Operability and Supportability

*1. Minimize Ground System Processing Stations*

Lowering life cycle cost through ground system integration should first be accomplished in the architectural layout of the launch system. One method used of functionally organizing the ground segment of a launch system is by defining *station sets*—logical groupings of facilities, systems, equipment and other operational assets that perform a common function.[7] Minimizing the number of facility processing stations, as well as the cumulative number of separate distributed systems, networks and equipment, is an effective means of lowering fixed infrastructure costs. Minimizing processing stations has the dual benefit of reducing fixed facility maintenance and upkeep, as well as reducing the cumulative number of: flight element processing station arrival preparations, personnel external access set-ups, equipment and service hook-ups, internal access setups, vehicle closeouts prior to processing station transfer, internal access removal, reconfiguration of external access stands and platforms, disconnection of vehicle services, and transfer from processing station. The foregoing functions are required for almost all vehicle hardware processing facilities.

*2. Vehicle Ground Service Locations at Launch Point*

Location of the vehicle fluid, gas, electrical, and hard-line data services are, in general, preferred to be located such that any required manual procedures at the launch point can be accessed from ground level or from the deck of the launcher (either fixed or mobile). Priority order of umbilical design approach in terms of life cycle cost attributes is: rise-off (most-preferred), side-mounted pull-away tail service masts, pre-launch elevated side mounted umbilicals, non-critical lift-off pull-aways, critical T-0 services arms (least desirable). Obtaining the most preferable design options for umbilicals and services is feasible if ground system attributes are made a priority by the design team early in the concept definition process.

*3. On-line Hazardous Pad Servicing vs. Off-line Hazardous Facility Processing*

Handling of hazardous commodities (for example, toxic hypergolic fuels and oxidizers) and components (such as pyrotechnic devices) are often performed late in the launch operations process at the launch pad. Another alternative is to perform the hazardous operations in off-line facilities and in parallel to vehicle assembly and pre-launch operations. However, life cycle cost trades should be performed to determined whether fixed recurring infrastructure costs are higher for on-line pad services, or off-line hazardous facilities (particularly for facilities dedicated to the function in question). Also to be factored in are overall launch throughput and launch surge requirements.

*4. Universal Assembly Facilities, Launchers, and Pads*

For launch systems that require more than one geometrical vehicle configuration in the manifest, the ground system designers should strive for commonality of assembly facilities, launchers and launch mounts, and launch pad equipment and services. If dedicated facilities, systems and equipment are required for each vehicle configuration, then life cycle cost will necessarily multiply. The system integration architect should strive for similar vehicle cross-sections and facility footprints, and carefully size any new facilities and systems for growth in vertical height of the launch vehicle(s), as well as for facility capacity expansion due future flight demand. For example, the Vehicle Assembly Building (VAB) at Kennedy Space Center currently has four high bays, foundation pilings were driven during construction in order to enable easier addition of fifty-percent more future capacity (two more high bays).

### D. Applied Technology for Launch and Recovery Functions

Finally, each ground system station set should be assessed during the concept definition, design, and continuous improvement phases of the life cycle for application of new technologies for greater system efficiencies and effectiveness. Ground system technologies should directly address the complexity and dependability of various launch operations and infrastructure functions, such as: assembly, handling and transfer; inspection and checkout; troubleshooting and repair; propellants, gases, and other fluid system servicing; material, information distribution; energy transmission, power quality, and lightning protection; flight element ocean recovery, and so forth.

The following are provided as some ideas suggested for applied spaceport technologies

1. *Technologies Simplifying Planned Ground Servicing Operations*
   - Electric Actuators for Flight and Ground Systems
   - Leak-free Systems
   - Advanced Hydrogen Detection
   - Advanced Cryogenic Storage and Distribution
2. *Technologies for Unplanned Troubleshooting and Repair*
   - Advanced Fault Isolation and Field Repair Tools
3. *Technologies for Inspection and Checkout*
   - Detection and Repair of Wiring In-place
   - Field Inspection Tools
   - Adaptive Machine Learning
4. *Technologies for Improved Safety*
   - Advanced Fire Detection
5. *Technologies for Improved Public Safety*
   - Space-Based Range

## VII. Conclusions

A method for managing and controlling life cycle costs of a space transportation system is urgently needed for ambitious space operations, and has been explored and documented. More research and analysis is required to prototype and model the proposed technique. Further, more analysis and investigation is needed to better quantify critical life cycle cost parametric relationships and application of various advanced launch system concepts. Supporting models and databases will help to better focus and mature various applied technology efforts and test capabilities.

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## References


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# Introduction

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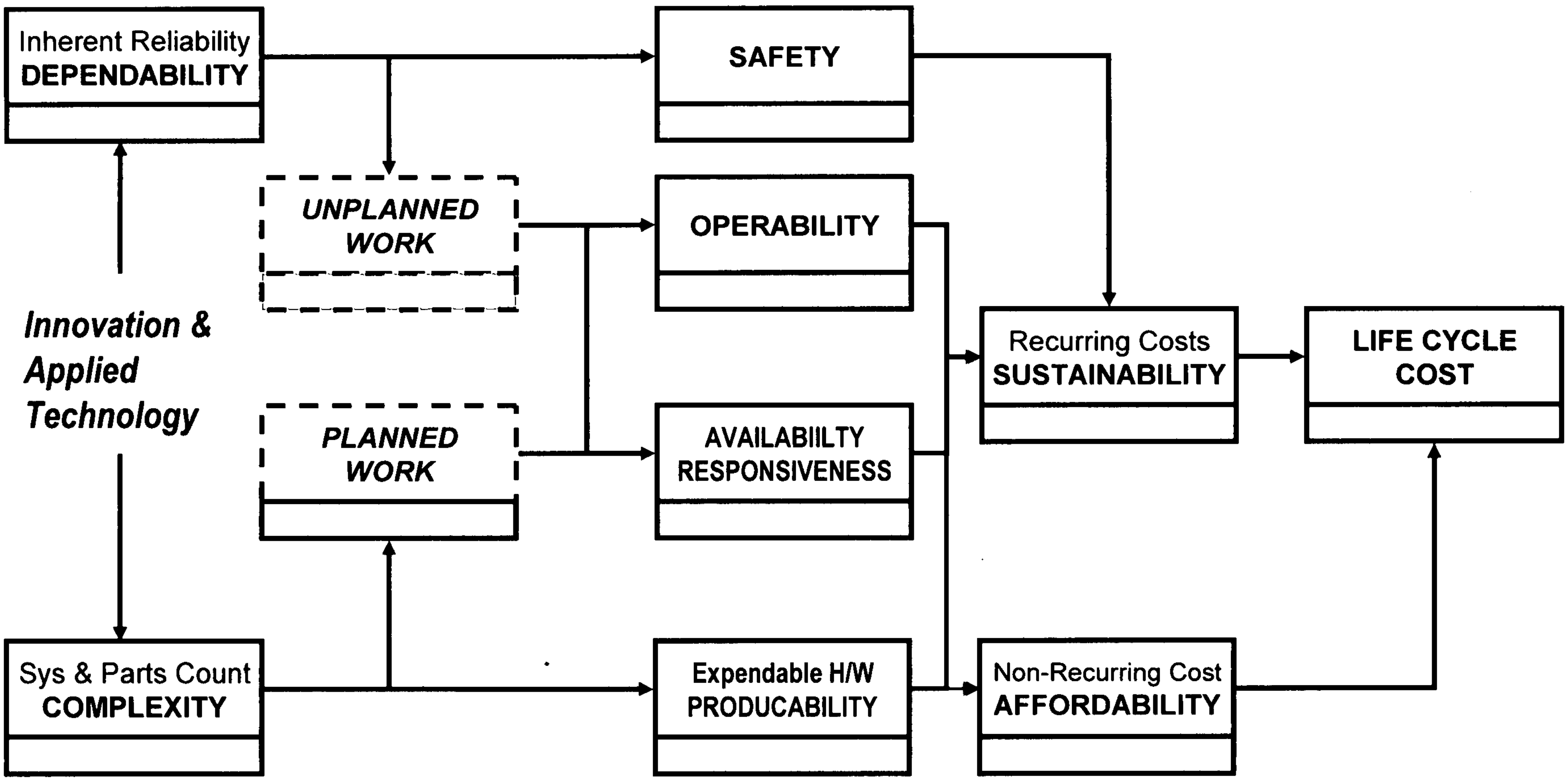
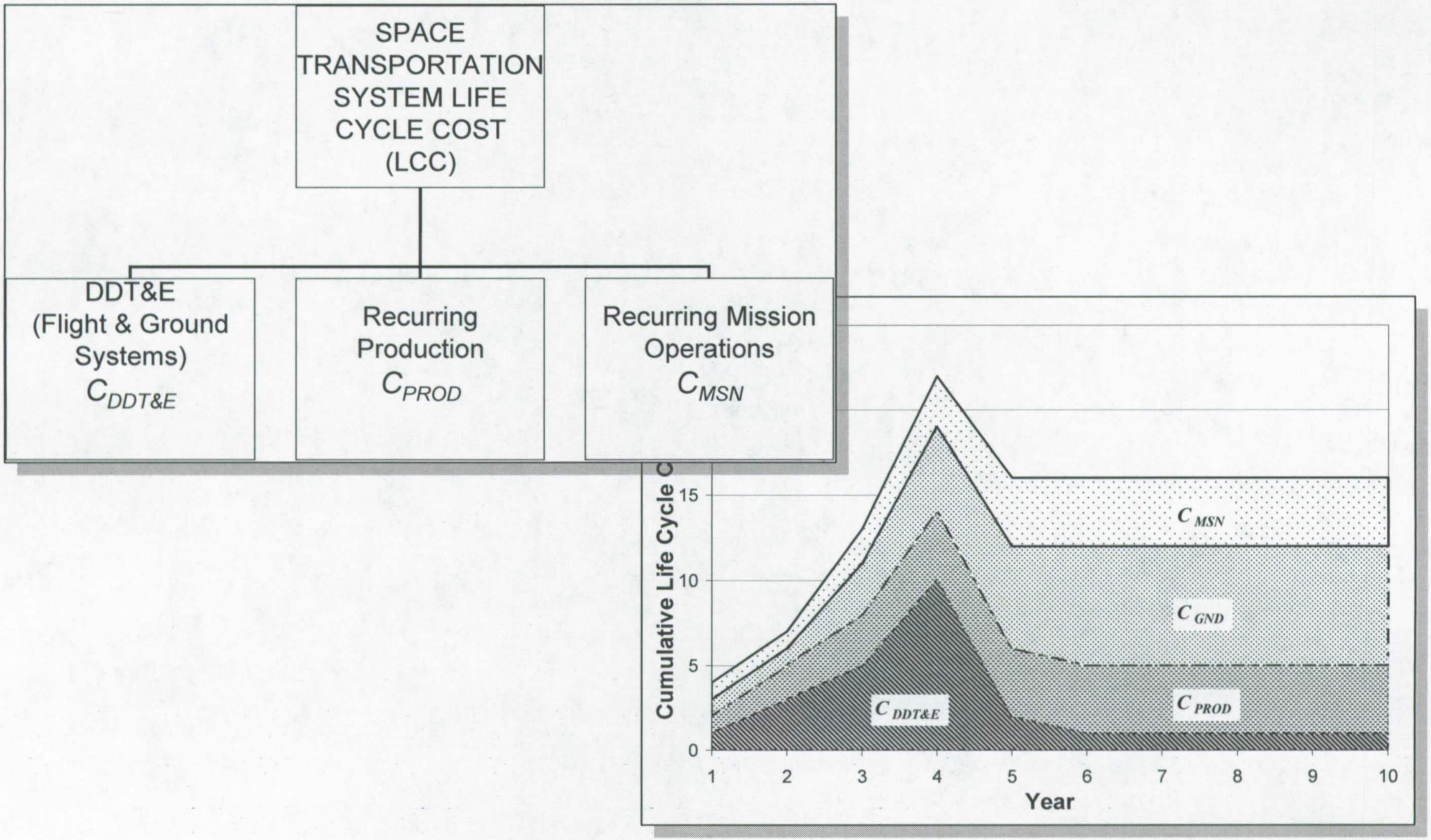
  - Non-recurring investment
  - Annual recurring sustaining costs
  - Capability shortfalls in system utilization
- Structured, disciplined methodology required
  - Control major cost-influencing metrics
  - During design and continuing through the test and operations
  - Mass properties allocation budgets, tracking and configuration control
  - Similar methodology is urgently needed for achieving affordability and sustainability objectives in our human space exploration commitments

# Design Influences on LCC



# Life Cycle Cost (LCC) Elements
## *By Phase*



# Candidate Space System Design Metrics

(1) Number of separate systems and subsystems
(2) Projected amount of unplanned work
(3) Projected amount of planned work
(4) Number of manual assembly and mechanical mating operations
(5) Number of flight element interfaces
(6) Number of ground interfaces and resultant GSE infrastructure
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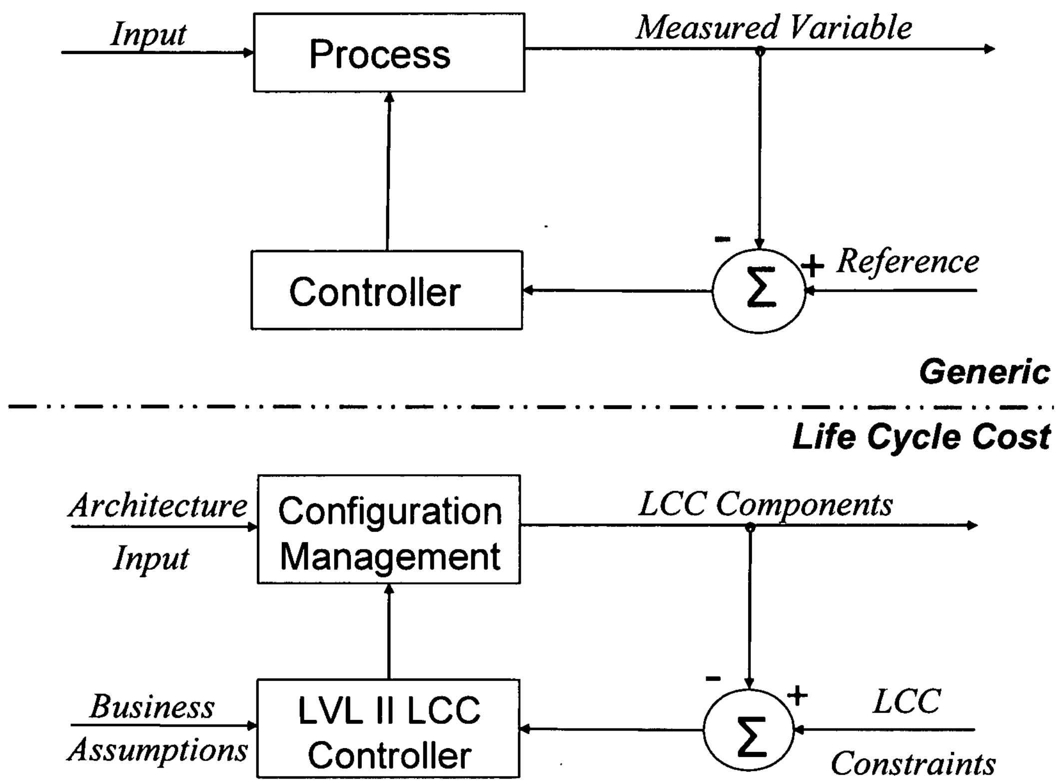
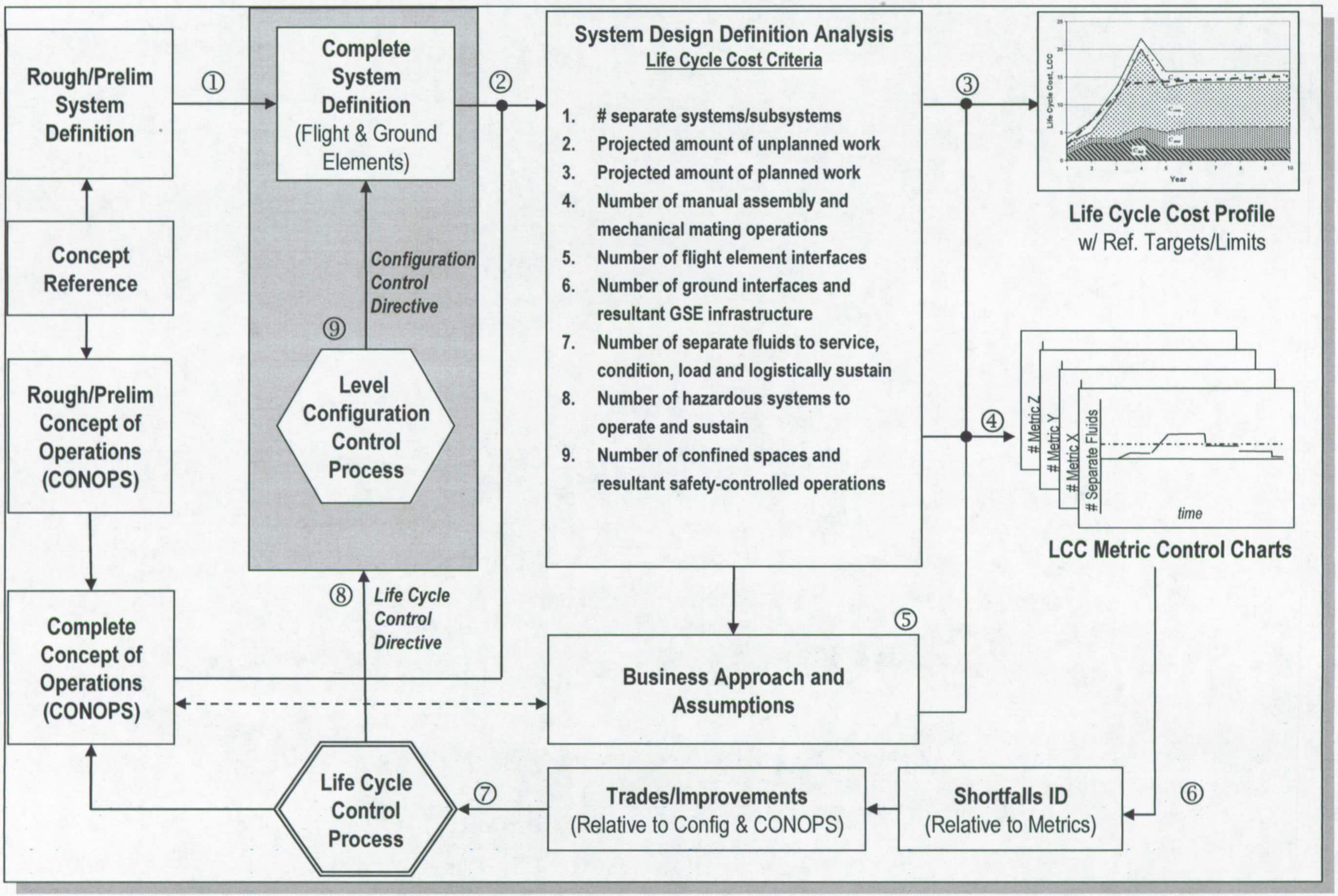
# Control System Analogy



# Life Cycle Cost Control (LC3) Method



# Example System Design Approaches and Technology

(1) Alter inherent reliability or dependability of flight and ground systems

(2) Alter inherent complexity through better *flight* system integration

- More functions with fewer hardware systems & subsystems

(3) Alter inherent complexity through better *ground* system integration

- More functions with fewer ground processing stations, facilities, systems, and equipment

(4) Apply new technology or design techniques that have gained engineering confidence

# Integrate Flight Systems and Subsystems for Operability

1. Element Configuration/Propulsion System Integration Techniques
   - LOX Tank Aft Vehicle Configuration
   - Load Launch Vehicle Propellants from Aft (for vertical take-off configurations
   - Avoidance of Interstage structures and other confined propulsion compartments
   - Thrust Vector Control Only --- Elimination of Dedicated APS Pods
2. Propulsion System/Power System Integration
3. Avionics System Integration Trade-offs

# Integrate Ground Systems and Subsystems for Operability

1. Minimize Ground System Processing Stations
2. Vehicle Ground Service Locations at Launch Point
3. On-line Hazardous Pad Servicing vs. Off-line Hazardous Facility Processing
4. Universal Assembly Facilities, Launchers, and Pads

# Apply Technology for Launch and Recovery Functions

1. Technologies Simplifying Planned Ground Servicing Operations
   - Electric Actuators for Flight and Ground Systems
   - Leak-free Systems
   - Advanced Hydrogen Detection
   - Advanced Cryogenic Storage and Distribution
2. Technologies for Unplanned Troubleshooting and Repair
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   - Field Inspection Tools
   - Adaptive Machine Learning
4. Technologies for Improved Ground Safety
   - Advanced Fire Detection
5. Technologies for Improved Flight Safety
   - Autonomous Flight Safety
6. Technologies for Improved Public Safety
   - Space-Based Range

# Conclusions

- Method for managing and controlling life cycle costs of a space transportation system urgently needed
- Specific techniques explored and documented
- More research and analysis is required to prototype and model the proposed technique
- More investigation is needed to better quantify critical life cycle cost parametric relationships
- Supporting models and databases will help to better focus and mature various applied technology efforts and test capabilities