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Efficience des Sentiers d'Evolution des Technologies des Systèmes de Transport Spatial (STS): une Analyse Qualitative

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Efficiency of the Evolution Paths for Space Transportation System (STS) Technology: a Qualitative Analysis

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Statement

Preface

This is a diary of a four year long journey searching for insight into technology's evolutionary paths, which were sometimes full of adventure, sometimes the cause of deep sighs as I wandered in the wild land, sometimes honoured, privileged routes visiting great wisdoms, and some surprisingly joyful times bearing knowledge.

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I would like to dedicate this thesis in honor and in loving memory of my late father. His support and encouragement throughout my life, gave me the will to pursue this goal and to overcome the many obstacles which I encountered along the way.

Contents

Chapter Titles

List of Abbreviations

3STO: Three Stages To Orbit
ABM: Anti-Ballistic Missile
AF: Air Forces
AFSC: Air Force Systems Command
AIAA: American Institute for Aeronautics and Astronautics
ARDC: Air Research Development Command
ARES: Affordable Responsive Spacelift
ARPA: Advanced Research Projects Administration
ASCENT: Analysis of Space Concepts Enabled by New Transportation
ASAT: Anti Satellite
AST: Office of the Associate Administrator for Commercial Space Transportation
AVR: Office of Certification and Regulation
CAIB: Columbia Accident Investigating Board Report
CAN: Cooperative Agreement Notice
CEC: Commission of the European Communities
CEV: Crew Exploration Vehicle
CFCs: Chlorofluorocarbons
CFSP: Common Foreign and Security Policy
CIS: Commonwealth of Independent States
CoPS: Complex Products and Systems
CRV: Crew Return Vehicle
CSLA: Commercial Space Launch Act
CSTS: Commercial Space Transportation Study
DARPA: Defense Advanced Research Project Agency
DART: Demonstration of Autonomous Rendezvous Technology
DDT: Dichloro-Diphenyl-Trichloroethane
DoD: Department of Defense
DOT: Department of Transportation
EELV: Evolved Expendable Launch Vehicle
EFIFEHT: Exogenous Factor Impact Free Evolutionary Hierarchical Tree
EHT: Evolutionary Hierarchical Tree

ESA: European Space Agency
ESDP: European Security and Defence Policy
ET: External Tank
FAA: Federal Aviation Administration
GAO: General Accounting Office
GDP: Gross Domestic Product
GN&C: Guidance Navigation and Control
GNP: Gross National Product
GPALS: Global Protection Against Limited Strikes
GPS: Global Positioning Satellites
GSO: Geo Stationary Orbit
H. R. House of Representatives
HS/H: High-speed/Hypersonics
HSCT: High Speed Civil Transport
HTHL: Horizontal Take off and Horizontal Landing
HTVD: Horizontal Take off and Vertical Drop
HTVL: Horizontal Take off and Vertical Landing
ICBM: Intercontinental Ballistic Missiles
IMU: Inertial Measurement Unit
IPCC: Intergovernmental Panel on Climate Change
ISS: International Space Station
KBE: Knowledge Based Economy
KLEM: Capital (K) Labor (L) Energy (E) and intermediate Materials (M)
KOP: Knowledge Oriented Policy
LEO: Low Earth Orbit
LFBB: Liquid Fly Back Booster
MAD: Mutual Assured Destruction
MEO: Medium Earth Orbit
MOL: Manned Orbiting Laboratory
MOU: Memorandum of Understanding
MSFC: Marshall Space Flight Center
MTBF: Mean Time Between Failure
MTCR: Missile Technology Control Regime
MTTF: Mean Time To Failure

NACA: National Advisory Committee for Aeronautics
NAI: National Aerospace Initiative
NASA: National Aeronautics and Space Administration
NATO: North Atlantic Treaty Organization
NGLT: Next Generation Launch Technology
NLS: National Launch Service
NRC: National Research Council
OMB: Office of Management and Budget
OMV: Orbital Maneuvering Vehicle
OSP: Orbital Space Plane
OTA: Office of Technology Assessment
PAD: Pad Abort Demonstrator
PAROS: Prevention of an Arms Race in Outer Space
PDA: Phased Development Approach
PSAC: President's Science Advisory Committee
R&D: Research and Development
RBCC: Rocket Based Combined Cycle
RLV: Reusable Launch Vehicle
RPM: Revolution Per Minute
SA: Space Access
SBAS: Satellite-Based Augmentation Systems
SDI: Strategic Defense Initiative
SDIO: Strategic Defense Initiative Organization
SLBM: Submarine-Launched Ballistic Missile
SLI: Space Launch Initiative
SMV: Space Maneuver Vehicle
SOA: State of the Art
SPOT : Satellite Pour l'Observation de la Terre
SRB: Solid Rocket Booster
SRG: Space Task Group
SRM: Solid Rocket Motors
SSME: Space Shuttle Main Engine
SSTO: Single Stage To Orbit
ST: Space Technology

STS: Space Transportation System
TAOS: Thrust Assisted Orbiter Shuttle
TBCC: Turbine Based Combined Cycle
TBO: Time Between Overhaul
TF: Technology Forecasting
TFT-LCD: Thin Film Transistor-Liquid Crystal Display
TPS: Thermal Protection System
TRIZ: Russian abbreviation of the meaning of "Theory of Inventive Problem Solving”
TRL: Technology Readiness Levels
TSTO: Two Stage To Orbit
US: United States
UK: United Kingdom
UN: United Nations
URM: Universal Rocket Module
USTR: U.S. Trade Representative
VTHL: Vertical Take off and Horizontal Landing
VTVD: Vertical Take off and Vertical Drop
VTVL: Vertical Take off and Vertical Landing
WMO: World Meteorological Organization

List of Symbols

°: Degree

Al_2O_3: Aluminium Oxide

$CINO_3$: Chlorine Nitrate

Cl: Chlorine

CO_2: Carbon Dioxide

g_o: Gravity Constant

H: Horizontal Take off and Horizontal Landing

H_2O: Water Molecule

h: Vertical Take off and Horizontal Landing

HCl: Hydrogen Chloride

Î: Vertical Take off and Vertical Drop

I: Vertical Take off and Vertical Landing

I_{sp}: Engine Specific Impulse

LOX: Liquid Oxygen

NO: Nitric Oxide

O_3: Ozone

P_f: Propellant Mass fraction

Si: Structural Index

Ҹ: Horizontal Take off and Vertical Drop

Ч: Horizontal Take off and Vertical Landing

Résumé

Contexte et challenge

X-20: Dyna-soar en 1963, DC-X: Delta Clipper en 1991, X-33 et X-34 en 2001, X-38: Crew Return Vehicle en 2002…

La liste des programmes de lanceurs réutilisables (Reusable Launch Vehicles - RLV) annulés après de lourds investissements est longue. Seuls trois RLV sont aujourd'hui opérationnels: la Navette Spatiale ('Space Shuttle'), le système de lancement Pegasus/L1011 et la navette Buran. La Navette Spatiale a effectué en octobre 2000 son 100ème vol depuis son premier vol en avril 1981. Cependant, deux des cinq orbiteurs de la flotte se sont désintégrés en vol, et la NASA a dû faire face à des coûts de rénovation très élevés. Le premier vol de l'ancienne navette russe Buran fut aussi son dernier, le 15 Novembre 1988. Seul le PegasusL1011 a pu être mis en service de façon relativement satisfaisante, avec 22 lancements à son actif depuis l'échec de son 14ème vol..

D'une façon générale, l'importance d'une industrie peut se mesurer en termes de revenu généré. Cependant, lorsque l'industrie considérée en influence d'autres, son poids économique est supérieur à ces revenus propres. Selon le Conseil International des Affaires Spatiales (International Space Business Council, 2005), l'effet de levier de l'industrie des lanceurs est de facteur vingt: elle a généré en 2004 4,65 milliards de dollars pour un total de 103.5 milliards de dollars générés par l'industrie spatiale. Le rapport Augustine (1990) a parfaitement exprimé l'importance des Systèmes de Transport Spatial (STS): 'Quand le transport spatial va bien, le programme spatial est florissant; quand le transport spatial connaît des difficultés, le programme spatial dans son ensemble est affaibli et il semble que toute erreur est alors amplifiée.

C'est pourquoi les conséquences économiques de l'échec d'un programme de RLV peuvent être beaucoup plus lourdes que le seul coût du programme, qui n'est déjà lui-même pas inférieur à plusieurs milliards de dollars.

Comment expliquer une liste aussi longue d'accidents fatals parmi les programmes de RLV? A la lecture des épitaphes, nous pouvons voir les raisons de ces accidents, telles que 'stratégie de certitude de destruction mutuelle (MAD)', 'fin de la Guerre Froide', 'technologie prématurée', 'augmentation des coûts' et 'pas de financement disponible'. Nous devons cependant en savoir davantage afin de pouvoir réduire la probabilité d'échecs supplémentaires de programmes de RLV et de stimuler un développement permanent de l'industrie des lanceurs, et de l'industrie spatiale en général.

Question de recherche et structure

Cette thèse est composée de deux parties. La première est une partie théorique qui présente la construction d'une méthodologie 'd'arbitrage entre les sentiers d'évolution des technologies de STS' (Chapitre 4), basée à la fois sur l'analyse du marché du transport spatial (Chapitre 2) et les technologies des STS (Chapitre 3). Enfin, dans une deuxième partie, nous présentons une étude de cas qui nous permet d'évaluer 'l'efficience des sentiers d'évolution technologique des RLV américains' (Chapitre 5).

Méthode

Cette étude vise à élucider les causes fondamentales des échecs des programmes de développement de RLV, et au-delà à susciter un dialogue fructueux au sein de l'industrie des lanceurs au cours du processus d'orientation des futurs programmes de développement de RLV. Nous formulons l'hypothèse que l'enfermement ('lock-in') dans un sentier technologique sous-optimal est la cause première des problèmes rencontrés. En effet, du point de vue de l'évolution technologique, les accidents peuvent être attribués soit à une orientation des programmes aboutissant à la poursuite d'une mauvaise direction en termes de sentier d'évolution, soit à une mise en œuvre inappropriée malgré la pertinence de la direction choisie. Cette dernière explication ne paraît pas invraisemblable au vu du triomphe passé du programme Apollo mis en œuvre par l'industrie spatiale américaine.

Comment procéder?

Nous développons dans un premier temps une méthodologie permettant 'd'arbitrer entre les sentiers d'évolution technologique pour les STS' et d'établir l'argument principal de cette étude.

Nous analysons dans un deuxième temps l'efficience des sentiers d'évolution des RLV américains selon cette méthodologie d'arbitrage, pour établir la conclusion principale de notre étude.

Méthodologie

Puisqu'il ne s'agit pas de prédire mais de construire un sentier crédible en arbitrant entre plusieurs sentiers d'évolution potentiels, nous ne sommes pas confrontés aux problèmes générés par le mécanisme complexe de l'évolution technologique, processus émergeant de l'interaction et de la co-évolution de facteurs endogènes et exogènes et caractérisé par une forte incertitude.

La méthodologie "Exogenous Factor Impact Free Evolutionary Hierarchical Tree"

Le coeur de la méthodologie proposée est de développer des sentiers d'évolution intégralement basés sur les facteurs endogènes, en identifiant les facteurs exogènes et en les isolant des mécanismes d'évolution technologique. Ces facteurs exogènes sont ensuite réintroduits séparément afin d'identifier les sentiers technologiques plausibles parmi tous les sentiers déterminés par les seuls facteurs endogènes. La méthodologie propose se décompose donc en trois étapes:

Etape 1: Inventaire des options technologiques du lanceur

Les éléments des options technologiques sont ici définis d'une manière suffisamment générale pour obtenir une description pertinente des variations technologique du lanceur à l'aide d'un nombre limité d'éléments, mais suffisamment détaillée pour fournir l'information de référence nécessaire pour effectuer un arbitrage entre les différents sentiers. Un inventaire des options technologiques viables est ensuite développé en combinant de façon appropriée les différents éléments selon une approche morphologique.

Etape 2: Construction des sentiers d'évolution hors facteurs exogènes

Nous définissons dans cette étape les règles d'évolution, à la fois en termes de classement héréditaire des éléments et de complexité croissante du produit, critères indépendants des facteurs d'évolution exogènes. Le mode de complexification détermine le processus externe d'évolution de la technologie du produit en déterminant le nombre d'étages de chaque génération du produit. L'arbre hiérarchique d'évolution est ensuite construit, en appliquant ces règles d'évolution à l'inventaire des options technologiques du lanceur.

Etape 3: Sélection des sentiers d'évolution

Nous analysons ici la crédibilité des sentiers d'évolution compte tenu des facteurs exogènes identifiés: les facteurs politiques, le marché, et la contrainte environnementale. Les sentiers plausibles sont ensuite sélectionnés parmi les sentiers crédibles en appliquant les critères d'évaluation suivants: difficulté de l'apprentissage et efficience de la création de connaissances et de leur consolidation. Le rôle de la connaissance est en effet fondamental dans une industrie 'intense en apprentissage' telle l'industrie des lanceurs.

Résultats

Afin de répondre à la question principale de notre étude, nous avons tout d'abord analysé le marché et les technologies du transport spatial. Plus précisément, nous nous sommes attachés à répondre aux questions de recherche suivantes:

Quel sera le moteur d'un développement durable du marché du transport spatial?

Le tourisme spatial est l'un des marchés les plus susceptibles de se développer durablement, et de soutenir ainsi l'industrie du transport spatial à long terme. Ceci s'applique particulièrement à l'activité suborbitale, qui est beaucoup moins exigeante en termes de technologie et d'investissement et représente donc une issue crédible à l'impasse générée par l'investissement initial nécessaire à la création d'un nouveau marché *ex nihilo*. L'industrie suborbitale a en effet la possibilité d'améliorer graduellement la capacité des lanceurs, suivant l'évolution de la technologie et du marché.

Comment percevoir la dynamique de l'évolution technologique des STS?

Nous avons conceptualisé la technologie des STS en suivant une approche trilatérale permettant de percevoir les différentes composantes du changement technologique, à savoir les aspects fonctionnels, les aspects structurels et les propriétés du produit. Nous avons ainsi développé une représentation de la dynamique d'évolution des technologies spatiales dans un espace cartésien, où chacun des axes représente un facteur technologique clé, à savoir: performance, réutilisabilité et fiabilité.

Afin de répondre à la question principale de notre étude - comment arbitrer entre les sentiers d'évolution technologique? – nous avons développé la méthodologie "Exogeneous Factor Impact Free Evolutionary Hierarchical Tree" présentée ci-dessus.

A l'aide de cette méthodologie, et en introduisant les facteurs exogènes, nous avons développé les sentiers d'évolution crédibles. En ce qui concerne les critères d'évaluation des sentiers crédibles, la "règle d'or" de l'analyse coûts-bénéfices s'avère ici inadaptée puisqu'un sentier d'évolution technologique en soi ne peut faire l'objet d'une estimation en termes d'investissement mesurable. C'est pourquoi nous avons établi de nouveaux critères d'évaluation pour comparer les sentiers d'évolution crédibles.

Notre analyse montre qu'un sentier correspondant à l'approche "bottom up"est plus plausible qu'un sentier correspondant à l'approche "top down".

L'approche "bottom up" caractérise l'évolution de la technologie des RLV, qui passe par le développement d'un étage inférieur réutilisable, puis l'augmentation progressive des capacités de vol de cet étage jusqu'au développement d'un lanceur totalement réutilisable. Ce mode d'évolution présente un risque faible en termes d'incertitude technologique, puisqu'il est basé sur une option technologique originelle moins exigeante et que les possibilités de réutilisation du lanceur augmentent graduellement en fonction de l'évolution de la technologie des composants, ce qui facilite l'apprentissage ainsi qu'une obsolescence minimale des connaissances au cours du processus d'apprentissage. C'est donc aussi le sentier d'évolution le moins exigeant en termes de création de connaissances puisqu'il favorise l'apprentissage incrémental.

L'étude de cas, “analyse de l'efficience des sentiers d'évolution des RLV américains” a montré que:

Après des investissements considérables en recherche, au vu des coûts d'opération extrêmement élevés de la navette spatiale et au vu de l'échec du X-33, l'industrie américaine des lanceurs s'est rendu compte de l'inadéquation de ses programmes de développement de RLV. Les Américains se sont alors tournés vers une approche "bottoms up", un terme proche de “bottom up” mais recouvrant une signification différente. Le premier désigne une stratégie donnant la priorité au développement technologique des composants afin de réduire l'écart entre la frontière technologique des composants et la technologie nécessaire pour construire l'opion technologique sélectionnée pour le lanceur. Le second désigne une stratégie donnant la priorité au développement et à l'évolution de l'étage inférieur (booster) des RLV.

L'approche "top down" n'est pas un sentier optimal pour l'évolution des RLV, non seulement à cause de l'inefficience théorique en termes de création et de pérennisation des connaissances mais aussi parceque l'adaptation d'une technologie non stabilisée entraîne des coûts d'opération extrêmement lourds (comme dans le cas de la navette spatiale), réduisant d'autant les ressources nécessaires au développement de la nouvelle génération de lanceurs. Ceci diminue la qualité potentielle des futurs lanceurs et entraîne la perte d'une part importance des connaissances et des expériences accumulées par l'industrie en retardant le développement de la nouvelle génération. Cette approche représente par ailleurs un risque technologique élevé dû à l'écart important entre le niveau technologique requis et la frontière technologique, comme dans le cas du X-33.

L'efficience de l'approche "bottom up" ne peut encore être rigoureusement établie, les données empiriques actuellement disponibles étant trop limitées pour donner lieu à une évaluation pertinente. Une preuve pourrait être fournie par l'analyse des données accumulées sur la performance des activités suborbitales ou sur les programmes de développement de l'étage inférieur (booster) des RLV tels le programme ARES (Affordable Responsive Spacelift) du Ministère de la Défense américain.

Recommandation: une approche combinée bottoms-up/bottom-up: la conception suborbitale

L'approche 'bottom-up' de l'industrie américaine des lanceurs est une stratégie nécessaire mais non suffisante pour le développement des RLV. Elle peut être appliquée à toute option technologique dans n'importe quel sentier d'évolution. C'est pourquoi, couplée avec une option technologique située dans un sentier sous-optimal, elle peut engendrer l'apparition de problèmes tels que des innovations composants localisées ou une boucle de rétroaction incomplète lors du processus d'apprentissage, avec une augmentation du temps de développement due au large fossé technologique séparant la technologie composant existante et la technologie requise pour construire le lanceur.

Là où l'approche 'bottoms-up' est déficiente, l'approche 'bottom-up' peut la suppléer, en indiquant quel sentier d'évolution technologique suivre afin de parvenir à un développement soutenu de l'industrie des lanceurs et de la technologie produit. La meilleure stratégie pour les programmes de développement de RLV devrait donc être une approche combinée: l'approche 'bottom up' pour le sentier d'évolution technologique, et la stratégie 'bottoms-up' pour le développement des technologies composants.

Il peut y avoir deux principales voies pour l'approche 'bottom-up' – l'approche 'propulseur d'abord' et l'approche 'véhicule suborbital'. En termes de concurrence, l'approche 'véhicule suborbital' est préférable puisqu'il n'existe pas de concurrent en place sur le marché des lanceurs suborbitaux, alors qu'un lanceur 'propulseur d'abord' est en concurrence avec les lanceurs expansibles du marché traditionnel qui est déjà saturé. En plus de ces avantages de marché, l'approche 'véhicule suborbital' offre une issue à une situation actuellement verrouillée en ne nécessitant que des coûts de développement relativement faibles.

Il doit cependant être noté que la pertinence de l'approche 'bottom-up' n'est pas encore prouvée en raison du manque de données empiriques. Des preuves positives devraient être disponibles une fois que les données de performance auront été accumulées à partir des activités suborbitales ou des programmes de RLV orbitaux 'propulseur d'abord' tel le programme ARES du DoD américain.

Malgré la réalité de l'évolution technologique, nous devrons peut-être attendre des années, ou même des décennies avant de voir une activité suborbitale florissante. En effet, l'activité suborbitale est basée sur des initiatives privées visant le nouveau marché du voyage spatial public, régi par les lois strictes des pertes et des profits. Il est donc très difficile d'entrevoir quelle en sera la forme à une étape aussi avancée de l'évolution du marché.

Chapter 1

Introduction: *Seeking Foresight for Technology Evolutionary Paths*

> *It digs to check whether the ground underneath its body is soft soil; if not, it pushes forward its front body and retracts the remainder its body to move forward, then, digs again to examine the hardness of the ground. The motion is repeated again and again until the earthworm identifies soft soil.*

This is the wisdom the earthworm uses when it crosses a paved road. Earthworms do not have sight to figure out which direction to take to find the shortest way over the road. They therefore simply keep going in one direction until they get to the opposite side of the paved road.

When it comes to the evolution of technology, one should have better foresight than the earthworm in identifying the plausible path. We will now start our journey to find the foresight to discern the shortcut to cross the road. We are happy to invite you on this journey.

1.1 Challenges

“X-20: Dyna-soar in 1963, DC-X: Delta Clipper in 1991, X-33 and X-34 in 2001, X-38: Crew Return Vehicle in 2002 …”

This is the list of the Reusable Launch Vehicle (RLV) programs cancelled after a significant amount of investment. There are only three RLVs - the Space Shuttle, the Pegasus/L1011 launch system and the shuttle Buran. The Space Shuttle recorded its 100th flight in October 2000 since its first flight in April 1981. However, two of the five orbiters of the fleet disintegrated during flights and NASA suffered significant refurbishment cost for each flight. The former Soviet shuttle Buran combined its maiden launch with its retirement launch on 15 November 1988. Only the Pegasus/L1011 has been relatively successfully operated, enjoying 22 consecutive successive launches to date after its third failure on its 14th flight.

In general, the economic significance of an industry can be measured by the revenue it produces. However, if an industry has a role in triggering other industries, then the economic consequence of the industry is more than the absolute revenue it generates. According to the International Space Business Council (2005), the leverage power of the launch industry revenue is about a factor of twenty: the revenue of the launch industry was $4.65 billion (excluding Space Shuttle/Exploration) from a space industry total of $103.5 billion in 2004. The Augustine report (1990) expressed well the importance of the Space Transportation System (STS): “When things are going well in space transportation, the space program seems to flourish; when space transportation is troubled, the entire space program languishes and any other error seemingly is magnified.”

The economic consequence of an RLV program failure might therefore be much heavier than the programs cost, which in itself is no less than billions of dollars.

What is the reason for such a long list of casualties in RLV programs? When we see the epitaphs, we can see the reasons for the casualties, such as “strategy for mutually assured destruction,” “cessation of the Cold War,” “premature technology,” “increased cost,” and “no funds available”… However, we need to know more than that in order to minimize the possibility of final casualties in RLV programs and to further stimulate sustainable development of the launch industry as well as the space industry in general.

1.2 Reactions

This study aims to investigate the root cause of the undesirable consequences of RLV development programs and further to induce a fruitful dialogue in the launch industry during their decision making process for future RLV development programs. We presuppose the lock-in in the sub-optimal technology path to be the attributable root source of the problems, based on the following reasoning:

From the technology evolutionary point of view, the casualties can be attributed to the fact that either the programs are locked in the wrong direction in terms of the evolutionary path, or, the path is right but implementation is not appropriate. The latter explanation is not unlikely when we consider the triumph of the former Apollo program implemented by the US space industry.

How to achieve the aim?

Firstly, we will develop a methodology to ‘trade off technology evolutionary paths for Space Transportation Systems (STS)’ and to construe the main theme of this study.

We will then conduct an analysis of the efficiency of U.S. Reusable Launch Vehicle (RLV) evolutionary paths based on this tradeoff methodology and will use the findings to construe the main argument of this study.

1.3 Key Research Issues

To discuss the main theme of the study, ‘how to trade off the technology evolutionary paths,’ there are two fundamental issues to be dealt with. The first is forecasting technology to predict or construct the future technology evolutionary paths and the second is the criteria to evaluate the plausibility of the path.

Problems in forecasting technology

The intractability of technology forecasting comes from the technology evolution process itself, the complex links within and between the endogenous and exogenous factors and the innate uncertain nature of these factors. What makes the prediction more difficult is that those endogenous and exogenous factors are interwoven and evolving together, interacting with each other during the evolution process.

There are theories and methodologies for predicting technology paths, and each has its own form of wisdom to handle the complicated technology evolution process. S-curve, Natural Trajectory, Innovation Avenue and TRIZ[1] Technology Forecasting (TF) are among such theories and methodologies.

S-curve induces ‘a pattern of growth of performance of technology’ which follows a phenological model of the growth of yeast cells in a bottle. This pattern of growth is the result of the complicated co-evolution process, and hence has exogenous factor immunity. However, the resolution of the prediction is too rough to express product technology options for which this study is seeking methodology to trade off; it only shows the industry wide change in the performance of heterogeneous technology, such as the speed trend from pony express to missiles, or a performance change of homogeneous technology such as lumens per watt for incandescent lamps.

The Natural Trajectory methodology (Nelson and Winter, 1977) deals with complexity by introducing ‘powerful intra project heuristics’ which are supposed to have semi-immunity from exogenous factors. It could show a spatial direction of the technology change in the evolutionary space consisting of performance characteristics. However, it could not show the details of the technology options producing the performance.

Innovation Avenue (Sahal, 1985b) introduces the conception of ‘technology momentum’ which is supposed to have semi-immunity from the exogenous factors to overcome the complexity of the evolutionary process. However, it only deals with technology options which are selected, or to be selected, to construe the innovation avenue.

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[1] TRIZ is the Russian abbreviation for "Theory of Inventive Problem Solving."

TRIZ TF relies on the axiom “the evolution of a technical system is governed by objective laws,” and therefore by studying the patterns or lines of technological system evolution, TRIZ TF could predict detailed technology change. The prediction is supposed to have quasi immunity from the exogenous factors as the pattern or line of the technological system evolution is induced from the study of patents which are already influenced by exogenous factors. The TRIZ TF methodology can precisely predict technology options to emerge but the problem is that it shows only a single path, something like a technology road map, and so there is no possibility for making any tradeoff.

Problems in tradeoff of the paths

For the evaluation of a project, there are methodologies based on cost benefit analysis. However, for evaluation of the technology evolution path, the existing methodologies based on cost and benefit analysis are not useful since the technology path is not a physical one but a notional one for which any investment and return appraisal is not appropriate.

How to solve the problems

For the problem of technology forecasting, since we intend to trade off the technology evolutionary paths, we do not need to handle the complicated endogenous factors and exogenous factors together. We can separate these two types of factors during the process of studying the technology evolutionary paths by sequentially applying these two factors for the construction of the technology evolution path. First we can develop physically possible evolutionary paths which are purely endogenously directed, and then we can apply exogenous factors to screen out sustainable paths for further tradeoff to determine plausibility.

For the problem of trading off the paths, we need to find appropriate evaluation criteria. We therefore look into two aspects of the nature of launch vehicle technology - the intrinsic nature, complex system technology and the extrinsic nature, dual use technology. This enables us to induce a key characteristic of the launch industry, and of the technology, since the evaluation criteria can be elicited from studying the key characteristics of the object to be evaluated. The complex system technology, as in any knowledge intensive area, with the breadth as well as depth of knowledge needed to achieve higher performance and property of the product, makes knowledge creation the most important thing in the industry. The dual use characteristic of the technology limits the transfer of technology across national borders, resulting in a sub-optimal learning process worldwide, and inversely calling for an optimal learning process for the launch industry at the national level.

In this regard, we elicit that the key characteristic of the launch industry is the fact that it is a ‘learning industry’ where Knowledge Orient Policy (KOP) is essential for the sustainable development of the industry. Knowledge creation has therefore become the critical factor for the efficient evolution of the industry and the launch vehicle technology. Accordingly, we will induce new evaluation criteria - facility of learning and efficiency of knowledge creation and preservation - to evaluate the plausibility of the technology evolution paths.

1.4 Methodologies

‘Exogenous Factor Impact Free Evolutionary Hierarchical Tree (EFIFEHT)’ Methodology

In order to develop a physically feasible technology evolutionary path which is purely endogenous factor directed, we will introduce the EFIFEHT methodology. The core part of the proposed methodology is to develop exogenous factor impact free evolution paths by conceptually disintegrating the exogenous factors from the technology evolution mechanism to induce exogenous factor impact free technology evolutionary paths.

The exogenous factors are then applied separately to screen the sustainable technology paths from among all the exogenous impact free evolutionary paths, and the plausibility of the technology paths based on the evaluation criteria is analyzed. The scheme of the proposed methodology consists of two steps:

First step: Develop Catalogues of the Technology Options for the Vehicle

In this step, the elements of technology options are defined in a manner which is broad enough to describe the vehicle technology variations effectively with a limited number of elements but detailed enough to retain sufficient reference information to trade off the technology paths. Catalogues of physically feasible technology options for the launch vehicle are then developed by appropriately combining the elements of the technology using a morphological approach.

Second step: Construct Exogenous Factor Effect Free Evolutionary Paths

In this step, the governing rules for the evolution are defined in terms of both heredity ranking of the elements and complexity growth patterns of the product which are not susceptible to exogenous factor change. The heredity ranking determines the internal process of the product technology evolution by directing which element of the technology is flowing down to the next generation or is being phased out. The complexity growth pattern determines the external process of the product technology evolution by directing the number of stages of each generation of the product. The evolutionary hierarchical tree is constructed, referring to the exogenous factor impact free evolutionary paths, by applying the governing rules to the catalogued technology options for the vehicle.

1.5 Structure of the Thesis and Key Questions

The thesis comprises two parts. The first part is the theoretical part for the tradeoff of technology evolution paths consisting of seeking the background knowledge in both the space transportation market (Chapter 2) and STS technology (Chapter 3). It studies the main theme of the thesis, ‘the tradeoff of the evolutionary paths of STS technology’ (Chapter 4). Finally, in the second part of the thesis, a case study is conducted to discuss the main argument of the thesis, ‘what is the efficiency of the U. S. reusable launch vehicle technology evolutionary paths’ (Chapter 5).

Chapter 2: *What would be the Locomotives to Lead Sustainable Development?*

We put this question as the first query of the study since the market and technology interact and evolve together and there is no future for technology evolution without the supporting market and vice versa. To answer the question, we will first provide an overview of the historical trends in space activity, and the institutional factors and technology which influence the market, to elicit candidate space activities which might become a locomotive to lead the future space transportation market. We also will carry out both a quantitative and qualitative analysis of two candidate space activities: military space activity and public space travel.

Chapter 3: *How to Perceive the Change of Space Transportation System Technology.*

In studying a new phenomenon, scientists, using their wisdom, first try to find a means to measure the phenomenon in order to study it. In tackling technology change, we will use the same wisdom. We first articulate the root of the product technology, the process of formation and manifestation of the product technology, to find an appropriate means to perceive the change in the product technology. Based on the articulation and literature study for existing methodologies, we will induce a new methodology, the so-called 'trilateral approach,' to perceive the multifaceted nature of the technology change, including the functional aspect, structural aspect and property of the product. Further, we develop a framework to describe the technology change in the past, as well as in the future, based on the trilateral approach conception.

Chapter 4: *How to Predict the Paths and How to Evaluate their Plausibility.*

Since we are studying the plausible evolutionary path, we can avoid intractable forecasting. Instead we will construct technology evolutionary paths for tradeoff. For this, we remove the exogenous factors from the evolutionary process and introduce the 'Exogenous Factor Impact Free Technology Evolutionary Tree (EFIFEHT)' concepts representing evolutionary paths which are purely endogenous factor directed. We will then apply the exogenous factors - politics, market and environment constraints - to screen the sustainable technology evolutionary paths and the evaluation criteria - facility of learning and efficiency of knowledge creation and preservation - to select a plausible evolutionary path.

Chapter 5: *What is the Efficiency of the U.S. Reusable Launch Vehicle (RLV) Technology Evolutionary Paths?*

To verify the presupposition that US RLV technology is locked in a sub-optimal evolution path, we will investigate US RLV programs, construct their technology evolutionary path, and analyze the efficiency of this path. Further, we will review strategic issues in RLV technology evolution, such as dual pillar, bottoms-up approach, etc. to determine the recommended strategy for STS development for sustainable development of the launch industry and technology.

1.6 Before Starting

The meaning of Space Transportation System (STS) broadly covers a vehicle or a combination of vehicles that carry passengers and/or cargo between the earth's surface and an earth orbit, and any supporting systems for the operation of the vehicle. Typical supporting systems include passenger/cargo processing systems, launch assist systems, landing facility systems, vehicle recovery/maintenance/turn-around systems, vehicle assembly/integration systems, logistics support systems, and traffic and flight control systems (adapted from HRST Synergy Team, 1997).

This study focuses on the launch vehicle technology and the term 'Space Transportation System (STS)' can therefore be read as 'launch vehicle' unless it is specifically stated to have a wider, more general meaning.

Understanding background knowledge on the anatomy of the product itself is helpful for any discussion on conceptual technology and hence an overview of the anatomy of STS is given in Appendix B-1.

Chapter 2

Space Transportation Market**:** *What Would Be Locomotives to Lead Sustainable Development?*

> *At the beginning of the 21st century, in 2001, two noticeable events occurred in the space arena of two space powers. On 28 April 2001, Dennis Tito became the first public space traveller on the Russian Soyuz, 40 years after Yuri A. Gagarin's flight into space. At the same time, in fiscal year 2001, the US DoD budget for space overtook the NASA budget for the second time with the inauguration of the Bush administration.*

Will Tito's space travel wake up the dormant space transportation market? And will the current suborbital space activities triggered by X-prize open a new route to sustainable development of the space transportation market which has currently lost its dynamics following the Iridium shock? Or will the weaponization of space, pioneered by the super power, induce a race in military space activity around the world, in which case, would such military activity be helpful for sustainable development of the space transportation industry or would it be the precursor for doomsday in space activity?

We will analyze whether emerging space activities can become a locomotive for sustainable development of the launch industry.

2.1 Introduction

The sustainable development of the launch industry is dependent upon the growth potential for space activity. Sustainability of space activities is directly influenced by the soundness of the launch industry since there can be no space system in earth orbit without a launch vehicle and there is no use for launch vehicles without space systems. Thus, in order to see the sustainable development of the launch industry and the accrued technology evolution thereof, one should investigate space activity which can lead to sustainable development of the launch industry.

In this chapter, we will seek an answer to the question ‘what would be the locomotive to lead to sustainable development of the space transportation industry?’ using two steps, as shown below:

First, an overview will be given of space activity, as well as of institutional factors and technology which influence the evolution of the space transportation market, in order to investigate meaningful movements in the space sector which might have potential to induce sustainable space transportation activity.

Second, an evaluation of the candidate space activity, by means of quantitative and qualitative analysis, will determine whether it would become a locomotive to lead sustainable development of the launch industry.

For the quantitative analysis, no separate market study is sought. Instead, reference is made to a literature study since any credible market study on space transportation requires resources which are far beyond the available resources for a Ph.D. thesis, and, more importantly, some market studies have been already carried out by the industry and are available for this purpose.

For the qualitative analysis, in the assessment of military space activity, we will review the crowding out effect, in budgetary as well as physical terms, due to the military space activity. For the assessment of public space travel, this market will be compared with another private space activity, the Iridium program, to analyze their respective success factors, as well as their hindering factors, in market evolution.

2.2 Key Factors for Market Evolution

There are a number of factors which affect the space transportation market evolution. In this section, we will briefly review important influencing factors for the evolution of the space transportation market, including technology, regulation and policy.

2.2.1 Technology

A number of scholars and practitioners sought the interrelationship between technology and the market, debating the technology push and market pull. Among them, pioneers Bartlett (1941) and Bush (1945) are proponents of technology push while Schmookler (1966), Myers and Marquis (1969), and Langrish et al. (1972) share the opposite view.

In spite of a long history of debate, no agreement has yet been reached (Thirtle and Ruttan, 1987). There may be different explanations for different industries, and even the same industry can differ by segments of the industry or market.

The initial generation of launch vehicles, both in the United States and the Former Soviet Union, was developed based on ballistic missile technology. The United States' Atlas and Titan originated from two Intercontinental Ballistic Missiles (ICBM) of the same names. The Russian Soyuz is a derivative of the first Soviet ICBM and the SS-6 Sapwood (AST, 2001). In this regard, in the commercial arena, the technology push is evident. As argued in the Commercial Space Transportation Study (CSTS) conducted by six aerospace companies[2] and the National Aeronautics and Space Administration (NASA) Langley Research Center in 1994, the introduction of a space transportation system which reduces launch prices by one or two orders of magnitude would lead to the emergence of new space transportation market segments, such as space tourism, etc. It has become an industry wide belief that the efficient evolution of the technology to build a launch vehicle, possibly a reusable launch vehicle, which reduces the launch cost by a factor of two and increases the reliability of the vehicle by a factor of two or more, will induce a new market, i.e. the technology will push the market.

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[2] Boeing, General Dynamics, Lockheed, Martin Marietta, McDonnell Douglas and Rockwell.

Hobday M. (1998) differentiated between two categories of market intervention in technology changes: complex system and commodity products. He argued that in the case of Complex Products and Systems (CoPS), users will get directly involved in Research and Development (R&D) and product design leading to user push or demand driven innovations, as has occurred in passenger aircraft. The space transportation system is one of the most complex systems and the direction of the technology development has been guided by government missions in both the public scientific and military areas. The pattern of user guided technology, as Hobday argued, is therefore evident. Current private suborbital activity shows that there is another area of the Space Transportation System (STS) where the market drives technology evolution.

Weigel (2002) categorized three different types of preferences for cost and risk in space system development – minimum cost, minimum risk, and balanced cost and risk – so there are different preferences in the selection of launch services. Indeed these act to induce the technology evolution of the launch vehicle toward reduced launch cost and increased reliability.

It is evident that there is a bilateral relationship between the market demand and technology evolution. It is more correct to say that both the demand side and the supply side influence each other and which one is the primary driver differs depending on the market segment as well as the supply sector.

It can also be noted that a successful technology development is not a sufficient condition for the evolution of a new market but is only one of the required conditions. There are many visible as well as hidden barriers to overcome in order to realize this potential market, as was evidenced by the downturn of the Iridium program.

2.2.2 Regulations

“Further, the fact that the regulatory regime continues to change introduces uncertainty to a segment in which uncertainties in technologies are already a major problem. This uncertainty concerning the regulatory regime itself is a major barrier to investment and expansion of private space activity" (Hudgins, 2001).

Regulatory uncertainty could be one of the most prominent barriers for nascent space businesses such as public space travel. There are three categories of regulations which bind space activity.

The first category concerns regulations which flow down from or enforce an international treaty or convention on space activities such as The Outer Space Treaty - Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, the Liability Convention - Convention on International Liability for Damage Caused by Space Objects, the Registration Convention - Convention on Registration of Objects Launched into Outer Space, etc.

The second category concerns regulations which directly govern space activities, such as the US Bill Banning Advertising in Space, the Zero Gravity Zero Tax Act, the Commercial Space Act, etc.

The third category concerns general regulations which are applicable to space activities, such as those relating to the environment, handling hazardous material, export licenses, etc.

Among these regulations, the second category is of the most imminent concern to entrepreneurs in the space business because these regulations are directly binding on space activities and have an inherently uncertain nature. In 1993, a Georgia-based marketing company announced plans to launch square-mile sized billboards into Low Earth Orbit (LEO) for the purpose of providing commercial advertisements. This encountered strong public opposition because of the concerns of infringement of the public's right to see clear sky. Finally, the company withdrew their plan before the inauguration of a bill banning advertising in space.

The USA plans to introduce a regulatory regime to promote the development of the emerging commercial human space flight industry and to extend the liability indemnification regime to the commercial space transportation industry. The proposed bill, H.R. 3245, Commercial Space Act of 2003, concluded the debate between the Office of Certification and Regulation

(AVR) and the Associate Administrator for Commercial Space Transportation (AST) of the Federal Aviation Association (FAA) for the role of overseeing commercial space activity. The Act placed all commercial space flight authority, including the authority to regulate commercial human space flight, with the AST (Congress, 2004). The AVR believes that it should regulate suborbital launch vehicles carrying passengers because it has regulatory authority over passenger-carrying vehicles that traverse national airspace under the U.S. Code for Aviation Safety. The AST, however, asserts that it was authorized to regulate the U.S. commercial launch industry including suborbital launch vehicles, even those carry passengers, in accordance with the Commercial Space Launch Act (CSLA) (Hearing Charter, 2003a).

The emerging issues from the CSLA show the complicated institutional process involved in trying to balance the interests of space entrepreneurs who are willing to wave strict compliance with safety regulations to promote public space flights with the health and safety interests of both the public engaged in the space flight and third parties.

The evolution of the space transportation market, especially for public space flight, is very sensitive to safety regulations. Requirements which are too tight hinder or curb the evolution of the market and those which are too loose might result in fatal failure of the vehicle in the early stages of operation causing the emerging market to stagnate or grind to a halt.

Since, there is no performance record to refer to in stipulating safety requirements for public space travel, the regulatory requirements would change in response to the actual performance in vehicle reliability. The market would therefore inevitably be highly unstable until the industry could accumulate enough flight performance data and improvements to the vehicle reliability to introduce safety regulations comparable to current general aviation regulations. This uncertain situation in the regulatory regime might act as a major barrier to investment and the expansion of private space activities (Hudgins, 2001).

Environmental issues are not of serious concern in current launch activities. However, with increasing concern over ozone depletion and the greenhouse effect, if launch activities increase, then they might become a forefront issue (Ross and Zittel: 2000, WMO: 2002).

2.2.3 Policy

Since the space age began with the launch of the first artificial satellite Sputnik on 4 October 1957, because of the dual use nature of space transportation system technology, the development of a space launch capability by a nation is recognized not only as the development of a space transportation system, but also as the development of a dual use capability. Hence, success in the development of a space transportation system by a nation is always accompanied by a high level of political attention worldwide. This is the one of the underlying and most profound reasons why the potential space-faring nations try to develop their own space launch capability even though the space transportation market is already over crowded.

The current space transportation market is known to be one of the most notoriously politically distorted markets. Most launch vehicle programs benefit from missile technology funded by governments. Even the Ariane rocket, which was developed for the commercial market, was developed with government funding through the European Space Agency (ESA) and the French government (Pace, 2003: 64) and the participating countries are encouraged to use the launch vehicle for any government payloads. The member governments of ESA also agreed to pay a surcharge of as much as 15-20 % if they used Ariane (Smith, 2001). In 1985, a U.S. company filed an unfair trade practice complaint against Arianespace asserting that participating governments were unfairly subsidizing Ariane. However, the investigation into the case by the Office of the U.S. Trade Representative (USTR) only found that Europe was behaving no differently from the United States which itself was pricing a commercial service offered primarily on the government-owned Space Shuttle (Smith, 2001).

The US government policy on the space transportation market aims to protect the US launch industry by mandating that US Government payloads fly on U.S. launch vehicles. At the same time, inter-governmental intervention was sought to limit certain government support and unfair practices in the international market (Fact Sheet-White House, 1994a, b).

The US-China bilateral trade agreement[3] for launch services restricts the number of Chinese commercial launches to avoid a possible competitive advantage, given its non-market economy, against US companies. In addition to the bilateral agreement, there is an indirect method of controlling Chinese launch services. The US effectively controls Chinese

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[3] The first agreement was signed in 1989, amended in1997 and the agreement expired on 31 December 2001.

commercial launch activity by controlling export licenses for US built payloads or payload components intended for launch by a Chinese launcher (Smith, 2003).

The new space initiative of the Bush administration, “Vision for U.S. Space Exploration - human and robotic missions to Moon, Mars and Beyond (Vision for Space Exploration)” will impact space transportation technology development programs. In the long run, it might have a negative impact on the technology evolution of the space transportation system which is essential for the sustainable development of the space transportation market. Negative impacts have already appeared in some areas. The Vision for Space Exploration acts as a strong drain on R&D funding from other areas, including launch vehicle technology development. According to NASA’s initial FY 2004 operating plan, the Orbital Space Plane (OSP) is ruled out and the majority of Next Generation Launch Technology (NGLT) programs are terminated or reduced in scope.

There are no markets which are completely independent from political intervention. However, the problem not only comes from the intervention itself but also from the uncertainty of it. This is especially the case in an industry such as public space travel which is in its embryonic stages in terms of both market development and technology evolution, and where a sudden policy change might curb or stifle the industry that otherwise might have flourished.

2.3 Paradigms of Space Activity

Nearly half a century has elapsed since the first man-made object was launched into space in 1957. Today, space activity is no longer an exciting event to draw public attention. Rather, it has become a part of our daily life regardless of whether we are aware of it or not. The motivation for space activity has also changed with changes in the socio-political environment.

2.3.1 Old Paradigms - National Prestige and Security

Sputnik Shock and Then…

On 4 October 1957, the Soviet Union launched Sputnik, the first man-made object in space. The success of Sputnik had a great impact in the world, especially on super-power balance, known as ‘sputnik shock.’ Sputnik shock opened up space as a new ground for competition between political regimes, between capitalism represented by the USA, and communism led by the former Soviet Union. The Soviets hammered the western world once again when they launched Yuri A. Gagarin into Earth orbit on 12 April 1961.

The space race was more than a competition in scientific and engineering excellence. It was a war between the two space faring nations but without munitions. John F. Kennedy’s memorandum to Vice President Lyndon Johnson on April 21 1961, which gave birth to the Apollo program, emphasized the importance of the space race, comparing it to winning a war. The memorandum stated: “Do we have a chance of beating the Soviets by putting a laboratory in space or by a rocket to go to the moon and back with a man. Is there any other space program which promises drastic results in which we could win. …Are we working 24 hours a day on existing programs? If not, why not. If not, will you make recommendations to me as to how work can be speeded up.”

The first big wave of space activity came from this highly political motivation (Dupas, 1995). The space race reached its culmination when the US sent Neil Armstrong to the surface of the Moon on 20 July 1969 and safely returned him to the Earth. In this early stage of the space era, the main mission for space activity was human spaceflight and scientific exploration required to promote national prestige or to demonstrate the excellence of a political regime.

Military in Space

The second wave of space activity came from the military in areas such as navigation, communication, reconnaissance, positioning and space weapons (Dupas, 1995). In 1982, the amount of funding for the US Department of Defense (DoD) space activity, which overtook the budget of NASA and continued to increase steeply thereafter, might be attributable to the Reagan administration’s Strategic Defense Initiative (SDI) program. During the 1980s, the Soviet Union launched about a hundred satellites per year and most of them are known to have been reconnaissance satellites. The primary motivation for rushed development of Buran was the increased concern of the Soviet Union over the unidentified military mission of Space

Shuttle. With the dissolution of the Soviet Union and the ending of the Cold War, the military budget in the USA continuously decreased during the 1990s.

In the beginning of the 21st century, with the inauguration of the George W. Bush administration, the militarization of space has become more of a reality. In 2001, the DoD budget for space activity overtook the NASA budget again. In December of the same year, the U.S. withdrew from the Anti-Ballistic Missile (ABM) Treaty[4] which banned the establishment of a national anti-ballistic missile defence system. In 2004, the Bush administration announced an ambitious Vision for Space Exploration. Since the achievement of this vision requires a heavy launcher to launch a Crew Exploration Vehicle (CEV), it has the potential to contribute to the weaponization of space by providing a means of transportation capable of placing heavy offensive military platforms in Earth orbit.

Space weaponization by one country could trigger a race in space weaponization worldwide that might lead to an increase in space activity and consequently development in the space market. On the other hand, the increase in military tension in space could lead to a cooling down in private activity in space. The US airline industry experienced a serious downturn after the ‘September 11 attacks’ US airline traffic initially dropped by 45 % due to passenger fears and security hassles, and US airlines posted cumulative net losses of $ 23 billion from 2001 to 2003 (Belobaba, 2004).

In the beginning of the 21st century, the resurrection of the old paradigm in space activity, space militarization, cast a question mark over whether the militarization of space would lead to a burgeoning in space activity and thus to sustainable development, or whether it would be the precursor to doomsday for space activity.

2.3.2 New Paradigms - Commercial Objectives

Commercial activity in space originated in the introduction of the first commercial communication satellite, Telstar I, which was launched on 10 July 1962, just 5 years after the launch of Sputnik. Since then, the communication satellite business has had to be a

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[4] The Anti-Ballistic Missile Treaty of 1972 forbade the parties both the United States and the Soviet Union from working on a continent-wide missile defense program.

successful self-sustaining business. Traditional communication satellites are usually launched into Geo Stationary Orbit (GSO).[5]

By the end of the Cold War, the space arena required a new paradigm for sustainable development. In 1999, Lord Sainsbury (1999) explicitly criticized the old paradigm and implicitly supported the new paradigm, commercial objective, when he provided answers to the House of Lords on the question of United Kingdom (UK) space policy: "In my experience, when national interest or national prestige is invoked as a concept, it is almost always a way of saying that it neither meets commercial objectives nor is it good science but we would like to do it anyway. I do not think that that is necessarily a good concept."

A Big Wave or a Bubble?

There was high expectation that a drastic increase in commercial space activity would come from the conception of using Low Earth Orbit (LEO) in the late 1990s. It was not only the space industry but also Wall Street who was fascinated by this new business opportunity. Iridium, a single commercial space project, succeeded in raising funds of over a billion US dollars from Wall Street. Theoretically, three GSO satellites can provide communication services for most of the Earth. However, attenuated signals coming from the more distant GSO satellites require bigger receiving antennas, as we can see from the big dishes in ground stations and the dish-type direct TV antennas. The new conception of using a LEO satellite constellation has the benefit of having a shorter distance between the Earth's surface and the satellite and makes mobile phone service feasible all over the world without any noticeable voice delay. Iridium proposed a constellation of 66 satellites in LEO at about 780 km altitude. Because the LEO communication satellite conception requires a number of satellites to build a serviceable constellation, the satellite industry as well as the launch industry could directly benefit from the new business. There were high expectations for a large emerging market in LEO satellite services, including a big LEO satellite service providing mobile voice telephony and data services in the 1-2 GHz frequency, and little LEO telecommunication systems using narrow bandwidth in the below 1 GHz frequency range, providing e-mail, two-way paging and simple messaging services.

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[5] An orbit of a satellite whose period of rotation is the same as the Earth and the trajectory is aligned with the Earth's equator. Hence a satellite rotating in this orbit appears as fixed in the sky when it is observed from a point on the Earth.

There is another activity in LEO: remote sensing using satellites in sun-synchronous orbit[6]. In the remote sensing sector, France was the first country to initiate commercialization of remote sensing data by nominating Spot Image as a commercial operator of the Satellite Pour l'Observation de la Terre (SPOT), the first of which was launched on 22 February 1986. Since then, the resolution of the images taken via commercial remote sensing satellite systems has increased. IKONOS and QuickBird offered sub-meter spatial resolution image form in 1999 and 2002 respectively.

Orbit (Service)	System	Number of Satellite (In orbit/ Operational)	First Launched	Status (As of 2005)
LEO (Voice)	Iridium	95/79*	1997	-In service Nov. 1998 -Filed for Chapter 11 in Aug. 1999. -Assets acquired by Iridium Satellite LLC in Dec. 2001. -Operational now
LEO (Voice)	Globalstar	52/40*	1998	-Filed for Chapter 11 in Feb. 2002. -Thermo Capital Partners acquired a majority interest in the company in Dec. 2003. -Operational now
LEO (Data)	ORBCOMM	35/30*	1997	-Filed for Chapter 11 in Sep. 2000. -Emerged from bankruptcy protection in Mar. 2002. -Operational now
MEO (Voice)	ICO	12/10*	2000	-Filed for Chapter 11 in Aug. 1999. -Emerged from bankruptcy after $1.2Bil investment by Eagle River Investment in May 2000. -Under development
LEO (Data)	AprizeStar	2/2*	2002	-Original plan was 48 satellites. -Under development
LEO (Data)	Teledesic	300/288	-	-Original plan was 840 active satellites in 1994. -Changed plan to 288 active satellites. -Teledesic gave up its frequency licence in July, 2003.

** denotes number of satellites licensed (Data from FAA and COMSTAC, 2004)*

Table 2-1 Low Earth Orbit (LEO)/Medium Earth Orbit (MEO) Communication Satellite Systems

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[6] Sun-synchronous orbit is that which has a rate of rotation of exactly 360 degrees per year. Hence satellites rotating in these orbits can view the ground at a constant Sun angle. Typical sun-syncronous orbits for remote sencing satellites have an inclination slightly higher than polar orbit - 90 degrees- and an altitude similar to LEO satellites.

The introduction of the International Space Station (ISS) and the new commercial business opportunity using the LEO satellite constellations gave rise to a strong belief that a third wave exponential expansion of space activity was possible. However, the market environment was not receptive to this nascent space activity using LEO satellite constellations. Only 9 months had elapsed from the date of its service start-up when Iridium defaulted on its debt. The bankruptcy of the front runner in the big LEO satellite industry cast a shadow over this embryonic industry resulting in a long list of Chapter 11 filings, as shown in Table 2-1.

While remote sensing satellites are very successful in terms of technological advancement, they still need time to prove their self-sustainability. There is no evidence of a dramatic growth in the LEO communication and remote sensing business, so it is very questionable whether this industry will need blue ink in the near future.

Public Space Travel

Following the sharp decline of the LEO satellite business activity in the late 20th century, a new emerging commercial market sector for the space industry, in particular the launch industry, arose at the beginning of the 21st century.

On 28 April 2001, Dennis Tito became the first public space traveller to personally pay for travel into space when he was launched to the ISS for a one-week visit via the Russian Soyuz launch vehicle. In April 2002, Mark Shuttleworth became the second space tourist. Dennis Tito is known to have paid about 20 million dollars for his journey (Tito, 2003).

On 21 June 2004, the first private manned suborbital space flight was concluded by Brian Binnie using SpaceShipOne. SpaceShipOne was air launched from a specially designed aircraft - White Knight - and reached an altitude of about 100 km. This occurred 42 years after Bob White earned his astronaut wings when he flew to an 80.5 km altitude with the US government's X-15 spaceplane on 17 July 1962. The X Prize[7] has continuously stimulated suborbital flight activity since Peter H. Diamandis founded it on 18 May 1996. In addition to

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[7] The $10 million cash prize was offered to the first team that privately finances, builds & launches a spaceship able to carry three people to 100 kilometers (62.5 miles) altitude and returns safely to Earth and repeats the launch with the same ship within 2 weeks.

SpaceShipOne, more than two dozen vehicle conceptions have been proposed to compete for the prize.

It has taken 40 years from the first human in space to see the first commercial passenger. Considering the price tag for a seat and the safety factor of the existing vehicles, there might be commercial passengers but the number will be quite limited if the scope of the business is restricted to orbital destinations and a short-term business time frame. However, if we expand the scope of the business to suborbital space flight[8] activity and increase the time frame over a longer period sufficient to introduce new space transportation systems to pursue orbital space flight, then there might be another vision for the future of space transportation market evolution.

From a monetary point of view, these two private initiatives accompanied by tens of millions of dollars are not comparable to those which occurred in the government sector costing tens of billions of dollars in military budget. However, in terms of the evolutionary potential for the space transportation market, public space travel also raised a similar meaningful question as that raised by the military space activity.

In the beginning of the 21st century, private space activity, in the form of public space travel, raised the question of whether space tourism will grow and lead to sustainable development of the space transportation market or whether it is just a niche market for the millionaires.

2.4 What will be the Locomotive?

In the previous section, we reviewed the background knowledge of the space transportation market, the technology and the institutional aspects of both regulation and policy. We also identified two noticeable movements, the increasing military space activity and public space travel, which might lead to the sustainable development of the space transportation market.

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[8] A mission flight where the maximum height of the intended flight path is beyond the atmospheric boundary but the maximum velocity of vehicle only enables a suborbital trajectory - the intentional flight path of a launch vehicle, reentry vehicle, or any portion thereof, whose vacuum instantaneous impact point does not leave the surface of the Earth. Adapted from, 49 U.S.G. §70102 (20).

In this section, we will investigate whether these movements could become a locomotive leading to sustainable development of the space transportation market through both quantitative and qualitative analysis.

2.4.1 Quantitative Review: Industry Perspective

In 1994, a Commercial Space Transportation Study (CSTS) analyzed 38 market segments and predicted the existence of potentially drastic increments in the space transportation market through the emergence of non-traditional space transportation markets, including public space travel. In 2003, the Analysis of Space Concepts Enabled by New Transportation (ASCENT) study analyzed 42 market segments in both traditional and non-traditional markets. The former market was divided into 11 market segments. The latter was comprised of 31 segments consisting of 15 evolving market segments (potential commercial space markets that have just begun, or that have a possibility of coming into existence before 2021) and 16 emerging markets segments (potential commercial space markets whose initial start date is not expected before 2021).

The CSTS is one of the most profound space transportation market studies in terms of the number of participants and the scope of the markets it surveyed. It covers almost all the envisaged market segments of the space industry to-date for both existing traditional and potential non-traditional markets. In spite of some deficiencies in the study, including a lack of consistency in the format and rules among the market segments (Dunn, 1995) and too much reliance on subjective judgements and assumptions in determining key input data, including the volume of the market and the elasticity of the market, the study is widely referred to in the space industry and was intended to provide a good starting point for any subsequent in-depth market study such as the ASCENT study.

The ASCENT study took place about a decade after the CSTS. It is considered a supplementary study to the CSTS and hence some improvements were made in the study methodology. Among them, the ASCENT study tried to improve the homogeneity of the results of market predictions by introducing common factors in the process of the prediction methodology, such as calculation of the gearing factor[9] and application of the s-curve theory for market saturation, etc. This resulted in a more conservative prediction than the CSTS prediction. Because the two market studies use different definitions and assumptions, an apple-to-apple comparison is not feasible and such a comparison only shows an approximation for each market. For a detailed description of each market segment reference should be made to the individual market study.

Table 2-2 shows the scope of both studies. Commercial space transportation means the launch vehicle is developed, produced, owned and operated by a commercial venture but it does not exclude the commercial launch of government payloads.

Title (Year)	Scope of Study	Studied By
CSTS (1994)	Review future commercial space transportation market by examining broad range of both existing and potential market segment elasticity	Six aerospace companies and NASA Langley Research Center
ASCENT Study (2003)	Reassessment of the finding of CSTS and Study for hypothetical Reusable Launch Vehicle (RLV) market shares.	Futron

Table 2-2 Scope of Industry Market Study

To review the industry market studies, we categorize market size as follows:
- Big: the expected market is for multi-millions of lbs payload per year with a reduced launch price of $400 or $600/lb to LEO.
- Dark horse: the expected market is for multi-millions of lbs payload per year at a reduced launch price of $100/lb to LEO.
- Medium: the expected market is for hundreds of thousands of lbs per year or more than 10 launches per year at a reduced launch price of $400 to $600/lb to LEO.
- Small: the market may exist within the price range of $400 to $600/lb to LEO but for less than hundreds of thousands of lbs per year or less than 10 launches per year

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[9] Means a ratio of the launch price against total end user cost for the service provided for user. In television broadcasting, only 0.7% of the end user price paid for TV programs is traceable to launch cost. In this regard, launch price change does not effect this market (ASCENT Study, 2003).

2.4.1.1 Overview of Market Study

The market study divides the space transportation market into traditional existing markets and non-traditional potential markets. If one defines non-traditional markets as any market that is envisaged but not realized at the present time as the two studies defined, then the categories of traditional and non-traditional markets can vary depending on when the market investigation is conducted since the space transportation market evolves. The categories of traditional or non-traditional space transportation markets in this study do not therefore necessarily need to comply with that of the market study performed over a decade ago or the study performed one decade later. For this study, the public space travel market is categorized as a non-traditional market because it is in a very premature stage in its market evolution. The definitions of the market segments are included in Appendix A-1.

Both studies predicted that there would be no big or dark horse markets in the traditional markets. The big or dark horse markets in non-traditional markets are predicted as shown in Table 2-3.

Market Segments	CSTS Study	ASCENT Study
Public Space Travel	Dark horse	Small
Human Space Exploration (Non-ISS)	Big	Small
Hazardous Waste Disposal	Big	No market by 2021
Space LEO Business Park	Dark horse	Small

Table 2-3 Forecasted Market Size of Non Traditional Space Transportation Market Segments

Only the CSTS study expected a big market potential for both Human Space Exploration (non ISS) and Hazardous Waste Disposal, and for two dark horse markets, public space travel and the Space LEO business park.

For human planetary exploration, the CSTS predicted three scenarios: Lunar out post 6 launches/year equivalent to 1,650,000lb/year; Lunar base 8 launches/year equivalent to 2,200,000/year; and Lunar base and Mars exploration, 12 launches/year equivalent to

3,390,000lb/year. Hazardous Waste Disposal is disposing nuclear waste into space, such as into Earth orbit, solar orbit, or a lunar repository, etc. The hazardous waste disposal market could be 2 million pounds per year over 30 years if the launch price to LEO was as high as $500 to $600/lb. The CSTS stated that terrestrial disposal of nuclear waste is only a semi-permanent depository and therefore a permanent solution might be more sellable to Congress.

The CSTS predictions for the human planetary exploration and hazardous waste disposal markets are not very realistic for the following reasons:

For human planetary exploration, there is too large a gap between the CSTS prediction and the current Vision for Space Exploration. The former predicts 6 launches per year while, under the latter, only a very restrictive number of launches are expected.

For the hazardous waste proposal, the idea has a fatal deficiency since there is always a risk of launch failure resulting in an unacceptable catastrophic situation - the impact to the Earth of the hazardous waste. It is therefore hard to expect that this methodology could get public support unless and until the technology matures enough to build a highly reliable vehicle to ease public concern. However, this advancement is not likely to be achieved in the foreseeable future.

For the LEO Business Park, the market includes the facilities and utilities service for research, production and space tourism. There might be some market for research and production but it is very hard to predict in any precise manner.

2.4.1.2 Military Space Market

The military space market can be regarded as encompassing communications, early warning, global positioning, weather forecasting, intelligence-gathering, weapon systems and testing. Because of the sensitivity and the classified nature of military space activity, difficulty exists in obtaining credible data for this market.

Commercial Space Transportation Study

For the DoD mission, primarily due to the sensitive and often classified nature of the program, there is a lack of information available and thus the CSTS prediction is based on the experience with DoD missions in the past together with current information gathered from public sources.

In the CSTS, except for GPS, no separate market is predicted for the military. The DoD mission program is included, together with the NASA program, the existing government mission market segment. The Strategic Defense Institute Organization (SDIO) test mission is included as part of a space test bed market segment. For the DoD mission in the government mission segment, it was assumed that the DoD would maintain a steady sizeable space presence, and would be based on an updated version of the National Launch Service (NLS) mission model of 240,000lb/20years or 176,000lb/10years. The DoD mission encompasses six main objectives: communications, early warning, global positioning, weather forecasting, intelligence-gathering and testing. The space test bed market, the SDIO mission, and SDI programs validating components and sensors for suborbital sounding rockets, will account for about 1,000 lb/year.

Analysis of Space Concepts Enabled by New Transportation (ASCENT) Study

As shown in Table 2-4, in the ASCENT study, military activity is more precisely studied. However, it also could not provide a complete prediction because of the limited information available in certain areas such as weaponization. The worldwide military communication satellite market is predicted together with the civil communication satellite market. For military remote sensing, a worldwide military satellite system dedicated to intelligence gathering and early warning is forecast. For GPS, the prediction includes U.S. and Russian programs. Europe’s Galileo program and China’s Beidou constellation as well as the Indian Satellite-Based Augmentation Systems (SBAS) are also included in the prediction. For Weapons Systems, a micro-satellite laser system is expected but further classified information is not provided.

Market Segments	CSTS Study	ASCENT Study
Military and Civil Communication	Note	Small
Remote Sensing: Military	Note	Small
Positioning	Small	Small
Space Testbed	Small	Not Studied
Weapon Systems	None	Small
Existing Government Mission	Small	Included in other segments

Note: the military prediction is consolidated in the existing government mission segment.

Table 2-4 Forecasted Market Size of Military Space Segments

Reviews

The main difference in the military space market predictions between the CSTS and the ASCENT Study is that the former only included the US market while the latter included the worldwide market. Neither study expects huge markets for military activity but they do expect the continuous presence of a significant market in this area. For space weaponization, CSTS does not include any weapons in space while ASCENT predicts the existence of such weapons. This is not so odd since, in 1994, when the CSTS study was carried out, the military space budget was at the peak of its downturn with the phasing out of the Cold War and the inauguration of the Clinton administration. However, in 2003, when the ASCENT study was carried out, there was evidence of signs toward the weaponization of space with the inauguration of the Bush administration.

2.4.1.3 Public Space Travel: Space Tourism

For the review of the public space travel market, we will first give an overview of the methodologies for the market studies since the two market studies use different methodologies and therefore a simple comparison of the size of the markets might be misleading.

Methodology of the Study

Before comparing these two market studies, it should be understood that there is a time difference between the two market studies. In 1994, when the CSTS was carried out, public space travel did not exist, while in 2003, when the ASCENT study was performed, the launch industry had already witnessed two public space flights, that of Dennis Tito in 2001 and of Mark Shuttleworth in 2002. This might have made it more feasible for the ASCENT study to do a practical market study than for the CSTS study.

The CSTS made reference to insights of specialists in neighbouring areas because there was no existing business for this market segment and so no experienced specialists were available in this area. For the study, contacts were made with the tourism industry, including adventure tourism companies, cruise lines, etc., in order to get their insights into the feasibility of space tourism and to get positive input based on analogy:

- The adventurous nature of tourism makes it the largest industry in the world and amounts to between 5 and 6% of the world's Gross Domestic Product (GDP).
- Individual seats on round-the-world cruise ships run to $300,000 per month and are booked solid.
- A permit to climb mountain Everest now costs $50,000 and there is a long waiting list.
- A place on an icebreaker costs $19,000 per person for trips into the Arctic Circle, and they are completely sold out.

For the CSTS study, interviews were conducted with airline personnel in order to measure their interest in investing and operating a LEO passenger travel service and to get their insights on vehicle safety, publicity, size of market, destination activity, etc. Airlines expect that there would be a demand for suborbital and orbital flights for no destination, but the larger, more robust market would be orbital flights with a destination.

For the quantitative forecast of the market, the CSTS relied upon rule of thumb and rationale. CSTS assumed that only households with an annual income equal to the ticket price or greater were financially able to afford the trip. If the annual income is less than three times the ticket price, the affordability factor is the square of the ratio of the annual income divided by three times the ticket price, etc.

The ASCENT study is based on interviews and questionnaires with millionaires, including questions on income, willingness to pay for space travel, age/ health condition, etc. The ASCENT study introduced some rationale to improve the credibility of the market forecast such as:

- Only those whose net worth is greater than 200 million can afford a $20 million ticket price (based on the Tito and Shuttleworth cases).
- Screening for physical fitness to travel.
- Market build-up in accordance with the S-curve theory with a 60 year evolution for market saturation, and
- Introduction of the concept of the gearing factor.

Market Predictions

The CSTS expected that the service factor for a viable market for public space travel would be the same as that of a commercial airliner providing regular service with a high level of safety. For the study of the space theme park, terrestrial theme parks and resort hotel were analyzed. The CSTS analyzed an annual transportation demand for 150 thousand pounds at a launch price of $600/lb to LEO and 8.3 million pounds at a launch price of $100/lb with high service factors, including routine scheduled services and airline-like passenger handling and safety. Orbital flights with a destination will be required for sustainable development. The ASCENT study is much more conservative in predicting the market than the CSTS. The ASCENT predicted a limited size of market. The forecasted market in 2021 is only 9 launches per year.

For suborbital activity, CSTS predicted it but recognized it as a temporal joy ride market. The ASCENT study did not include suborbital activity in the market study.

Reviews

Orbital Public Space Travel

The CSTS expected a huge market for space tourism but only based on some extreme assumptions, such as a launch price of $100/lb to orbit and airline-like safety levels. It is hard to expect that any one of these assumptions will be achieved in the foreseeable future.

The ASCENT study only forecast a very limited market for public space travel. By applying the gearing factor it could eliminate the erroneous simplification of the launch price impact over the end user service price in general. However, since the gearing factor is fixed based on the existing launch vehicles, it could not capture the impact of technology advancement on the gearing factor. For example, for public space travel, the baseline technology is the Soyuz, and hence the gearing factor is fixed at 34 %. This means the lowest possible ticket price is 13.2 million dollars even in the case of zero launch cost. The lowest cost includes a capsule price of about 10.4 million dollars, and a training and service fee of about 2.8 million dollars. However, once the space transportation technology evolves to build a Reusable Launch Vehicle (RLV) which does not need an expendable capsule, then the gearing factor could be drastically increased so that the launch market becomes more sensitive to changes in the launch price. By applying the S-curve theory to the market build up, a more precise prediction could be made. However, a 20-year market prediction against a 60-year market saturation period, coupled with a conservative assumption in regard to the gearing factor, prevents proper evaluation of the sustainable growth power of this market.

Suborbital Public Space Travel

The ASCENT study did not include the suborbital market in their prediction, but this does not mean that it denied the existence of the suborbital market. It did not include the suborbital public space travel market since this was not within the scope of the market they studied - the orbital launch vehicle market. The Futron (2002) study on space tourism, on which the ASCENT study on orbital public space travel is based, predicted that the suborbital public space flight market would be more prosperous than the orbital public space travel market. The former will evolve to 15,000 passenger flights per year by 2021, representing revenues in excess of US$ 700 million, while the orbital passenger market will accommodate only 60 passengers per year by 2021, equivalent to revenues of about US$ 300 million (Futron, 2002).

The CSTS included Suborbital Public Space Travel but considered it as a dead-end joy ride market lacking the potential for sustainable development.

2.4.2 Qualitative Review

We have reviewed the quantitative market study of the launch industry. However, we could not find decisive clues as to which future potential market would lead to sustainable development of the space transportation market.

We further analyze two movements - military space activity and public space travel - in a qualitative manner and considered whether they might lead to sustainable development of the space transportation market.

2.4.2.1 Military Activity in Space

An increase in military space activity influences the space transportation market in various ways. There are two directions from which to influence the space transportation market: the demand side and the supply side. For the demand side, the increment in space activity would directly increase the up and/or down mass to and from the orbit, leading to an increment in the space transportation market. However, there might be a crowding out effect which weakens these positive effects on the market. In addition to the traditional crowding out phenomenon in governmental R&D activity, the peculiarity of the space environment induces physical crowding out of the payload in space caused by a limited radio frequency spectrum or an increase in detrimental space debris in the case of military conflicts in space. For the supply side effects, since space transportation system technology is a typical dual use technology, there might be a positive technology spillover effect to the commercial sector.

Trends in Military Space Activity

Space activity is known to be a leading-edge technological sector. However, surprisingly, very little economic data on the space industry are publicly known. There are still no unified definitions of the industry categories established for the space sector and even the poorly identified categories only emerged after 1992 when a systematic data survey was carried out on worldwide space activity by the American Institute for Aeronautics and Astronautics (AIAA) (Hertzfeld, 2002). When it comes to military space activity, things are far worse. Very limited economic data have been made available for most of the space faring nations.

And even to date, there are still limitations in obtaining credible worldwide figures for military budgets in space because of the classified nature of military space programs which are not open to the public.

The lack of standardized reliable economic data for the space industry prevents precise economic measurement for such things as volume or growth of worldwide space activity. We therefore rely upon proxy data which can show the trends of the quantitative change in space activity for our study. There are two categories of proxy data which can show the pace of activity: the number of launches and the governmental budget for space activity. For the former, there are well archived worldwide data by country, but it is not always possible to distinguish whether the mission of the launch and payload thereof is for military purposes or not. For the latter, in some countries, there are well archived government budgets by agency[10] which are open to the public, but that is not the case for all countries.

Here, we studied U.S. NASA and DoD budgets to capture the trends in civilian versus military space activities worldwide. This might not be sufficient to capture the precise change but it might be enough to capture the trend of the change on a worldwide level. After the dissolution of one of the two super powers in space activity, the former Soviet Union, the US became the only one to invest a significant amount of Government budget into military space activity. It constitutes 95 % of the total world expenditure for military space in the beginning of the 21st century. Comparison of civilian budgets is not as disproportionate as the military budgets but the US share is nonetheless also significant, equivalent to 62 %, including 57 % for NASA alone, of the total worldwide expenditure (Bochinger, 2004).

Fig. 2-1 shows the figures for DoD and NASA budgets since 1958. The dash-dot line represents the DoD space budget, the dotted line represents the NASA budget, and the bold line shows the sum of both.

There are three crossing points: the DoD budget crosses upward in 1982 and 2001, and crosses downward in 1993. The total budget fluctuation shows a cyclic trend over 20-year periods. The first two periodic changes are evident. However, the third period seems to be in

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[10] The National Aeronautics and Space Act of 1958 directed the Aeronautics and Space Report to include a 'Comprehensive description of the programmed activities and accomplishments of all agencies of the United States in the field of aeronautics and space activities during the proceeding calendar year.' Since then, the governmental budget for the activities by agency is presented (Hertzfeld, 2002).

the early stages of rising. In predicting space activity for the period of 2000 to 2020 and beyond, we can assume that future space activity will follow the cyclic pattern of the past four decades. However, we need to look into the quality factors of the cyclic change in order to gain more insight into the trends for future change.

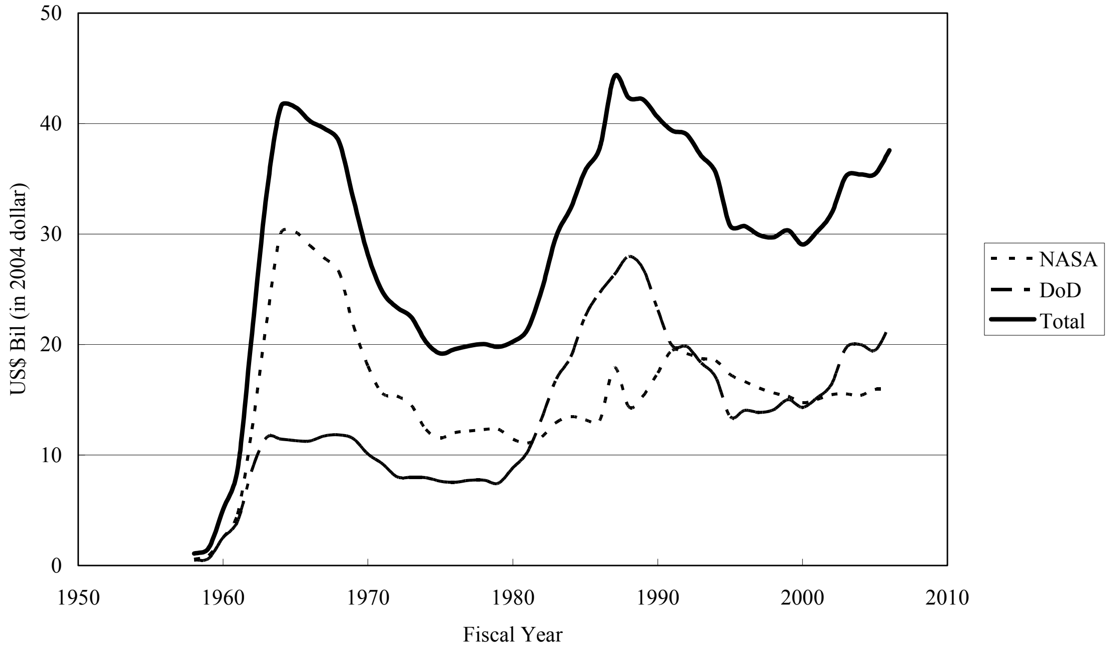

Fig. 2-1 US NASA and DoD Budget Trend in 2004 Dollars (Data Retrieved from Smith, 2005)

As shown in the Fig. 2-1, during the 1960s, the NASA budget increased drastically as a result of the space race between the United States and the former Soviet Union but the space budget of the DoD remained steady. Similarly, during the 1980s, the US DoD space budget steeply crept up to support the Reagan Administration's SDI. In the early part of the 21st century, the DoD budget rose again with the implementation of the missile defense program by the Bush administration. The re-election of the Bush administration in 2005 and the continuation in DoD office of Rumsfeld, a strong missile defence proponent, suggests that there will be a continuous rise in military space activity for the first decade of the 21st century. In regard to weaponization, there is increasing international tension between a super power that is willing to take advantage of their superiority in this area and the rest of the world who might be wary of a disturbance in the balance of military power due to weapons in space. The Bush administration seems ready to cross the Rubicon, or may in fact already have crossed over. The US withdrew from the ABM Treaty in December 2001, effective as of July 2002. US President Bush directed the Secretary of Defense to proceed with fielding "a set of initial missile defense capabilities beginning in 2004, including ground-based interceptors, sea-based interceptors, additional Patriot (PAC-3) units, and sensors based on land, at sea, and in space." (Ibrügger, 2004)

Fig. 2-1 shows that there is an upper boundary in the total space budget which is slightly higher than 40 billion in 2004 dollars. This means the real cycle of the space budget is decreasing in oscillation patterns since a budget generally expands over time as the volume of the economy of a state expands. The constant is therefore actually decreasing in relative proportion to the total budget as well as to the volume of the economy. If the third period occurs, then the volume of activity might either follow this decreasing oscillation pattern, i.e. within the upper boundary, or it would lead to a big market enabling sustainable development in space activity, or it may end up somewhere between these two.

Crowding Out Effect

With regard to budget crowding out between civil and military space R&D activity, as shown in Fig. 2-1, the history of past U.S. space activity budgets shows that there is no crowding out between civil space R&D activity, represented by the NASA budget, and military space R&D activity, represented by the DoD space budget. However, the peculiarity of the space environment might induce other types of crowding out.

R&D Activity Crowding Out

With regard to R&D activity crowding out between military (government) and commercially financed R&D, since about half of the monetary value of federal R&D carried out by private firms is on a contract basis, the rapid increase in federal R&D outlay will presumably result in a similar increase in the value of commitment by firms to perform government R&D (Lichtenberg, 1984). There is some debate over whether there is crowding out between the government financed R&D activity and commercially financed R&D activities. Those who argue that there is crowding out explain that the military and commercial R&D share human resources of similar competence, and increasing R&D activity in the military domain drains human resources in specific areas since there is a lack of elasticity in supply of highly trained scientist and engineers. Therefore in the short run, wages increase and the rising cost of R&D

activities, both in the military and the commercial domain, finally results in a reduction in R&D activity in the commercial domain since there is negative price elasticity in the demand for R&D in the private field (Cowan and Foray, 1995). Others who criticize the argument consider that there are mechanisms for supplementing supply in the short run, including greater use and immigration of trained personnel (Cowan and Foray, 1995). As Hartley and Singleton (1990) demonstrated, it might be possible to elicit contradictory pictures of positive, negative or insignificant effects of the defence R&D on investment using the same data set (qtd. Cowan and Foray, 1995). Further study still needs to be conducted on the crowding out issue in general. However, if we narrow in on a specific industry, then the case is more straightforward.

Crowding out of R&D Activity in Launch Industry

In general, crowding out might be feasible when there are two R&D pipelines - governmental (military) budget and commercial funding. In space transportation system technology development, most of the existing space transportation systems are developed through government funding and it is only in recent years that privately initiated programs have emerged, such as the Pegasus/L1011 launch system which is based on the technology of the government funded Taurus. There have been some initiatives using both governmental and private funding in the development of a launch system, the X-33 and X-34 programs, but both programs failed to develop operable launch vehicles. Crowding out in R&D activity between the government budget and private commercial funding is therefore not common in the launch industry for the time being.

Physical Crowding Out

The portion of the frequency spectrum from 1755 to 1850 MHz is denied to U.S. commercial users because it is the spectrum band of choice for military (and other government) communications, as well as precision targeting. It is likely that the DoD will be wary of freeing up the disputed spectrum bands due to increasing information demands for the war on terrorism and increased homeland security efforts (Hitchens, 2002a). Since the spectrum is a limited resource, the crowding out between military space activity and commercial space activity is inevitable if space activity increases.

Space debris can crowd out space systems in orbit either by directly damaging the system by collision[11] or by increasing the development cost of the space system to shield it from debris collision. A space debris report issued by the UN in 1999 revealed that in a nominal case, a business as usual scenario, there is no significant threat from space debris for the coming century. However, the militarization of space, with space as the place of battle, would increase the space debris produced from military operations against adversary space targets. This might crowd out any system in space. Once the density of debris in space reaches a certain level then a cascading phenomenon may occur amongst the debris which might drastically increase the number of debris objects preventing any safe space activity. If this happens, then the natural recovery of space will require years, even multi-millennia, depending on the altitude of the orbital debris and solar flare activity. Any anthropocentric cleaning might not be feasible, not because it is not technologically feasible but because it is not economically feasible. Among the weapons intended for space, the kinetic energy anti satellite (ASAT) weapon is the most detrimental for peaceful space activity because it inevitably increases space debris drastically once it collides with an adversary target. The technology for the kinetic energy ASAT is already available to the space powers[12] and the threat of the ASAT weapon to space activity is therefore a real one.

Space Sabotage

To take out a sophisticated space weapon system such as space based laser, the adversary only needs to send a large amount of sand or gravel rocketing through low earth orbit where the space weapon circulates (Saperstein, 2002, cited in Hitchens, 2002b). If such sabotage happens then it not only negates the adversary's sophisticated space weapon system but also any commercial space systems.

Technology Spillover

In a similar way to commercial aircraft technology, which largely benefits from developments in military aircraft (Mowery and Rosenberg, 1982), commercial space transportation system

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[11] Impact with a small pebble, travelling at average relative speed in space, is equivalent to being hit with a 22 caliber long rifle bullet (Saperstein, 2002, cited in Hitchens, 2002a).

[12] The U.S. F-15 launched direct-ascent Miniature Homing Vehicle ASAT weapon underwent a single test against a satellite target in 1985 and demonstrated a hit–to-kill technology using a thermal infrared homing device (Baines, 2003). The Former Soviet Union tested a ASAT system using a SS-9 intercontinental ballistic missile to launch a chaser satellite on a one- or two-orbit rendezvous trajectory, under 2,000 km altitude during 1968 and 1982 (Baines, 2003).

technology could benefit from the extended technology frontier induced by military R&D in space transportation technology. The U.S. DoD’s National Aerospace Initiative (NAI) of High-speed/Hypersonics (HS/H) could extend the technology frontier of the airbreathing engine. This might be the key technology for the development of a reusable first stage for a commercial space transportation system and might help induce a new space transportation market such as space tourism.

Will the Military Space Activity Spread Out

It might be beyond the scope of this study to predict the feasibility and the consequences of a race in space military activity. However, a very limited preliminary review might be feasible.

According to the literature on space militarization policy, it is hard to deny that the installation of a weapon in space by a super power might induce a reaction from other space-faring nations, but the details of such reaction may differ by country.

Europe

A report made for the North Atlantic Treaty Organization (NATO) Parliamentary Assembly by a sub committee on the proliferation of military technology, stated a firm belief that the stationing of strike weapons in outer space by any nation, and the deployment of ASAT weapons, both space and ground based, could lead to an arms race and increase threats to important commercial and military assets in space (Ibrügger, 2004). Despite the fact that Washington is committed to building missile defences designed to protect not only US territory but also friends and allies, many European allies have mixed views on strategic ballistic missile defence programs (Ibrügger, 2004). European countries have strongly objected to the U. S. decision to withdraw from the ABM Treaty (Dupas, 2002). To be credible and effective, any Common Foreign and Security Policy (CFSP) and European Security and Defence Policy (ESDP) must be based on autonomous access to reliable global information so as to foster informed decision-making. Space technologies and infrastructures ensure access to knowledge, information and military capabilities on the ground that can only be enabled through the capacity to launch, develop and operate satellites providing global communications, positioning and observation systems (CEC, 2003). European policy is to maintain independence of their defense from the U.S. The Ariane program, the Galileo program, and national reconnaissance and military communication satellite programs are evidence of this policy in relation to space activity.

Russia and China

Russia and China are strong proponents of negotiations at the United Nations (UN) Conference on disarmament to expand the 1967 Outer Space Treaty to ban all types of weapons by introducing the Prevention of an Arms Race in Outer Space (PAROS) (Hitchens, 2002a). Since these two nations are those who would seriously lose their strategic position in Mutual Assured Destruction[13] (MAD) deterrence once the U.S. deploys weaponry in space[14], it is evident that these two nations would develop counter measures to the space weaponry. However, it is hard to expect these two nations to develop a space weaponry system comparable to that of the U.S. since Russia could not afford the budget to build such expensive space weaponry and China lacks the technology to build it. Instead they are developing countermeasures to enable them to maintain their second strike capability[15] and/or negate or eliminate the means for an adversary to use their sophisticated weaponry system in space as well as on the ground.

Will the Military Space Activity Become a Locomotive?

There is a strong possibility of reaction from another country if a country places weaponry in space. However, the reaction might differ by country depending on the capability they have in terms of technology as well as budget.

There is also a difference in the requirements in military space activity for those willing to acquire first strike capability[16] and those willing to maintain Mutual Assured Destruction (MAD) capability by keeping second strike capability. For the former, the country needs to

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[13] Mutual Assured Destruction (MAD) is a doctrine of military strategy in which two opposite sides keep strong nuclear weapons and therefore, a full-scale use of nuclear weapons by one against the other would result in the destruction of both sides.

[14] Space weapons, especially those aimed at terrestrial targets and those primarily designed for defence of satellites would have inherently offensive and enhancing first strike capability (Hitchens, 2002a).

[15] Second strike capability is a strategic nuclear force structure which can survive after absorbing a large scale nuclear surprise attack so as to inflict large-scale damage on the attacker.

[16] First strike capability is a strategic offensive nuclear structure which is sufficient to strike first and effectively eliminate the enemy's second strike capability.

place heavy offensive military platforms in space, while for the latter, there are various ways to negate or eliminate the adversary's capability in space and on the ground, such as rotating the ICBM to dissipate the thermal load to be received from a space based laser, or space sabotage to negate an enemy's sophisticated target acquisition satellite, etc. There is no evidence that any country, except for the forerunner in space weaponization, plans to acquire heavy offensive weapon in space.

In general, there is some rigidity in the government budget since there is much indispensable expenditure on such things as education, terrestrial defense, etc.

In this regard, even with a race in space militarization, the growth of the governmental military budget for space activity on a worldwide level would be restrictive. It is therefore hard to believe this activity alone could act as the source of sustainable development for space activity.

Instead, once any physical conflict occurs in space which is accompanied by destruction of the adversary's space assets using the kinetic energy ASAT weapon, a huge amount of space debris would be produced. This would cause physical crowding out, not only for space weapon systems but also for commercial space systems, by directly damaging the asset or through increased development cost for the space system due to the requirement for heavy shielding against space debris.

2.4.2.2 Public Space Travel

In the launch industry, there is growing interest in public space travel, including suborbital and orbital space flights. The latter became a reality when Dennis Tito privately paid approximately 20 million dollars for a 6-day visit to the International Space Station (ISS) in 2001 (Tito, 2003). Interest in the former has been stimulated by X-prize.

Comparison of Private Initiatives

It will be worthwhile to compare two private space business initiatives - public suborbital space travel and Iridium - to get insight into the future evolution of the potential market for public space travel.

Hindering Factors

Catch-22 trap: both the space tourism and mobile satellite service markets are highly uncertain but require high initial investment to examine the market. The RLV for public space travel needs to have low service cost with private human rated safety, but the amount of initial investment for RLV development might well be more than 20 billion dollars (Hearing Charter, 2003b). This, coupled with an uncertain market, induces a Catch-22 situation. Without investment, there would be no firm market; without a firm market it is hard to induce private investment. Iridium succeeded in overcoming this Catch-22. The Iridium program attracted the interest of Wall Street and had 4.8 billion dollars of investment by the end of 1998 (Inkpen et al. 2000) but failed to achieve the projected market share.

High technical risk: both markets require cutting edge technology and are therefore high technology risks. Public space travel needs a low launch cost and a higher level of vehicle safety which call for a large extension to the technology frontier. In the case of the Iridium system, the premature technology, such as the heavy hand held set (seven inches long and approximately one pound in weight) and the poor performance in a closed area, might have contributed to the poor capture of the market.

Orbital physics: mobile satellite service benefits from orbital physics since, once a payload is in orbit, it then continuously circulates the Earth and provides service for years. However, public space travel could not take such advantage of orbital physics. The duration in orbit of the human payload is very short, possibly only days or weeks. This might offer a much bigger traffic load for space transportation systems than the satellite business, but, in the early stage of public space travel, it will act as a burden until space travel becomes a trivial thing.

Successive Factor

Public space travel is a new market having no terrestrial competitor. Rather, terrestrial tourism actors could be the pioneers for the new market. On the contrary, the mobile satellite service provider experienced a high landing rights barrier together with increased competition from terrestrial service providers which seriously damaged its front runner advantage in the market.

Will Public Space Travel Become a Locomotive?

At a glance, it looks like public space travel is in no better a position than the mobile satellite service which has almost gone out of business after billions of dollars of investment, except that it is not competing with terrestrial technology.

However, if we widen our conception of public space travel to include suborbital space flights then we can avoid all the hindering factors.

Suborbital activity is far less demanding in financial terms and hence it is easy to break out of the Catch-22 trap. It might only require hundreds of millions of dollars of investment to procure an operable fleet of suborbital vehicles, such as a derivative of StarShipOne.

The technology requirement to build a suborbital launch vehicle is far less demanding than an orbital launch vehicle and the technology risk can be minimized. The suborbital industry could ramp up the vehicle capability step by step as the market and the technology evolve.

The peculiarity of the human payload, which only stays in orbit for days or weeks, acts as the hindering factor for market evolution in the early stage of public space travel (orbital flight). However, once the technology has advanced high enough to build a launch vehicle which makes orbital insertion a trivial activity in terms of cost and technology, then it would act as a driving force for sustainable development of the market with repeated frequent flight requirements. In this regard, public space travel could be one of the most possible final destinations for the revolutionary space transportation market, having the capacity for sustainable development.

To attain this revolutionary destined market, there should be a revolutionary supply of space transportation systems, the reliability of which is high enough to accommodate risk averaging for public passengers and the price of which is low enough to induce the interest of people of average wealth. Once the public space travel market takes off, it would then act as a strong market pull for technology evolution, in both performance and service cost as well as reliability, and the technology evolution in the Space Transportation System (STS) would also stimulate other space transportation market segments.

However, we should reserve our final answer to the question since public space travel is in its embryonic stage. Such private initiative is strictly controlled by the profitability of the business and this is very difficult to predict given the many uncertainties in technology evolution as well as in the institutional environment through aspects such as regulation and politics.

2.5 Conclusions

After the downturn of the Iridium program in the late 1990's, a shadow has been cast over space activity, especially in the space transportation market. At the beginning of the 21st century, in 2001, two significant movements arose in space activity and the evolution of the space transportation market.

The first was the increasing military space activity, as could be seen from the military space budget over-taking the public space budget of one of the leading space powers and its subsequent withdrawal from the Anti-Ballistic Missile (ABM) Treaty. The second was Tito's space flight which opened up a new era in space tourism and emerging suborbital launch vehicle programs stimulated by X-prize.

In order to review whether these new movements in space activity could lead to sustainable development in the launch industry, two different approaches are sought, quantitative and qualitative reviews.

For the quantitative review, we investigated the industry perspective by referencing to two industry market studies, the Commercial Space Transportation Study (CSTS) in 1994 and the Analysis of Space Concepts Enabled by New Transportation (ASCENT) study in 2003.

For military space activity, neither market study expected big market potential to lead sustainable development of the launch industry. However, both studies confirmed a significant continuous market in this field.

For orbital public space travel, the CSTS predicted a big market which might lead to sustainable development of the launch industry, but under assumptions which were too extreme to envisage in the foreseeable future, such as a launch price of $100/lb to orbit and an airline-like safety level. The ASCENT study introduced techniques to reduce erroneous prediction, such as gearing factor in price elasticity and S-curve theory in market growth pattern. It might show a more realistic pattern of ramping up of the market development but the prediction only shows a 20-year period against a 60-year market saturation period and the gearing factor is fixed to current technology. Accordingly, ASCENT only predicts a limited market for public space travel - about 9 launches in 2021. It is also prohibitive to show the complete figure for the market potential and to examine whether it would lead sustainable development of the launch industry. For suborbital public space travel, neither market study recognized it as high potential market. The CSTS only recognized it as a temporal joy rider market and it was beyond the scope of the ASCENT market study.

For the qualitative analysis, we performed an analysis of the crowding out phenomenon owing to military space activity and the hindering and success factors for the public space travel market, and found that:

For military space activity, it is highly possible that the weaponization of space by a super power may occur. This may inevitably trigger counter measure activity from other space-faring nations such as Russia and China who need to keep their Mutual Assured Destruction (MAD) capability or the European association which seeks to maintain its independence. This might temporarily increase the volume of payloads but it would not lead to sustainable development of the space transportation market in the long run because of the rigidity of governmental budgets. There are also various ways to maintain strategic interest without placing heavy offensive weapon in space. Instead, there would be the risk of an increment in space debris in the case of physical conflict in space with the Anti Satellite (ASAT) weapon. This might cause detrimental crowding out of space activity in Earth orbit, either by increasing the cost to shield the space systems or by damage from collision, leading to doomsday for space activity.

Public space travel is one of the most probable destined markets for sustainable development in the long run, especially for the space transportation industry. Suborbital activity did not receive much recognition from either of the industry market studies. However, in our analysis, suborbital activity is more than an intermediate market, having growth potential for a big market and having the least risk in terms of technology as well as market evolution. Suborbital activity is far less demanding in terms of the technology and the investment requirements and can effectively break out of the Catch-22 trap. The suborbital industry could ramp up the launch vehicle capability progressively with the evolution of the technology and the market.

We can be assured that the era will come when the space transportation industry becomes a self-sustaining industry, when the new paradigm 'of private initiative, by private funding and for private activity' flourishes in the space transportation market. The economic system generates a large amount of wealth by satisfying private individual consumption through private funding, just like Wal-Mart, Microsoft, etc.

The space transportation market might have already entered the new era but we are just not aware of it. However, it is too early to predict comfortably whether the public space travel market can evolve into the big market required to lead sustainable development of the launch industry. Perhaps it will only evolve into a niche market, like general aviation in the aviation industry, or it may not prove to be a self-sustainable industry. Such private initiative is strictly governed by the profit and loss rule but this is prohibitively difficult to predict in a new market because of the uncertain nature of the technology evolution and the exogenous factors which influence the market, such as regulation, policy, etc.

In the next chapter, in order to tackle the main theme 'How to trade off Technology Evolution Paths,' we will investigate some of the background knowledge needed for the study - that of the space transportation system technology and how to perceive the dynamics of technology change in the space transportation system.

Chapter 3

Space Transportation System Technology: *How to Perceive the Change of Space Transportation System Technology*

> *In the physical world, one cannot build a house from the roof down because it is impossible to ignore or violate the laws of nature. In a notional world, one could build a house in this way because everything is possible in a notional world. However, possible does not necessarily mean supportable and that is the reason why we are searching for sound ground as well as coherence when we build a conceptual framework.*

We aim to develop a conceptual framework to gauge the change of space transportation system technology. To attain this objective, first we must find concrete ground on which we can build a conceptual framework. This ground could be reached by studying the root of the technology change rather than studying the surface of the technology change which has innately intractable manifold variations.

We will investigate the root of the technology change by articulating the process of the formation and manifestation of product technology to gain a fundamental understanding of product technology which will then provide the concrete ground on which the conceptual framework stands.

3.1 Introduction

In the previous chapter, one important exogenous factor in Space Transportation System (STS) technology - the market - has been studied. In this chapter, the main subject of the study - the STS technology itself, with the question, ‘how to perceive the change of STS technology’ – will be studied, leading into the following chapter where the main theme of this study, the tradeoff of technology paths, will be discussed.

A number of scholars have studied the methodology to gauge technology changes. However, it is rare that scholars initiate their study from the conception of the product technology. It is very difficult to develop a well structured methodology to gauge the technology change without a firm perception of the product technology itself, just as it is hard to build long lasting houses without well established ground.

We will therefore first look into the root of product technology, the process of formation and manifestation of the product technology, in order to grasp the fundamental understanding of the conception of the product technology and to induce theoretically possible criteria and methodologies to gauge the technology change.

We will then investigate existing methodologies using a literature survey to verify whether our understanding is compatible with existing knowledge and to learn more about the methodologies and their limits.

Based on our perception of the criteria and the methodologies to perceive the technology change and the literature study, we will propose an appropriate methodology to perceive the product technology, the so-called ‘trilateral approach.’

We will then develop a static framework to perceive the product technology based on the trilateral approach which can provide a snapshot of the product technology. Finally, we will develop a dynamic framework to gauge product technology change based on the static framework. To improve the comprehensibility of the dynamic framework to be proposed, topology will be used which is simple but informative enough to capture the trends of the technology change.

To discuss the subject of product technology, the terminology ‘technology’ should first be defined. Scholars have attempted to define the term ‘technology’ but, as yet, no universally agreed definition is available. This study uses Dosi’s definition with minor changes: “a set of knowledge, both directly practical (related concrete problems and devices) and theoretical (but practically applicable not necessarily already applied), know-how, methods, procedures, experience of success and failures and also, of course, *those of the knowledge embodied in*[17] physical device and equipment.” (1984:13-14).

In this study, we use the term ‘measure’ as quantitative access with quantitative information, ‘perceive’ as qualitative access with qualitative or quantitative information, or quantitative access with qualitative information, and the term ‘gauge’ to mean either ‘measure’ or ‘perceive’.

3.2 Articulating Product Technology

In order to find the answer to the question ‘how to perceive the change in STS technology,’ we look into the study object, product technology, to induce theoretically possible criteria and methodologies to gauge the product technology change.

3.2.1 Formation and Manifestation of Product Technology

From simple oil lamps to the complicated state of the art International Space Station (ISS), the innate nature of product technology ought to be the same.

Ancient people used knowledge of the burning properties of animal or vegetable oil, the wetting property of linen, and the heat and light producing property of fire, to produce and utilize the oil lamp.

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[17] The part in italics is added by the author because, as Simon (1973: 1110) articulated, “Technology is not things; it is knowledge-knowledge that is stored in hundreds of millions of books, in hundreds of millions or billions of human heads, and, to an important extent, in the artifacts themselves.” Hence, technology should be knowledge embodied in physical devices or equipment rather than physical existence itself as Dosi perceived.

The simple architecture of the oil lamp, a stone-shaped low open dish with a wick - a strip of linen coiled in the oil that had an end hanging over the end of the dish - embodied then dated technology. It is humans who give birth to an artifact by combining the material (stone, oil, and linen) and technology, or more broadly knowledge, to construe the formation of the product technology.

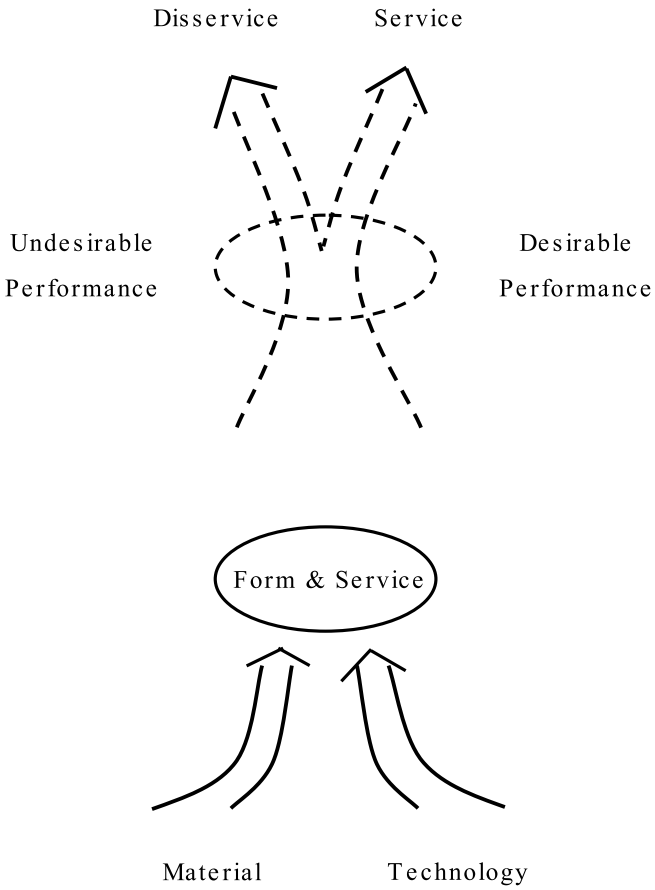

Fig. 3-1 Process of the Formation and Manifestation of Product Technology

Once the lamp has been ignited by a human, no further human intervention is required for the lamp to work. It continues working, dismantling the hydrocarbon to carbon and hydrogen which interact with oxygen to produce carbon dioxide and water with soot and radiation until the oil is depleted or the flame extinguished by human or natural intervention. It is the nature, more precisely the chemical and physical nature, of the inner structure. Simon (1996) expressed this as inner environment, constituting the substance and organization of artifacts. Here, the meaning is the same but ‘inner structure’ is used rather than inner environment. Here, the oil, wick and dish constitute the inner structure, and the oxygen in the air and the air current constitute the outer environment. Both the inner structure and outer environment produce the performance of the lamp which is representative of the manifestation of embodied product technology. Simon (1996) perceived this as the interface between the inner environment and the outer environment. As the inner environment is relevant to the outer environment, and vice versa, the artifact will serve its intended purpose.

The manifestation of the product technology, in other words the functioning of the product, is a physically indivisible continuous process. Once the lamp is lit, continuous combustion produces radiation energy from the flame together with soot[18]. The service, illumination of the surrounding area where the lamp is located, then manifests itself at the speed of light. The function is the positive part of the manifestation of the product. The negative part exists in the dysfunction of the product which yields undesired performance through the generation of carbon dioxide and soot.

The desirable performance, the production of visible radiation, yields a service for humans, illuminating dark areas or producing an elegant mood. However, undesirable performance, production of carbon dioxide and soot, can yield a disservice to living beings causing problems such as cerebral anoxia (lack of oxygen in the brain), death in a tightly enclosed room due to deprivation of oxygen caused by the burning lamp, or damage to the respiratory organ due to contamination from the soot.

Fig. 3-1 shows the process of the formation and manifestation of the product technology. The elliptical shape denotes a product. The figure in the unbroken line represents the formation process of product technology and the figure in the dotted line represents the manifestation process of product technology.

We can divide the process into three stages, as follows:

1) Formation stage: from the bottom, humans create products by merging material and knowledge.

2) Embodied stage: once the creation is complete, the technology is embodied in a product.

3) Manifestation stage: as discussed in the metaphor of the oil lamp, once the product is activated then nature becomes the actor in the performance of the product, giving both desirable performance which yields the service identified on the right side of the figure and undesirable performance which yields the disservice identified on the left side of the figure.

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[18] The current physics explained that soot is initially composed of fragmented carbon super-molecules containing dozens of carbon atoms linked together into plates or filaments of one kind or another from which radiation energy is emitted.

3.2.2 Theoretically Possible Methodologies to Gauge the Product Technology

As we reviewed in paragraph 3.2.1, there are three different stages to perceive the product technology: formation, embodied, and manifestation stage, and each stage has its own criteria and methodology to gauge the change of technology. Fig. 3-2 summarizes our articulation of the criteria and methodologies used to gauge product technology.

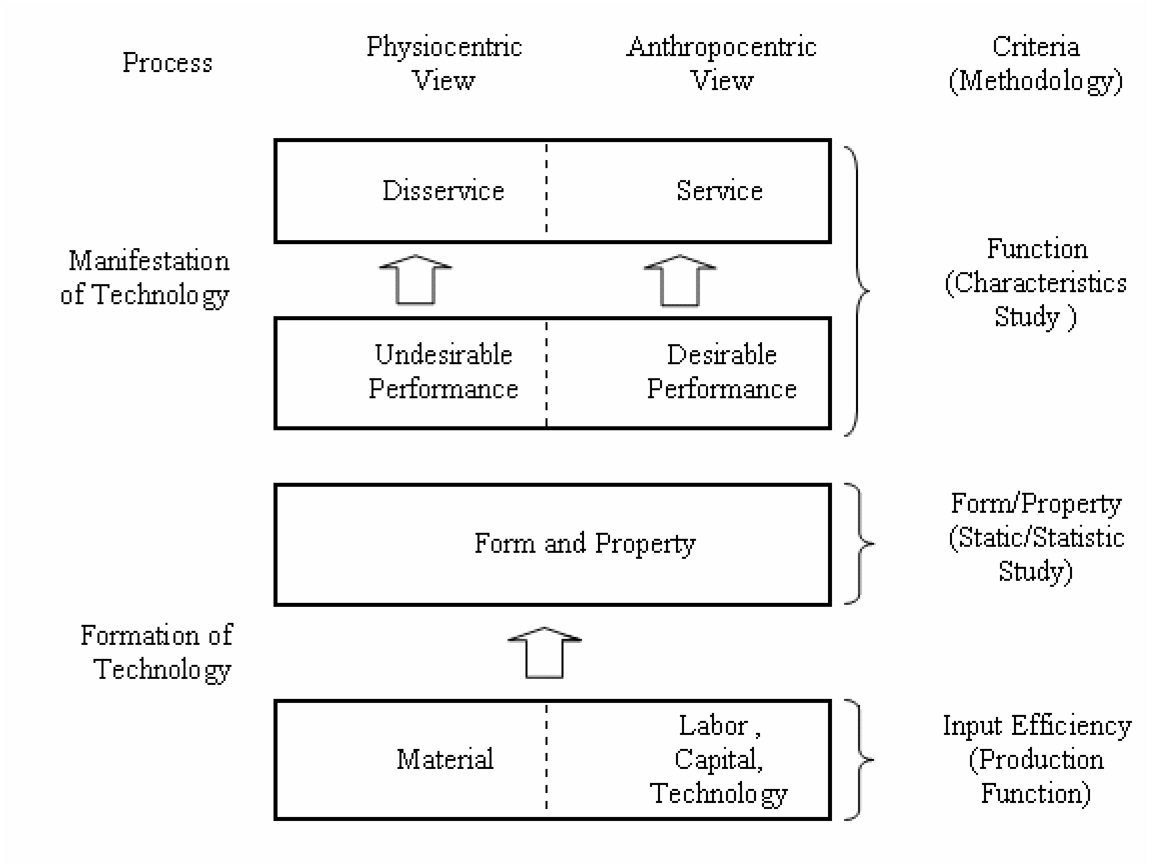

Fig. 3-2 Criteria and Methodologies to Gauge Product Technology

There are two contrasting views on the perception of product technology: the anthropocentric view which focuses on desirable performances yielding service from the product and the physiocentric[19] view focused on undesirable performances which yield disservice. Humans have developed technology as a means of increasing human satisfaction by manipulating nature. Hence, nature is almost always regarded as an object for manipulation. It is only in

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[19] We borrowed this term from Meyer-Abich (1997). He used the term in contrast to the anthropocentric in his “Human in Nature: Toward a Physiocentric Philosophy.”

relatively recent years that nature itself has become a subject of study in the process of production and consumption activities, as is the case with increased concerns over degradation of the quality of nature and depletion of natural resources. For the form and property studies, it cannot be categorized by the dichotomy of views.

The formation stage:

A methodology such as production function can be used to measure technology change, using the criteria of input efficiency of production, by means of measuring the shift in the production function.

The embodied stage:

In this stage, one can perceive the product technology embodied by reversely extracting it from the products, i.e., by means of the reverse engineering process. If our goal is to capture technology embodied in a product, then this is a useful way to achieve the goal. However, our goal is to study the technology change and therefore we can avoid the exhausting effort of reverse engineering to reconstruct the product technology. Instead, we can perceive the technology change by studying the form and property of the products.

A product as a system has peculiarities that are hard to capture at first glance but can be appreciated by monitoring the whole life of the artifact. We can call this the property of a product in order to avoid confusion with the ‘characteristics’ conception which is already preceded by a wide body of knowledge. Other aspects of the physical state of the inner structure include the form of the product, both the shape of the components and the assembly thereof, and structural aspects of the components, i.e. the interrelationship among the components.

In the embodied stage, the methodologies of static and statistic study are contemplated to perceive technology change by studying the static nature of the product technology, such as morphology for the shape of the product and components, and the structural aspects of the product such as complexity, decomposability and architecture, and by studying the statistic nature of the product technology such as reliability and reusability.

The manifestation stage:

In this stage, theoretically, one can gauge the change of product technology by studying either the performance of the product or the yield resulting from the performance, i.e. the service, but not necessarily both.[20] Both are derived from same process, manifestation of the product technology, but can be differentiated by the way in which the process is viewed. The former captures the physical meaning of the process while the latter captures the utility meaning of the process.

In this stage, the methodology of characteristics study can be used to gauge the technology change using the criteria of function of the technology, either the performance or service factor.

3.3 Literature Study: Methodologies to Gauge Product Technology Change

In the previous section, we induced the theoretically possible methodology and criteria to gauge the technology change including input efficiency, form and property study, and functional study.

We will review the existing methodologies to gauge the technology change using a literature study to examine the compatibility of our understanding with existing knowledge, and to gain further insight for inducing a new methodology to gauge the product technology change.

3.3.1 Anthropocentric View

The anthropocentric view has a longer history and most of the arguments relating to technology are based upon this view.

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[20] Saviotti and Metcalfe (1984) distinguished the form and functional aspects of the product by introducing technical characteristics and service characteristics which represented structural and functional aspects of the product respectively, but did not distinguish between the performance and service (1984: 143)

3.3.1.1 Production Function

The neo-classical production function is the most striking example in the anthropocentric view, where the natural factor, material, is missing and only the anthropocentric factors of capital and labor appear. The neo-classical production function might be the first theoretical model that can show technological advancement. In spite of the simplicity and clarity of the conception, the production function is not appropriate for studying a specific product technology.

Firstly, the primary interest of the production function is the efficiency of inputs, usually with a high degree of categorization, such as capital and labor and their substitution in the technology development. Hence, the technology advancement is conceived as an exogenous factor that can be measured by the shift of the production function so that the change is only perceived indirectly and at highly aggregate levels such as the economy system level and the regional level.

Secondly, technology change can be measured as the shift of the production function; however, the shift of the production function represents not only the change of the product technology but also the process technology as well. Hence, it is problematic to isolate the product technology change from the total technology change. In reverse, this can be a useful feature of the production function when studying both product and process technology together.

3.3.1.2 Characteristics Approaches

There are some different methodologies which fall into the category of characteristic approaches, including the Hedonic approaches of Saviotti (1985), the Characteristics Surface Approaches of Dodson (1970), the Technical and Service Characteristic Approach of Saviotti and Metcalfe (1984), and the Composite Approaches of Sahal (1985a).

Characteristics approaches directly address product technology and there are no doubts about the usefulness of this approach in developing the framework to measure technology changes.

However, there are some areas that need to be improved in the existing characteristics approaches. Firstly, further study is needed for the selection of the characteristics and methodology to determine the weight of the characteristics. Secondly, some important aspects of product technology are either missing or not well recognized, such as property and the architectural aspects of the product.

Hedonic Approach

The origin of the characteristics conception may be controversial. However, Court's (1939) hedonic price study could be conceived as the first to apply the characteristics conception in representing the quality factor of a technical product. Griliches' (1961) study induces many responses on the hedonic techniques. Lancaster's (1966) proposition that not the good itself but the characteristics it poses give rise to the utility, and the consumption technology conception, provides a theoretical foundation for the hedonic price technique approach. The Hedonic approach uses the conception of the quality or technology change as a process of the hedonic price regression, but technology change is not the primary interest of the study.

It was Saviotti (1985) who studied the measurement of technology change using the hedonic price approach. The hedonic price technique has innate limitations in measuring the technology advancement. Hedonic price technique methodology for measuring technology change implicitly assumes that the price change of a product can be decomposed into a quality or product technology change effect and a pure price effect. The price change is much more susceptible to the process technology than product technology, and there are many factors which influence the price of a product but are independent of technology, such as interest rates, management efficiency, etc. However, it is not a simple task to isolate the technology change effect from others.

The Hedonic approach is useful to study the product technology and process technology changes together. Both product technology and process technology change can be captured by the change in the price of the unit characteristics. However, there are some products, such as a launch vehicle with its distorted price determining mechanism, for which any meaningful interpretation or correlation of the price change with technology change is precluded.

Characteristics Surface Approach

Dodson (1970) studied a quantitative assessment of the State Of the Art (SOA) and technological advances in SOA. SOA is defined in terms of selected physical and performance characteristics and the technology advancements are measured in the distance of outward movement of a SOA surface from the initial SOA surface. Dodson's approach is exceptional as it conceptualized the notional problematic phenomenon, technology change, into the topological model which is simple to understand and strongly appeals to our intuition. However, it contains two limits. First, as the SOA is defined as the state of best implemented technology as reflected by the physical and performance characteristics actually achieved during the time period in question, the methodology can be used for a historical study of technology change but is not appropriate for future technology change. Second, the approach could not provide the weight of the characteristics and hence there are limits in the quantitative study of technology change.

Tradeoff Surface Approach

Alexander and Nelson (1973) used the conception of tradeoff surface in gauging the technology changes. They assumed that the object or device under development can be adequately characterized by a limited number of parameters and that the development process acts on this set of parameters in such a way that the value of the set is increased. This methodology improved the approach of Dodson as it categorized the parameters as performance parameters that give the device value to the user, thrust or weight in case of the aircraft engine, and technical parameters which make the performance parameters possible, such as turbine inlet temperature or overall pressure ratio. They noticed the dependence between the two parameters and hence appropriately avoided using these parameters redundantly. The technology change is defined as this movement of the tradeoff surface. They examined this methodology by using turbine engine data. The tradeoff surface of mixed parameters consisting of turbine inlet temperature, thrust, weight, specific fuel consumption, and dynamic pressure, in the form of semi-logarithm showed the highest degree of statistical correlation while the tradeoff surface of pure performance characteristics produced poor correlation. This approach is similar to Dodson's SOA approach in its conception of the technology change and almost the same as the Hedonic technique in its problem solving method. As in the case of the hedonic approach, with the exhausting effort in manipulating characteristic data, one may build up a tradeoff function which might look as if it conforms to the proposition of the approach. However, the rationale for the selection of the parameters and their weights needs to be justified..

Technical and Service Characteristic Approach

Saviotti and Metcalfe (1984) introduced a framework consisting of technical characteristics and service characteristics, and patterns of mapping relating these two sets of characteristics. They clearly distinguished between the notion of form and function, where function refers to performance of required services and form to the internal structure of the technological artifact used to perform the function. Their notion of technical characteristics is similar to the technical specification of the product, such as type of engine, size of engine, number of cylinders, stroke, and compression ratio, etc. while the service characteristics mean speed, number of passengers, luggage space, etc. They suggested finding the weights of service characteristics by market survey and then calculating the weight of the technical characteristics by solving equations derived from the linearly mapped relationships between the two sets of characteristics. Their conception is clear in theory; however, practically, the application might be too complicated to handle.

Composite Approach

Sahal (1985a) consolidated his previous studies for the measurement of technology change, the so-called composite approach. He perceived the technology change as the degree of lack of resemblance between various patterns of innovation. Two different aspects of technology were studied: a Wholistic index of technology, representing a yardstick of advances in the surface structure of technical knowledge over time, and a Holistic index of technology representing a yardstick of advancement in the deep structure of technical knowledge over the course of time.

The conception of the Wholistic approach is similar to tradeoff surface approaches except for the methodology used to measure the technology changes. Sahal used a surface of constant probability density, so-called isodensity contour by analogy with a contour of points at equal altitude above sea level in a map, for a given distribution of the variables representing design (e.g., stroke length) as well as performance characteristics of the technology. The technical change can be measured as the generalized distance between two comparative product groups. For the Holistic approaches, the mathematical process is same as for the Wholistic approaches except for the variables which are dimensionless and are supposed to represent the law-like aspects of technology, the so-called deep structure of the technology.

The composite approach introduced resemblance concepts for capturing technology change with elegant mathematical manipulation methodology to convert the concepts to work. This appears to have been somewhat successful in showing the trends of the technology change through the application of empirical study. However, as with the other characteristic approaches, the root deficiency remains the same - the rationale used to choose the characteristics and the weight of the characteristics. Sahal also used design variables as well as performance variables to represent the state of technology. However, the variable representing physical dimensions might be a good differentiation for the product shape but not necessarily for the technology.

The Holistic approach using the dimensionless variables inspired by the coefficient of physical laws or engineering equations might enable us to avoid the variable identification problem, but the problem of determining the weight of the variables in general remains. However, if we scrutinize the problem at the individual product level, the problem becomes clearer and more manageable by manipulating or combining the variables. Lift to drag ratio of an aircraft can be used to evaluate the aerodynamic efficiency of the aircraft and engine performance can be measured by both thrust to weight ratio and specific fuel consumption. The weight of these two factors can be determined by the type of mission - a fighter aircraft might have a higher thrust to weight ratio than specific fuel consumption but the reverse might be true for a military transport aircraft or a commercial aircraft. We can calculate the exchange ratio between the aerodynamic efficiency and the specific fuel consumption ratio. Also, a single index might be feasible if we narrow down our interest, for example, to focus on the technology relating to the efficiency of flight operation. In this case, mile.seat/galon.fuel would be the representative variables.

3.3.2 Physiocentric View

There is evidence that environmental pressure has an influence on some technology changes, as seen in the cases of Dichloro-Diphenyl-Trichloroethane (DDT) and Chlorofluorocarbons (CFCs). However, general trends such as dematerialization or decarbonization trends in technology development are still open issues. Herman et al. (1989) investigated the dematerialization trends in the production and consumption phase through studies of the automobile industry, energy consumption per Gross National Product (GNP) and waste disposal. Wernick et al (1997) showed dematerialization trends in some selective primary material such as timber, copper, steel and lead, and some industry and industrial products such as containers, cars, and aircraft. For aircraft in particular, because the dematerialization saves both fuel and money, there is a strong drive to reduce mass. However, as they admitted, they did not intend to elicit dematerialization or decarbonization trends in general but confined the trends locally to the United States, and only for selective materials or products.

As the CFCs and greenhouse gas cases demonstrated, the earth itself is a Meta system, the environmental change of it has huge inertia, and hence it takes considerable time for any changes to become apparent. It takes decades, or maybe centuries, to recognize the changes and adverse effects and to take appropriate measures to remedy these effects through changes in the socio-political system, such as institutional, cultural and technological changes.

In the case of the CFCs, after their introduction in the 1930s, it took a few decades for the potential ozone depletion caused by decomposed chlorine atoms produced in the process of ultraviolet photo decomposition of CFCs to be recognized by Molina and Rowland (1974). Farman et al. (1985) found the first evidence of significant but temporary changes in the ozone over Antarctica a decade later and then the Vienna Convention, an international convention for the protection of ozone layer was adopted in 1985 (Glas, 1989). According to the report of the Intergovernmental Panel on Climate Change (IPCC, 2001), atmospheric concentrations of main anthropogenic greenhouse gases has increased substantially since the pre-industrial era, and most of the observed warming over the last 50 years is likely due to increases in greenhouse gases. The international resolution, Kyoto Protocol, was inaugurated about 100 years after the first scientific argument on the greenhouse effect was raised. It was in 1896 when Arrhenius argued that variations in carbon acid (carbon dioxide) composition in the atmosphere change the temperature of the Earth's surface in his "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground."

There might be an already existing force which attracts the socio-political system toward the physiocentric view and influences the technology development path toward being environment friendly. However, we might have to wait a few decades to see a generalized physiocentric trend in technology development, such as dematerialization or decarbonization, because of the huge inertia in the socio-political system.

There are two main issues in discussing natural aspects in the process of technology evolution: the depletion of materials and the degradation of the environment. Ayres and Kneese (1969) explained the environmental pollution and control problem by means of the material balance problem. In the 1970s, further scholars, including Simon (1973), Rosenberg (1971), Ruttan (1971), and Starr and Rudman (1973), studied environmental problems and the related technological issues.

Contrary to the anthropocentric view of the perception of the product technology, the physiocentric view has not yet been widely studied.

Production Function

It is more than coincidental that the production function becomes the first one that introduces the physiocentric conception. Minhas (1963) introduced the material factor, in addition to capital and labor, in the production function. Berndt and Wood (1975) extended the input factor to include energy to develop the KLEM model consisting of capital (K), labor (L), energy (E) and intermediate materials (M).

Ayres (1998) further elaborated the production function, a meta-production function based on both the 'cowboy' and 'spaceship' economies. The former is comprised of conventional factors, both capital (K) and labor (L), and the latter is comprised of three factors, capital (K), knowledge or information capital (H) and renewable resources input (R). The production function of an era can be expressed by the combination of these two functions. These new product functions recognize natural resources as an input of the product and hence could be interpreted in some way as a deviation from the anthropocentric view but not as an adoption of the physiocentric view. It is also innate in the deficiency of the production function to describe product technology change as discussed above, to measure the technology change indirectly and at a highly aggregated level, and to reflect on both product and process technology.

Exergy Approach

Since Georgescu-Roegen's (1971) initiative to link entropy law with economic process, economists have tried to explain some economic processes by means of entropy. The meaning of the exergy[21] conception is relatively easier to grasp than that of entropy. Some economists are enthusiastic about the conception and have tried to inter-link the exergy analysis with environmental problems since exergy discharged to the environment during the production or operation process impacts on the environment. Szargut (1980) pioneered the inter-linking of exergy with environmental impacts and Ayres et al. (1998) extended exergy analysis to resource and waste accounts. Furthermore, exergy analysis by means of ecological indicators was investigated by Xu et al. (1999) and Gong and Wall (2001). The exergy analysis can describe the ecological impacts of a system by a unified quantitative scalar-exergy. However, it has limitations in discriminating the qualitative factors, i.e. toxic low exergy material is much more harmful to ecology than non-toxic high exergy material, as discussed by Wang and Feng (2000).

Despite the limit of the exergy concept in relation to environmental issues, i.e. it cannot differentiate the quality factor of the material, it is still worth investigating exergy in the study of sustainable development since it provides a new dimension to measure the thermodynamic state of matter in relation to the environment and offers a new way of thinking, which is neither anthropocentric nor physiocentric biased, in explaining changes of matter as Ayres investigated.

Ayres (1998) used the exergy concept to measure technology advancement. He conceived the technical efficiency as the intersection of exergy efficiency and service delivery efficiency.

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[21] Rant (1956) termed the term exergy which means technical working capacity. Szargut et al. (1988) defined Exergy as "the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible process, involving interaction only with the above mentioned components of nature"

The former is a ratio of delivered exergy - meaning workable energy delivered to a driveshaft - to the exergy embodied in fuels. The latter is the ratio of final service output to delivered exergy or work input.

Functional Study

Ayres and Kneese (1969) conceived the disservices (e.g. killing fish, increasing difficulty of water treatment, increasing risk to public health, soiling and deterioration of buildings, etc.) rendered by the residuals from both the production and consumption process and explained environmental pollution. It was Pittman (1983) who took a noticeable step toward the physiocentric view. He argued that not only the desirable output but also the undesirable output such as water and air pollution should be taken into account in developing a multilateral productivity indicator. Saviotti and Metcalfe (1984) also discussed unwanted services such as pollution and noise as factors of the service characteristics representative of technology change. Reinhard et al (1999) defined environmental efficiency as “the ratio of minimum feasible to observed use of an environmentally detrimental input, conditional on observed levels of the desirable output and the conventional inputs.” He noted that, while the environmentally detrimental input can be measured, the environmental repercussions cannot be easily measured.

3.3.3 Form and Property Study

Form and property study cannot be categorized by the dichotomy of views.

3.3.3 1 Form

For studying the form of the product, the static nature of the product technology, such as its morphology and structural aspects, are investigated.

Morphology

The term morphology, meaning the study of shape or form, comes from the classical Greek term ‘morphe.’ Morphology has been used in various scientific fields to study form or shape, for instance in anatomy, biology, geology, etc.

As far as products are concerned, morphology is widely used in the field of metallurgy and surface science to study the shape or structure of material at molecular level.

Zwicky (1948) extended the morphology approach from concern with the geometric shape of things and the change of these shapes over time to embrace all characteristics of things, whether they are material or spiritual, and achieve a schematic perspective over all possible solutions of large-scale problem - morphology methodology. Morphology lent itself well to Zwicky’s investigation of objects as he argued that “The morphological method essentially is nothing more than an orderly way of looking at things.” (1948: 121)

Morphology methodology seeks all the possible technology options to solve a problem by detaching any prejudices. Zwicky (1967) demonstrated 576 different possibilities for propulsive power plant conceptions by applying morphology methodology. Prior to this, only 5 conceptions were known.

There are a few studies using morphological analysis to link technology changes. Among these few, Foray (1990) used morphological analysis of technology for ferrous casting in order to study diffusion and lockout of the technology.

Structure

Structural aspects of a product can be perceived using two characteristics: the frequency of the inter-link between the components - complexity and decomposability - and the patterns of the interrelationship - architecture.

The notions of complexity, decomposability and architecture are not mutually exclusive but closely connected. Complexity can be best expressed by the notion of decomposability as

Simon (1996) noted that the complexity of a product is not necessarily proportional to the sum of its parts but to the interrelationships among the parts. Modular conception, a widely investigated pattern of architecture, could not be understood without the notion of decomposability.

Complexity

Hobday (1998: 700) argued that complex products and systems evolve with increased complexity from one generation to another due to ever-rising demand on performance capability and reliability. Meanwhile, simplifying factors by means of modularization or standardisation may impinge on the products as well. Salamatov (1999) articulated the complexity change in the product evolutionary process such that from the very beginning the system starts increasing its main useful function at the expense of simplicity, ‘picking up’ a multitude of supplementary sub-systems – the expansion period of the technical system. Evolution is then confronted with objective constraints on the physical, economic and ecological complication of the system leading to the convolution period accompanied by both simplification and idealization of the sub-systems. TRIZ students proposed such an evolutionary process as a possible pattern of technological systems: increased complexity first, followed by simplification. (Clarke, SR.: 2000, Gahide: 2000, Mann: 2003).

Kauffman (1993) introduced the N-K model of complex systems, where N stands for the number of elements in a system and K stands for the number of dependencies or epistatic relations per element. The model was applied to study product technology innovation by Frenken (2001).

Decomposability

Decomposability is an important property of product structure, the effect of which emerges throughout the whole life of the product, including development, production and operation. The typical characteristic approaches based on functional study are not appropriate to capture this aspect of the nature of the product because a change in decomposability of the product, such as the introduction of the modular concept or of the platform concept, does not change the performance of the product. However, the design and production process, as well as the operation process, largely benefit from these conceptions. As Sanchez and Mahoney (1996) argued, since a modular product architecture creates a nearly independent system of loosely coupled components, modular conception design allows the development of each module independently of the change in other modules and hence concurrent development of modules is feasible to reduce the development cost. The modular conception of aircraft engines reduces the maintenance cost of the engines by filling the pipeline of the logistics support with modules rather than millions of dollars worth of whole engines.

Simon's parable of the two watchmakers is far from realistic but nonetheless demonstrates the power of decomposability. Tempus and Hora were two highly regarded watchmakers. However Hora prospered while Tempus lost his business because of the difference in decomposability of the watches they made. The watch Hora assembled could be constructed from the individual parts to decomposable subassemblies and then to final assembly, while the watch Tempus assembled went directly from individual parts to final assembly. When they put down the work pieces to respond to customer calls, Hora only lost the effort invested in building up a subassembly while Tempus lost the effort invested in building the whole assembly (1996).

The notion of decomposability is not profound. However the impact of the application of this conception is far reaching for industry. Product modularity, since the introduction of IBM's 360 mainframe adapting modular design concepts in 1964, spread out to the manufacturing industries.

Architectures

The term architecture is a very slippery notion to grasp and hence a firm definition has not yet been established. A number of scholars have attempted to give a definition of architecture, among them:

Abernathy and Clark (1985) defined product architecture as a complete set of component interface specifications. Rechtin and Maier (1997: 251) defined architecture as "the structure - in terms of components, connections, and constraints - of a product, process, or elements." Ulrich (1995:420) defined architecture of a product as the scheme by which the function of the product is allocated to physical components. The National Aeronautics and Space Administration (NASA) (1992) defined architecture as "how functions are grouped together and interact with each other. Applies to the mission and to both inter-and intra-system, segment, element, and subsystem" (qtd Eisner: 249).

Two groups are similar in their definitions: one is based on the relationship between components and functions such as Ulrich and NASA, and the other excludes the functional aspects, only focusing on the interface between the components or processes as with Abernathy and Clark, and Rechtin and Maier. Baldwin and Clark discarded functional aspects in defining modularity because of the difficulties in basing a definition of modularity on function, difficulties which are inherently manifold and non-stationary (2000: 63).

Henderson and Clark defined architectural innovation as "innovations that change the way in which the components of a product are linked together, while leaving the core design concepts (and thus the basic knowledge underlying the components) untouched." (1990: 10).

Henderson and Clark (1990) emphasized the competitive changes among new firms in the emergence of architectural innovation as the architectural change of a product destroys the usefulness of the architectural knowledge of incumbents since architectural knowledge tends to become embodied in the structure and information process of the incumbents' organization. Under architectural innovation, incumbents experience more hardship than under radical innovation. Under radical innovation, incumbent firms recognize the uselessness of their existing knowledge and experience and so tend to actively adapt themselves to a new technology. However, under architectural innovation, incumbent firms sometimes under evaluate the urgency of the architectural change in a product and its impact on competition and so misread the change requirements on their operating system to respond to the architectural change, or even though they correctly acknowledge the change requirements of their existing operating system, difficulties exist in distinguishing between what should be changed and what could remain the same (Henderson and Clark, 1990). Sometimes the experience of the previous generation can act as a barrier in evaluating new architectural innovations and so leads incumbent firms to fail to properly react to the architectural change (as in the case of the photolithographic alignment industry, 1962-1986) (Henderson and Clark, 1990).

3.3.3.2 Property

For the study of property, aspects of the statistic nature of the product, such as reliability and reusability, are investigated.

The property of a product refers to the nature endowed on the product when it was physically born but which can only be identified by the performance of the product throughout its whole lifetime. This is similar to the functional characteristics but the difference is that the property could be determined by the repeated operation of the product and is usually measured in terms of probability.

Reliability

Reliability of a product can be defined as “the measure of its ability to perform its function, when required, for a specified time, in a particular environment. It is measured as a probability” (Leitch: 2).

Measurement of reliability differs according to the type of product operation. The reliability of a product can be measured by the Mean Time To Failure (MTTF) for non-repairable products or Mean Time Between Failure (MTBF) for repairable products.

For most reusable products, the failure rate with time changes shows specific patterns, the so-called bathtub curve. From the beginning of the product lifetime, a high failure rate is experienced due to design or production problems. The failure rate then reduces rapidly with corrective actions to the exposed problems coupled with increased learning in regard to production and operation. After a longer period of stable failure rate, the rate rises again when the product wears out. The pattern of the failure rate for expendable products does not show a bathtub curve but rather an asymptotic curve since there is no wear out of the product.

It is evident that technology has evolved to increase the reliability of the product in general. The passenger aircraft has increased its reliability with the introduction of the new generation of vehicles (Boeing, 2002).

Reusability

Reusability can be defined as the measure of the property of a product to be used again after salvaging or special treatment.

There are two different concepts of reusability: one relates to the specific physical product, i.e. the property of a product and components thereof that allow repetitive use against wear or tear out, and the other relates to the specific design of the product, i.e. the property of a product and components thereof that allow it to be used in more than the application for which it was designed, with or without modification.

As Boulding (1966) argued, in the cowboy economy the reservoir to extract and pollute is unlimited, while in the spaceship economy the reservoir is limited. Hence, in the spaceship economy, consumption is no longer regarded as a good thing, contrary to the case in the cowboy economy, and any technological change which results in the maintenance of a given total with a lower throughput (that is, less production and consumption) is clearly a gain. In this regard, in the future spaceship economy, the technology would evolve to increase the reusability of the product. The reusability then becomes a barometer to measure the technology change.

3.3.4 Reviews

In section 3.2, we induced theoretically possible methodologies to gauge product technology change, including input efficiency studies, state studies and functional studies. The literature study confirms that existing methodologies are well matched with the theoretically predicted methodologies.[22] However, there are some methodologies we expected but which are not well established in the existing methodologies.

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[22] The Pythagorean concept conceives technological change by studying the number of patents, innovations, etc or the crucial importance of the uniqueness and novelty of an event (Sahal, 1981:22). The conception might measure the product technology in some way but, as Sahal (1981) noted, it fails to reflect the changes in technology themselves, describing only changes in the number of techniques. Hence, it was not included in this literature study.

Physiocentric View

The methodologies used to capture the technology changes in the physiocentric views are very similar to those of the anthropocentric views, including the production function and functional study of the product by means of the ecological indicator or environment efficiency.

It should be noted that technology changes are not explicitly discussed in most of the physiocentric approaches where focus is on the methodology to capture the degree of environmental impact and the policy to induce environmentally compatible technology for sustainable development.

The lack of methodology to link the physiocentric view with gauging the technology change can be explained by the fact that in the past, in the cowboy economy, there was no inducing force to change the technology and so there was no way to differentiate the technology. However, in the future, in the spaceship economy, the technology would evolve so as to reduce the environmental impact and make material savings. The physiocentric view is not essential to those who are studying the historical trend of technology change. However, for those who intend to study future technology evolution, it would be a good barometer to gauge the technology change.

Form and Property Study

There are some studies that interlink the technology change and form of the product, such as complexity, decomposability and architecture, but there is a lack of studies which explicitly discuss property with regard to technology change.

Why do we not find property in any existing study? Is property not the right barometer to measure the technology change? As explained below, we believe it is not.

For the reusability of a product, as Ayres (1998) argued in the cowboy economy, the materials are not rare resources, so the less important the reusability of the material would be. However, in the spaceship economy, the material is no longer an infinite resource so the reusability of the material becomes an important factor to evaluate the technology. For those who study the historical technology change, the reusability could therefore not be an effective barometer to capture the change of the technology. However, if one studies the future technology evolution, then the reusability of the product would become an important factor.

For the reliability of the product, we suppose that the reliability factor is not missing and is not conceived as a separate property factor but is rather conceived as a service characteristic in existing studies. Customers pay more money for an automobile, not only for its high performance in speed and comfort, but also for the expectation that the vehicle will have a high level of reliability and safety as well.

3.4 How to Perceive Product Technology

There are many methodologies to gauge technology changes. However, no single methodology has been developed yet which appropriately represents all the various aspects of the product technology, not because of insufficient study but because of the innate multifaceted nature of the product technology itself, which is beyond the grasp of a single methodology.

This study will therefore not seek a specific methodology to perceive various aspects of product technology but will rather adapt all the methodologies, as we induced in the previous section, except for the input efficiency study which is not appropriate to study technology itself. Since the proposed approach includes three facets of the product technology – functional aspect, form and property - we call it a ‘trilateral approach.’

Based on the proposed approach, a case review will then be made of space transportation systems in order to gain insight into the peculiarity of STS technology for further development of our framework to describe the change of the STS technology.

3.4.1 Trilateral Approach

If we have complete knowledge of the functional mechanism or the form and property of a product, then we can evaluate the technological change either by studying functional performance, or studying the form and property of the inner structure of a product, but not necessarily both. This is because, in theory, performance of a product is a manifestation of the product technology which is embodied in the inner structure of the product, and it may well be that no manifestations exist that are not caused by the inner structure. However, in practice, we need to study both in order to perceive the technology changes[23] because our knowledge of the functional mechanism of product performance is limited and there are some properties of the product that represent technology advancement but are not easily recognizable by studying one time performance of the product. For example, if we take the static nature of the product, decomposability requires structural study of a product, and statistic properties of the product, reusability and reliability, are understood by studying the repetitive performance of the product. Therefore, in reality, for the perception of the product technology we need to investigate the functional aspect as well as the form and property of the product.

The trilateral approach is clear in theory but in order to apply it to gauge product technology, some areas need to be refined, as explained below.

For the study of the form, we would not study the morphology of the components and product since it is difficult to develop a barometer to gauge technology change based on the morphology which is full of variations. We will therefore only study structural aspects of the product technology.

For the study of the functional aspect, with the growing concerns over the environmental issues, the future technology would evolve in such a way as to reduce dysfunction of the product and therefore, in addition to the anthropocentric view, the physiocentric view is also incorporated in the proposed approach.

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[23] Saviotti explained this issue in another way. He argued that technologies can differ in terms of service characteristics or technical characteristics, just as birds and aircraft can be considered as two different technologies while the both provide air transport service (his notion of the technical characteristics are similar to the notion of form or structure, and service characteristics are the same as the performance in this study). (1996: 64).

Functional aspect of the product technology comprises both performance and service characteristics. Here, we only study performance characteristics in order to perceive the change of the product technology for the reasons explained below:

As we already discussed in paragraph 2.2, both derive from the same process, manifestation of the product technology, but differ in the way the process is perceived.

As Lancaster (1966) revealed, customers are interested in the utility of an artifact that can be represented by service characteristics. The service characteristics are important to discuss customer theory. However, for technological aspects, service characteristics have limited application because some service characteristics can be improved without technology advancement but at the cost of degradation of the others. As an example, the safety factor of a launch vehicle can be improved by adding redundancy in safety critical areas without technology advancement but the other service factors, such as the payload capability, become degraded.

For the anthropocentric view, the criteria and measuring methodology for the performance of the product technology is well established. However, for the physiocentric view, the criteria and measuring methodology are not well established, since:

First, the limits of current knowledge prevent a complete assessment of the undesirable performance of a product, as evidenced by Dichloro-Diphenyl-Trichloroethane (DDT) and Chlorofluorocarbons (CFCs). In other words, there is a possibility of finding a surprising effect at a later date than when the product is introduced.

Second, the resulting disservices, such as greenhouse effects or Ozone (O_3) depletion, are not linear to the outcome of individual product performance because of the externality and assimilation of the earth system. Ozone depletion caused by Nitric Oxide (NO) is dependent on contingent externality and density of the atmospheric Chlorine (Cl) released from CFCs since there are titration reactions between the two ozone depleters which convert into Chlorine Nitrate ($ClNO_3$) and Hydrochloric Acid (HCL), both of which do not react with ozone (Brühl et al 1992). The Earth's atmosphere assimilates ozone depletion to a certain level in the process of continuous production and destruction of ozone in the atmosphere.

Third, the process matters for the environmental efficiency of a product and hence the whole process of the product interface with the environment needs to be studied in order to gauge the environmental impact of a product. To appreciate the environmental impact of the foam insulation of an external tank of the Space Shuttle, the emission of the ozone depleter, the Chlorofluorocarbon (CFC-11) blowing agent applied in the formation of the foam during the manufacturing, in addition to the atmospheric changes caused by the carbon monoxide produced during the re-entry burn of the thousands of kilograms of polyurethane-type foam per flight, should be evaluated.

The first issue has an insurmountable limit and, since the problem goes beyond our knowledge, this has been accepted as a devil's requirement in the process of the development of technology. As for the second and third issues, these could be somehow manageable. For the second issue, we can measure the outcome of undesirable performance, such as nitric oxide and Aluminium Oxide (Al_2O_3) particles, in order to differentiate the product technology rather than measuring the problematic results of ozone depletion. The third issue, however, is not the most critical problem since we can study anyway the whole process of environmental impact.

For the property study, not all the properties of a product will be studied, but some key aspects, which are indispensable to describe the technology change for a future launch vehicle, are studied.

3.4.2 Space Transportation System Technology

As discussed in the previous paragraph, firstly, investigations are made into the functional aspect of the STS technology, from both the anthropocentric and physiocentric viewpoints. Secondly, a study is made of the structural aspects of the product technology. Here we will review STS technology based on the trilateral approach to induce a framework to describe technology change for STS.

3.4.2.1 Functional Aspects

Desirable Performance: Anthropocentric View

The theoretical velocity change of a launch vehicle is defined by the function of two factors, the efficiency of the engine and the ratio of the vehicle initial mass to final mass as developed by Tsiolkovsky in 1903. However, the real achievable velocity is reduced by losses resulting from environmental influences on vehicle performance. The following Equation, derived from Tsiolkovsky's Equation, shows the interference of the environment with vehicle performance.

$$\text{Launch Vehicle } \Delta V = g_o I_{sp} \ln \frac{M_i}{M_f} \text{ - Gravity Loss – Drag Loss – Control Loss}$$

Eq. 3-1

I_{sp} is engine specific impulse, M_i is vehicle initial mass and M_f is vehicle final mass, and g_o is gravity constant.

As shown in Eq. 3-1, vehicle performance, the maximum velocity, is a function of the engine performance I_{sp}, the efficiency of the structure expressed by the ratio of the vehicle's initial mass over final mass, the gravity constant and various losses induced by gravity, atmospheric drag and changing the vehicle trajectory. The performance of the vehicle is influenced by environmental factors such as the gravity constant and the atmospheric density.

Specific impulse, I_{sp}, a well known factor to express the efficiency of the performance of an engine, is defined as the number of seconds a kilogram (kg) of propellant will take to produce a kg of thrust. The higher the I_{sp}, the less the propellant needed to propel the launch vehicle to a certain velocity.

The efficiency of the structure, also known as structural index or propellant fraction ratio, is also a key determinant for the acceleration capability of the vehicle.

Undesirable Performance: Physiocentric View

The operation procedures of a launch vehicle include pre-launch operation, launch and ascent flight, and in orbit and reentry operations.

There are no significant environmental issues during the nominal pre-launch operation. Tens of gallons of fresh water are sprayed on the launch platform to dissipate heat and absorb sounding during the initial fuel burn. Most of the water evaporates from the heat of the rocket exhaust, while the remainder would be dispersed by the force of the exhaust gases.

During the launch and ascent flight, sources of environmental disturbance include the expendable stages, the release of the residual propellants from the spent stages, and emissions and energy transferred to the atmosphere. The expendable part of the vehicle drops to the surface and impacts on the surface. Tons of residual propellant in the expendable stage would be forcibly released when the tanks rupture during descent or upon impact with the surface of the ocean (or some remote surface on the Earth). The fuel released during the descent would volatilize quickly while the remainder that reaches the surface would form a surface sheen covering several square kilometers and then evaporate or disperse into the atmosphere. Residual liquid oxygen instantly vaporizes without noticeable consequence (US Army, 2003). A launch vehicle converts the huge amount of chemical energy of the propellant into kinetic energy through a combustion process in order to obtain the desired performance, the acceleration of the launch vehicle. This conversion process is inevitably accompanied by a disturbance to the environment, including changes in the chemical and physical state of the atmosphere. Emissions change the chemical composition of the atmosphere producing greenhouse gas, Carbon Dioxide (CO_2) and ozone-destructive catalytic gases such as Nitric Oxide (NO), Water Molecules (H_2O), and particles including Al_2O_3 and soot. The high velocity with which the launch vehicle passes through the atmosphere also produces undesirable effects, such as noise and formation of Nitric Oxide (NO) behind the strong shock wave. The level of noise differs depending on the type of launch vehicle but it is known that little to no impact to the environment is expected if the launch is performed in a remote area. During orbital insertion and orbital flight, no noticeable environmental impacts have been reported.

During the reentry of reusable vehicles, the strong shock wave produces Nitric Oxide (NO). It is estimated that the Shuttle orbiter produces about nine metric tons of Nitric Oxide (NO) during each reentry (DOT, 1992). Additional Nitric Oxide (NO) may be produced as a by-product of the ablation of the thermal production system. The sonic boom would occur over a large area below the reentry vehicle.

There are two known atmospheric changes caused by emissions of launch vehicles: global warming and ozone depletion. With the former, no noticeable concerns have been reported. The Intergovernmental Panel on Climate Change (IPCC, 1999) report does not include the impact of rocket emissions on greenhouse gases since aviation, which has much more traffic than launchers, is expected to account for only 3 % of the total projected anthropogenic production of greenhouse gases by 2050. Accordingly, rocket emissions would have a negligible greenhouse impact even with a significant increment in the number of flights.

In regard to ozone depletion, according to the World Meteorological Organization (WMO, 1999), the current limited launch activity leads to a small, less than 0.1 %, decrease in global column ozone. However, if the number of launches were to increase, the impact of rockets could not be disregarded. The WMO (2002) predicted that by the year 2050, under certain plausible scenarios, ozone loss due to rockets may become greater than that due to chlorofluorocarbons if the launch activity increases by 60% per decade and the growth rate is realized through Solid Rocket Motors (SRM) and sustained over the next several decades.

As the WMO (2002) predicted, the environmental impact would be a serious issue with the increment in launch activity and hence it can be expected that the technology advancement will take the environmentally friendly path in the long run.

3.4.2.2 Structural Aspect

Structural aspects of the product, including complexity, decomposability and architecture can represent the state of the technology change.

Complexity

Clarke (2000) argued that a possible pattern for the evolutionary process of technological systems was, first, increased complexity, followed by simplification. This pattern might be seen in some launch vehicle development programs.

Design for maximum performance has been a predominant design philosophy for liquid fuelled rocket engines and hence it has become more and more complex. The design and production technology specification is therefore tightly controlled in order to avoid extra weight on the system. There are some cases of simplification. The design goal of the RS-68 engine which powers the Evolved Expendable Launch Vehicle (EELV) Delta IV is to lower development and production cost. The design process for the engine was therefore totally different from that for past rocket engine development. All the design trades were based on cost, resulting in a drastic reduction in the total number of parts compared to other engines of equivalent size or performance. The LE-7A and LE-5B rocket engines for the H-IIA Launcher also reduce complexity by reducing system components and plumbing in the H-IIA (Maemura et al. 2002).

The growth pattern of complexity could show the state of technology evolution from the viewpoint of the structural aspects.

Decomposability

The modular concept design is a typical design wisdom that benefits from decomposability. For launch vehicles, the modular conception is not well developed. The Space Shuttle, which was built with 1970s technology, with its lack of modular conception design, suffers from high maintenance costs as well as non-flexibility in the system upgrade.

It is only in very recent years that the conception of modularity in the launch vehicle area has been discussed. Medvedev et al (2002) asserted that practical realization of the modular concept, as well as an introduction of reusability for separate stages (modules) of STS, was one of the most promising ways for enhancing operational capabilities and reducing costs for current and future advanced STS. The proposed launch vehicle, Angara, adapts the modular concept for its first stage Universal Rocket Module (URM-1) to be mated with two different variants including the ‘Rockot’ launch vehicle derived ‘Breeze-KM’ and the newly developed Universal Rocket Module (URM-2) second stage. The design parameters of the URM-1, including diameter 2.9m, length 25.1m, propellant mass ~120 ton and main engine 200 ton thrust, are the result of an in-depth tradeoff to provide a robust solution over a wide range of operation and forecasted international market changes (Medvedev et al, 2002).

If we look at the capability of the first stage of Angara, it might be regarded as a modular conception. Sanchez (1995) argued that modular product architecture provides an important source of strategic flexibility to respond to changing markets and technologies by rapidly creating product variations based on new combinations of new or existing modular components. However, if we look inside each stage, it is more likely to be a series of multi products, rather than a single product having modular architectures, because of both the functional and structural similarity of each stage.

From the technology evolutionary point of view, technology innovation is motivated by the extent to which the product architecture is decomposable or nearly decomposable (Baldwin and Clark, 1997, 2000). There is no reason why the STS technology evolves differently from other complex systems. However, in the early stages of the technology evolution less concern is given to decomposability which would increase the complexity of the launch vehicle. However, as the technology matures, decomposability conceptions, such as the modularity and platform conceptions, would prevail to decrease the complexity of the vehicle. Decomposability of the vehicle would then be a good indicator of technology advancement.

Architecture

As Henderson and Clark (1990) emphasized, architectural innovation disturbed the competitiveness among firms since architectural change of a product destroys the usefulness of the architectural knowledge of incumbents. Architectural innovation not only nullifies the learning and knowledge of the product architecture, as well as organizational learning, but also requires a huge design and verification effort for both the system and any components changed thereof. Hence the consequences of the architectural innovation in the launch industry are more crucial than in any other industry.

As discussed under decomposability, once STS technology is matured, with the emergence of the dominant design, the product architecture would have evolved with increased decomposability, in the form of modularity or platform design.

The modularity or decomposability can be regarded as internal architectural change. There is also external architecture change - the change in the number of stages of the launch vehicle. The STS is exposed to external architectural changes during its technology evolution paths because the current multi stage launch vehicle architecture is an inevitable result of the limits of the product technology. When aspects of the product technology, such as structural index and/or engine efficiency, have evolved enough to remove this constraint, then there are chances for external architectural change to appear, reducing the number of stages of the vehicle.

3.4.2.3 Property

The properties of the launch vehicle which can be best captured by probability or stochastic means, including reliability and reusability are discussed.

Reliability

The failure occurrence for expendable launch vehicles shows a different pattern compared to that of the reusable vehicle which might have a typical bathtub curve pattern of the product reliability with time. The reusable vehicle has a record high failure ratio at the beginning which is then reduced while corrective action is taken on faults revealed in the vehicle due to design and production problems. Once the failure rate has decreased to a certain level then it may remain stable for a certain operational period, converging to the design reliability. As the vehicle gets older in its lifetime then the failure ratio rises again due to increased wearing out of the parts. Proper refurbishment of the vehicle might postpone the start of a wear out failure. The expendable vehicle also shows the same pattern of improvement in the failure ratio from the beginning but does not show a wear out failure phase because each flight occurs with a new vehicle. The expendable vehicle avoids the phenomenon of wear out failure since all flights are virgin flights, but it is not this factor which results in a positive impact on vehicle reliability. All flights made by an expendable launch vehicle are exposed to the same risk of failure due to defective material and workmanship.

For this reason, once the reliability of the expendable vehicle has reached a certain level, it is hard to predict significant improvement in reliability in the long run. From the beginning of the launch vehicle development, design problems are the key reason for the level of vehicle reliability. After clearing design problems, the production problem then becomes the major issue in the poor performance of the vehicle. Even after clearing the production problem there still remains the problem of poor workmanship and defective material. Tight quality control might reduce this deficiency to a certain level but cannot remove it completely.

It is evident that with the advancement of technology, in the components as well as in the system, the launch vehicle has increased its reliability. However, when correlating the reliability with technology advancement, the stages of the product life cycle of the launch vehicle should also be evaluated. For the partially reusable Shuttle, the technology is based on 1970s technology but it is still in the early stage of technology evolution. For the expendable launch vehicle, as it is based on 1960s technology, it is in a matured stage of technology evolution. The reliability of the expendable launcher is comparable to that of the Space Shuttle, but this does not mean that the technology level of the expendable conception is comparable to the reusable conception.

Reusability

In the launch industry, there are only a few cases available to study the property of reusability. The partially reusable Space Shuttle and Pegasus/L1011 launch system are proven technology (Buran might be a reusable vehicle but its maiden flight also became its retirement flight). Hence it is not possible to study the trends in the relationship between technology advancement and reusability based on empirical data.

However, taking the analogy of the aircraft industry and using scientific/engineering rationale, it is fairly predictable that there would be a positive relationship between STS technology and its reusability once the conception is pursued.

Reusability can be determined either as a function of the number of times the main structure is used or the ratio of the refurbishment cost against procurement cost of a new vehicle. If the latter criterion is applied, then the current published Space Shuttle's reusability which is based on the former criteria would be reduced by an order of magnitude.

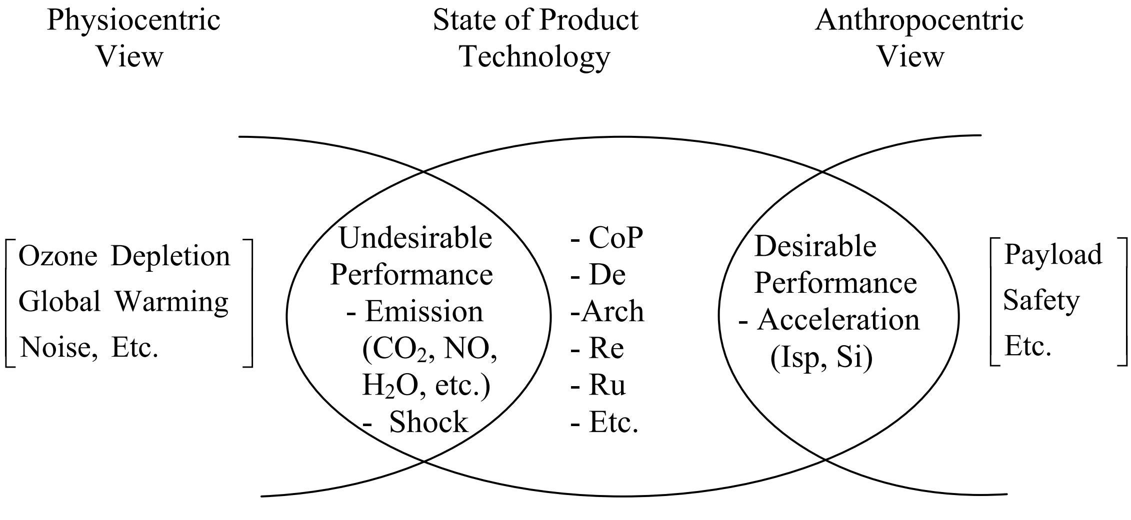
3.5 How to Describe the Change of Product Technology

In a previous section, we adapted a trilateral approach to perceive the product technology, and investigated STS technology based on this approach.

In order to study the framework to describe the change of the product technology, it is more convenient and less problematic as an intermediate procedure, to study the static state of the product technology. The framework to describe the technology change can then be developed based on the static perception of the product technology.

3.5.1 A Framework to Describe Product Technology

Fig. 3-3 shows our perception of the static state of product technology customized to STS technology based on the trilateral approach.



Legends: CoP - Complexity, De - Decomposability, Arch - Architecture, Re - Reliability, Ru – Reusability, Isp – Engine Specific Impulse, Si - Structural Index

Fig. 3-3 Static State of Space Transportation System Technology

Desirable performance, accelerating the vehicle to yield the service (delivery of the payload to orbit), can be measured by the efficiency of the engine and vehicle structure. Undesirable performance, emissions and shock to yield disservice such as depletion of the ozone or global warming, can be indirectly measured through the gas emitted. Structural aspects, such as complexity, decomposability and architecture, as well as property, including reusability and reliability, are incorporated as important factors to measure the product technology.

The ellipse in the figure does not mean the physical product but represents the conceptualized state of the product technology. The three parts are separated according to the types of factors which are recognizable through different views of the same object. Hence, physically, any one of these factors represents the whole nature of the product and the values of the factors are mutually affected. For example, desirable and undesirable performance present a dichotomy in meaning but this does not mean that these two factors are mutually independent since they come from the same internal structure of the product. A high performance airbreathing engine can be obtained by increasing the chamber pressure and the temperature of combustion at the cost of increased Nitric Oxide (NO) emissions, and a high performance structural efficiency increases the desired performance of the vehicle concurrently reducing the fuel requirement to accelerate the vehicle and so also reduces emissions.

Reliability and safety are closely related notions but differ in that reliability can be expressed by the percentage of times that the vehicle transports passengers or cargo successfully, while safety describes how safe the vehicle and/or passenger or payload, and any third party, is. An operation configuration enabling high abort capability or a product configuration introducing a crew escape system can improve the safety of the crew but not the vehicle reliability.

3.5.2 A Framework to Describe Product Technology Change

In the previous section, we elicited a framework to describe the static state of STS technology. This elegant framework includes factors which are representative of the multifaceted nature of the product technology.

We can develop a framework to describe the technology change using the static framework. However, it would then be too complicated since the static framework itself is already relatively complicated.

We need a less complicated framework but one which is informative enough to capture the streamlining of the technology change and which is applicable to both existing and future technology.

To construct a simple and easily comprehensible framework, topology can be used since this can be directly appealing to human intuition. By introducing appropriate topology, the intangible notion of product technology change can be mapped into the conceptual evolution space to produce sensible topology.

Some scholars use topology to explain technology evolutionary paths. Among them, Nelson and Winter's (1977) notion of natural trajectory depicts a technology trajectory in the characteristic space. Sahal (1981, 1985b) introduced technological guideposts and further developed the notion of the innovation avenue to explain the technology evolution path in relation to socio-economic forces which may alter and guide the path of technology evolution.

In addition to the use of topologies to explain the direction of the technology evolution path, there are scholars who use topologies to describe product technology change. Among them, the tradeoff surface of Knight (1963), which introduced a two dimensional tradeoff curve for digital computers, might be the earliest work, followed by Dodson (1970, 1985) who further developed the tradeoff surface to State of the Art (SOA) defined by physical and performance characteristics to measure technological advances.

3.5.2.1 Evolution Space

For the topology of technology change a Cartesian evolution space is presented, each axis of which represents key factors of the launch vehicle technology. The selection of the key factors is based on the factors as developed in the static framework. However the number of these factors which constitute the evolution space should be restricted to three because of the limits of human perception of visualized space.

Key Factors

The STS becomes a space transportation system as it transports the payload to space. To reach space is not highly demanding but staying there is highly demanding because of the high delta velocity required to balance the force of gravity with the centrifugal force of the vehicle to keep it in space. Hence the acceleration capability is the primary characteristic that should be kept in most launch vehicles.

The Rocket equation (a.n.a. Tsiolkovsky equation) defined the velocity of a rocket as the function of two factors: the engine efficiency, represented by specific impulse, and the ratio of rocket initial mass to final mass, the so-called structural index. Because of the extremely high velocity requirements to attain orbital velocity, rocket designers have struggled to improve these two factors. Hence the design heuristics, 'maximum performance and minimum weight' have become the prevailing norm in the launch vehicle industry for the past half-century. Here, Propellant Mass Fraction (P_f) = 1 – (Vehicle Final Mass (M_f) /Vehicle Initial Mass (M_i))

Fig. 3-4 shows the performance characteristics of existing product technology. The line in the figure shows Propellant Fraction-Engine Isp Threshold line for Two Stage To Orbit (TSTO) and Single Stage To Orbit (SSTO) conceptions, and the marked position shows the state of technology for launch vehicles to date.

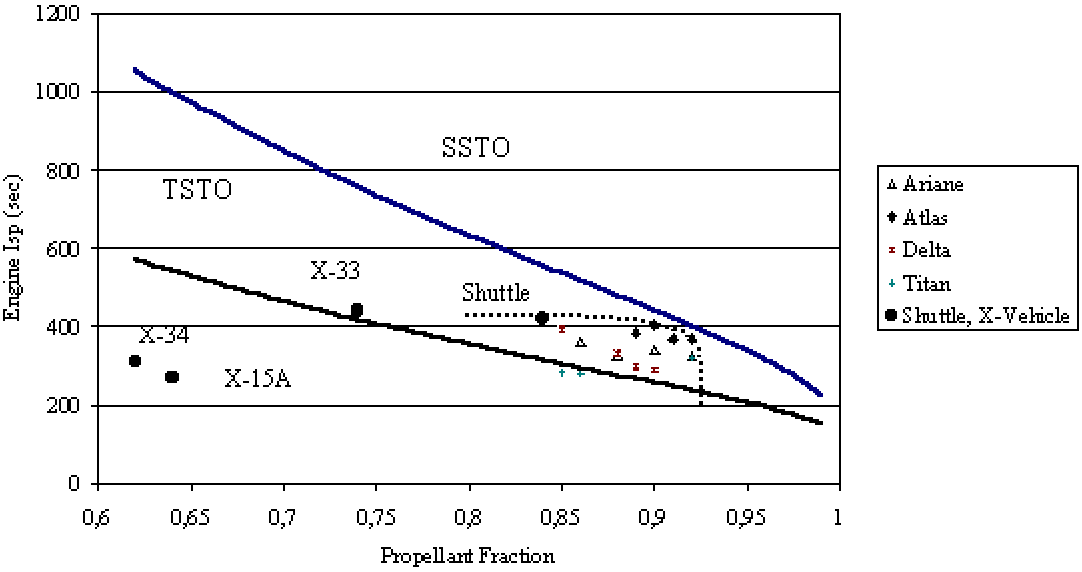


Fig. 3-4 Technology Frontier of Launch Vehicle

The launch vehicle data shown in the figure are hypothetically reconstructed values that are based on real data and apply simple assumptions such as the propellant fraction ratio of each stage is the same and the engine Isp remains constant during the whole flight envelope.[24]

The section marked SSTO means any combination of Isp and Propellant fraction in this region is sufficient to develop a single stage vehicle to carry its payload to orbit and is therefore definitely sufficient as well for Three Stage To Orbit (3STO) vehicles. Similarly, the TSTO region is sufficient for all stage options except SSTO. However, more than three stages are not desirable because of the increasing complexity of the vehicle and the decreasing benefit obtainable by adding extra stages.

The dotted line in the figure represents the technology frontier for launch vehicle technology, which is about 400 seconds for its engine performance and about 92 % of its propellant fraction. The propellant fraction is a function of vehicle initial mass and final mass.

In Fig. 3-4, the expendable launch vehicles are well grouped near the Technology frontier. However, the partially reusable or fully reusable winged launch vehicles, including Space Shuttle, X-15A, X-33 and X-34 are scattered in this characteristics field and appear far less efficient in their structural index, as compared to the axis of propellant fraction, because of the heavy wing structure, thermal production system and landing gear.

Since the two factors, Engine Isp and Fuel Fraction induce the same performance, i.e. accelerate the vehicle to a serviceable velocity, we can introduce a new factor (ξ) which combines these two factors to represent a single stage equivalent delta velocity of the vehicle, i.e. an achievable velocity of a hypothetical single stage vehicle based on the in situ engine technology and structural technology. This is similar to Sahal's holistic approach using the dimensionless variables, but here the variable keeps the dimension. In Eq. 3-2, g_o denotes gravity constant, I_{sp} means engine specific impulse and Pf means propellant mass fraction.

$$\xi = g_o I_{sp} \ln(P_f - 1)$$

Eq. 3-2

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[24] The calculation of threshold Isp and propellant fraction includes a velocity margin to compensate for velocity loss due to gravity, drag, thrust and steering loss, and a 1.5 to 2 % propellant margin for residual and contingency margin. Mass data is from http://www.astronautix.com, viewed on 28 September, 2004.

We can select the remaining two factors to construe evolutional space.

The reliability of a space system is always high priority in the design because of the inaccessibility of the faulty product to repair. For a launch vehicle, especially for manned missions, reliability can never be over emphasized because any failure of the vehicle means loss of human lives and huge long lasting impacts on space activities, as evidenced by the two former Shuttle failures. For the future RLV in particular, reliability would be a good barometer to differentiate the level of the technology since there are strong market forces to lead the technology evolution toward increased reliability, such as high cost payload and public space travel, etc.

However, when using this factor to evaluate a technology, caution should be taken. If we compare heterogeneous launch vehicle technologies that are in different stages of the technology evolution path then it would be problematic. The reliability of an expendable launch vehicle, such as Soyuz, can be comparable to the partially reusable Space Shuttle, but this does not mean that the expendable launch vehicle conception has reliability comparable to that of the reusable launch vehicle conception. For a comparison of reliability therefore, the state of evolution of the competing technology should also be contemplated and could then act as a good barometer to compare the technology advancement of the competing technologies.

The reusability of a vehicle will be one of the most important properties for future launch vehicles with its potential to make synergetic improvements in vehicle reliability as well as reduce launch cost. Without this factor, the evaluation of the technology advancement of the launch vehicle may be misleading. As shown in the Fig. 3-4, the reusable winged vehicles, X-34 and Shuttle, acquire new characteristics – reusability - at the cost of increased structural index, i.e. degrading propellant mass fraction.

Accordingly, three key technology factors - performance, reusability and reliability - are selected for the three axes of a Cartesian coordination system to represent the evolution space of the STS.

Further Factors

Undesirable performance factors, such as the ozone depletion impact caused by the launch vehicle operation become more serious as space activity increases (WMO: 2002, Ross and Zittel: 2000). It is reasonable to expect that the technology would evolve in such a way as to reduce the environmental impact, such as the ozone depletion impact. Therefore, it is desirable to consider the environmental efficiency, especially for the ozone depletion impact, as a factor in indicating the change of the product technology. However, measurement of the environmental impact is not straightforward because of the externality of the environmental change of the earth system and the assimilation capability of the earth system. The measurement of the emission of the disturbing substance might be a good alternative to gauge the environmental impact; however, it would require more study to develop such measurement methodology. Moreover, such a study falls within another discipline and is far beyond the scope of this present study. Hence, in this study, this issue will be left as an open question for further study but with recognition of the importance of the environmental efficiency factor for the evaluation of future STS technology change.

Structural aspects, such as complexity, decomposability and architecture are not contemplated as factors to construe the evolutionary axis, not because they do not reflect the technology change but because of the intractability in measuring the magnitude of the change.

3.5.2.2 Topology for Space Transportation System Technology Change

Fig. 3-5 illustrates conceptual trajectories of STS technology change in the evolutionary space. The x-axis represents reusability of the vehicle in lognormal value of the number of flights. The y-axis represents reliability of the vehicle in lognormal value of the mean number of launches to failure for a RLV and the mean number of launches between failures for expendable launch vehicles. The z-axis represents the single stage equivalent delta velocity of the vehicle.

The z value of the upper plane denotes threshold velocity for an SSTO vehicle. The z value of the lower plane denotes threshold velocity for a TSTO vehicle. The curved bold-lined arrow in the center of the figure shows the technology evolution trend for the reusable concept. The three curved, broken-lined arrows represent projection of the bold line arrow to three reference planes: X-Y plane, Y-Z plane and X-Z plane. The reliability for the expendable conception would be an asymptotic pattern according to historical data (FAA, 2002a).

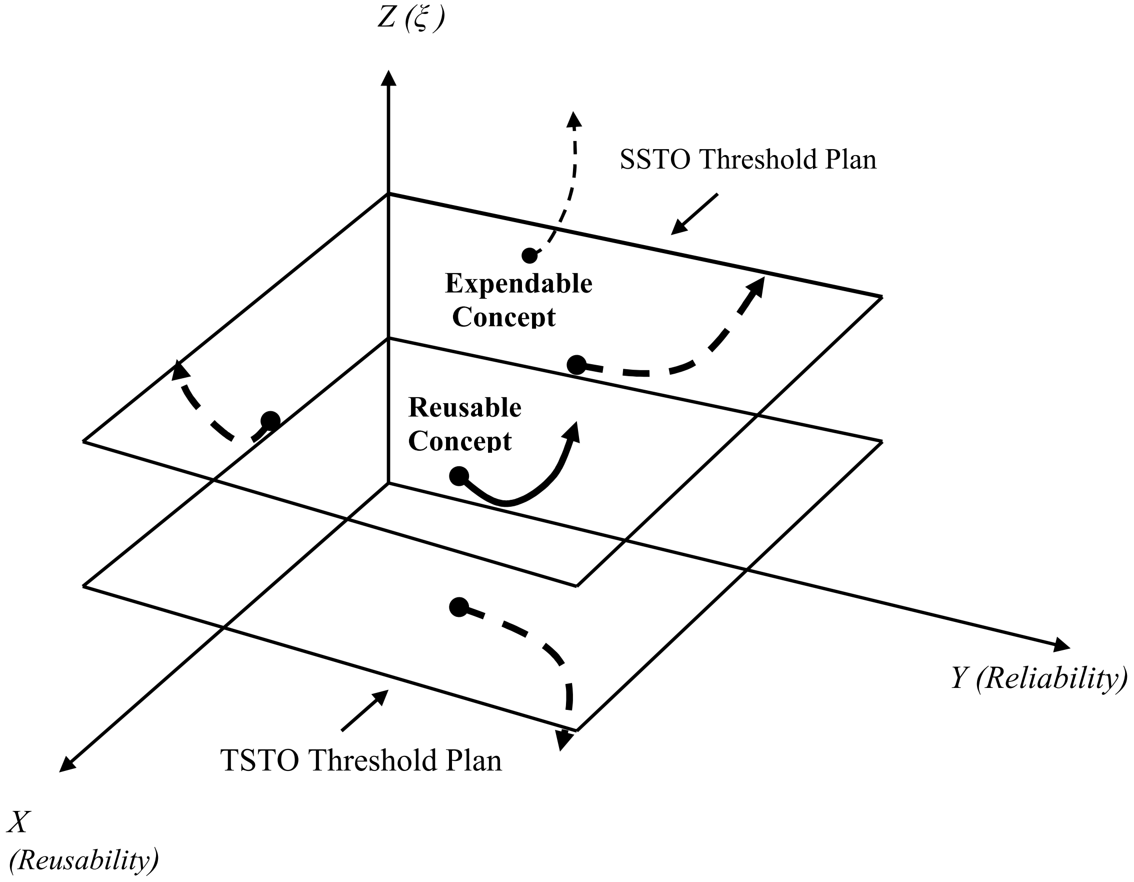

Fig. 3-5 Conceptual Space Transportation System Evolutionary Trajectory

The same can be true for RLVs by analogy with historical data from other transportation systems such as aircraft[25] (Boeing 2002). The evolution of engine and structural efficiency (ξ) for a technology option and reusability could also have the asymptotic pattern as this is the most common technology evolution pattern, known as S-curve theory.

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[25] The reliability of each generation of the commercial jet aircraft represented by hull loss and fatal accident rate have been improved but the improvement slowed down as the third and fourth generation show negligible differences. (Hull loss means any airplane damage that is too substantial to be repaired economically and fatal accidents are those that result in fatal injury, which results in death within 30 days as a result of the accident.)

The highest positioned curved broken-lined arrow shows the technology evolution trend for the expendable concept. The reliability of improvements in the expendable launch vehicle is restrictive compared to that of the reusable concept because of the peculiarity that each flight is the virgin flight of each production, and technology advancement in the design reliability of the vehicle can be eroded by poor workmanship and defective material occurring during the production process.

For the reusable launch vehicle, as shown in the partially reusable Space Shuttle, the value of the ξ is lower than for expendable concepts. This is not because the technology adapted is inferior to that of the expendable concept but because of the degradation of the structural index due to the heavy recovery system involving wings, landing gear and the thermal production system. However, the reusable concept could benefit from the synergy effect between reusability and reliability. The higher the reusability, the higher the reliability would be. Once the initial flight is successful, reliability can then be accumulated through the number of flights of the vehicle which are free from poor workmanship or defective material. There might be poor workmanship or defective material during the refurbishment or repair of the vehicle, but these might be trivial when compared to those that could happen during the manufacture of the whole vehicle.

The suborbital conception is not shown in the figure since it is not an orbital launch vehicle. However, since it also could evolve to become an orbital launch vehicle, it is worth mentioning. It might have the same evolution pattern as that of the reusable launch vehicle but it would have a higher value in reusability as well as reliability with its airplane like structure, as shown by StarShipOne and X-15. The main advantage of the suborbital conception is that it is not susceptible to the threshold velocity because the vehicle does not need to have a multi stage configuration to accelerate the payload to orbital velocity. Hence, it can be designed to have a robust configuration which is less susceptible to architectural change during the technology evolution.

3.6 Conclusions

Product technology is a very slippery notion and so it is very hard to master. To capture the notion, we started our investigation from the bottom, articulating the root of product technology, the formation and manifestation process of the product technology, rather than starting from surface of the product technology.

Based on this articulation, we divided the formation and manifestation process into three stages to capture technology change, and induced theoretically possible methodology and criteria to gauge technology change in each stage, including production function study with the input efficiency criterion in the technology formation process, static and statistic study with form and property criteria respectively in the embodied stage, and characteristics study with the functional criterion of both anthropocentric and physiocentric views in the manifestation stage.

The literature survey showed that existing methodologies are well matched with the presupposed theoretically possible methodologies. However, there are some methodologies that are presupposed but not well recognized in existing methodologies including the physiocentric view on the characteristics study and statistical study for property criterion. We analyzed two possible causes to which these discrepancies could be attributed.

In the past, in the cowboy economy, where the reservoir to extract and pollute is unlimited, there are no inducing forces to decrease dysfunction of the technology, to decrease environmental impact, and to increase the reusability of the product to save the resources. Therefore these factors could not gauge the technology change in the past. However, in the future, in the spaceship economy, these factors become more important in developing product technology. Therefore, for those who study future technology evolution, these factors become an indispensable barometer to gauge the product technology change.

Some properties, such as reliability, are not totally missing in existing characteristic studies, but they are supposed to be conceived as service characteristics.

Based on our study for the theoretically possible methodologies to capture the technology change and our review of the existing methodologies, we concluded that any new or existing methodology which gauges a single aspect of technology could not appropriately capture technology change which has a multifaceted nature. We therefore proposed a trilateral approach including functional aspect, structural aspect and property of the product to capture the product technology.

To develop a framework to describe technology change, as an intermediate process, we developed a framework to define the static state of Space Transportation System (STS) technology based on the review of the STS technology using the trilateral approach.

Finally, a framework of evolutionary space was developed consisting of a Cartesian coordination, each axis of which represents the key factors of:

(i) engine performance and structural efficiency,

(ii) reusability, and

(iii) reliability, which have been selected from a framework describing the static state of STS technology to show the topology of the trend of the technology change of the space.

The factors representing the physiocentric view are missing in the framework, not because they are unimportant but because of the intractability in developing a single unit of measurement to represent environmental efficiency and because a study of these factors would require the involvement of another discipline with which this study is not familiar. The issue is therefore left open with an acknowledgement of the need for a separate study on the environmental impact of STS technology for any tradeoff purposes. The structural aspects are also not included in the proposed framework because of the intractability in inducing any single dimension barometer to represent these aspects such as complexity, decomposability and architecture of the product.

The framework to capture the static and dynamic nature of the product technology is peculiar to space transportation systems. However, the methodology used to conceptualize the product technology, such as the trilateral approach can also be applicable to the study of other product technologies.

In the following Chapter, the major theme, how to trade off the technology evolution paths, will be analyzed based on the conception of the space transportation technology investigated in this Chapter.

Chapter 4

Tradeoff for the Evolutionary Paths of the Space Transportation System Technology: *How to Predict the Paths and How to Evaluate Their Plausibility*

> *When one generation selects a technology option today, it not only means making a selection for that generation but it also means making a selection for future generations since technology is path dependent.*

When launching a multi-billion dollar Space Transportation System (STS) development program, it is usual to study the cost and benefit of the specific technology option to be selected. However, there is also a common lack of consideration for the plausibility of the technology path which will emerge since there is no known immediate motivation for such consideration and there is no well known methodology which would make such consideration feasible.

Our study will focus on the second issue, 'how to trade off technology evolutionary paths,' since the motivation is dependant on the degree of willingness of the current generation to sacrifice their immediate interest for the sake of the next generation's potential interest and, although the interests of both generations conflict, the concerns are more ethical than economic.

4.1 Introduction

In the previous chapters, we looked at the background knowledge for both the market and the technology for Space Transportation System (STS). This background knowledge is necessary to examine the main theme of our study, 'how to trade off technology evolutionary paths,' and will provide us with a tool to tackle the main argument of the study, 'what is the efficiency of the U.S. reusable launch vehicle technology evolutionary paths?', which will be investigated through a case study in the following chapter.

There are a number of methodologies for technological forecasting to predict the future. However, it is still a problematic task to predict future technology change because of the inherent nature of the technology evolution process which is full of uncertain endogenous and exogenous factors, and the interaction of these two factors during the technology evolutionary process make it an even more intractable task to predict what future technology will unfold.

In this study, we do not intend to predict what the future evolutionary path will be. Instead, we will seek to answer the question of what the future evolutionary paths should be, what methodology can be used to construct feasible evolutionary paths, and how to select plausible paths from among them.

In order to attain the objective, we will first study the literature on existing methodologies for technology forecasting and forecasting technology path to learn where the boundary of the existing methodology lies and to get insights which will enable us to construct a feasible technology path for the study.

Secondly, we will develop a methodology, the so called 'Exogenous Factor Impact Free Evolutionary Hierarchical Tree' methodology, to construct physically possible technology paths.

Thirdly, we will develop sustainable technology evolution paths by screening out these paths from the other possible paths taking account of the exogenous factors. Finally, we will trade off the plausibility of the technology evolutionary paths for STS.

4.2 Backgrounds

Why trade off the technology evolutionary paths? The answer is not simple but rather straightforward. First, space transportation system technology evolution is path dependent; second, any rupture or change of the technology path has a serious economic impact on the launch industry; and third, the space launch arena still has a hand in selecting a path and hence it is of more than academic interest to investigate the methodology for trading off technology evolutionary paths.

Firstly, technology evolution is path dependent (Arthur: 1983, David: 1985). The original concept of path dependency, as introduced by Arthur and David, is to explain the sub-optimal lock phenomenon on technology due to the externality of the technology evolution: increased return, irreversibility due to customer learning and habituation which is initiated by temporally remote events, including domination by chance elements rather than systematic intervention. As seen in the QWERTY case, the array of the keyboard is the result of trial and error searching for a typebar array to minimize kinks in the typebar, since one strikes keys the bars of which are nearby in a rapid manner, it frequently clashes and jams. However, once the users are accustomed to the array of the keyboard then it is difficult to adapt to new array even if the new array offers superior ergonomics. Through the introduction of ball typing technology and the electronic type machine, it is feasible to design the keyboard array in consideration of ergonomics without the concerns of the kinking problem. Here, the path dependence is maintained by human behaviour rather than by the technology itself. Since the mechanical bar is removed from the typewriter, there is no technological reasoning for the QWERTY array except to show the history of the technology evolution of the artifact, like a vestige in an organic system. Later, the conception of path dependence expanded to include the path dependency of the technology itself. The complex system has strong path dependence arising from the endogenous factors of the technology, both the product technology and the organizational integrity of the technology. Complex systems, as the knowledge intensive area provided more opportunities for learning and positive feedback, offered major contributions for path dependency (Arthur, 1994). Rycroft and Kash (2002) argued the technology design of a complex system also induces path dependence. Complex technologies are characterized as complementary - that is, any single technological component or subsystem is dependent upon the availability of other technologies that can be connected or integrated. Hence, the complementary relationship is an obstacle to embarking on a different technological trajectory and therefore induces the major source of path dependency (Rycroft and Kash, 2002). Space systems demonstrate a culmination of the path dependence of the product technology since the path dependency of the system flows down to component level by means of space proven components' heritage control.

Secondly, rupture or changes in the technology paths cause serious damage to the evolutionary process of the industry, accompanied by huge social costs. It is therefore never too early to investigate the sustainability of technology evolutionary paths because, should the evolutionary paths of technology be ruptured in any way, including through institutional intervention, it might result in the unexpected discovery of the dysfunction of a product or a sudden policy change. For example, President Bush's political initiative, the "Vision for US space Exploration - human and robotic missions to Moon, Mars and beyond (Vision for Space Exploration)" announced in January 2004, [26]changed the main stream for STS technology development from Reusable Launch Vehicle (RLV) conceptions to expendable heavy launchers to carry Crew Exploration Vehicles (CEV). If this stream continues, then it could change the path totally and, once it happens, it would then be too costly for the launch industry to rebuild the lost path as the disruption of the path nullifies the existing investment as well as all the accumulated knowledge and learning in the industry. In the worst case, it can prevent any recouping of the industry, even with costly restoration efforts as was experienced by two allied nations in their aircraft industries when the industry and the technology evolution thereof was ruined for political reasons after the second world war.

Thirdly, even if there are good reasons for the tradeoff of evolution paths, if there are no means to intentionally intervene in the evolution of the technology path then no meaningful contribution can be expected from studying which path is the most plausible. There are possibilities to intentionally select the path as Hobday (1998) explained in his theory of Complex Products and Systems (CoPS): unlikely to use commodity goods, users will become directly involved in R&D and product design, leading to 'user push' or 'demand driven' innovation. Space technology, especially space launch system technology, is highly politically

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[26] The main stream of government policy for space transportation systems has moved from reusable to expendable concepts - Heavy Expendable and Crew Exploration Vehicles. This might erode learning and investment already made in the area of reusable launch vehicles in the USA. The new US space policy, introduced in January 2005, leaves open the possibility for the development of a reusable launch vehicle. However, in practical terms, budget constraints preclude any full-scale reusable launch vehicle programs since these would require significant investment and it is skeptical whether the limited government funds for NASA could support the pursuit of two full-scale developments for launch vehicle programs.

sensitive. When a country develops a launch vehicle, it can be understood that the country has more than just the launch capability for a satellite. Three days after the first satellite Sputnik was launched into space, the Guardian (7 Oct. 1965) pointed out that, "the Russians can now build ballistic missiles capable of hitting any chosen target anywhere in the world,” (qtd. Harford, 2000). That is still true for launch technology, i.e. it is a dual use technology. In most space faring countries, government is the main actor in the evolutionary process of the technology since government is usually the founder of the technology development as well as the major consumer of the technology. Hence, launch technology evolution is intentionally designable through national space transportation policy in general or through a specific national space project.

Once a tool for the tradeoff of the technology evolutionary paths is developed, then it could be used to evaluate the efficiency of the historical evolutionary path of STS technology, as in the following chapter, or it could be used as a reference for the decision making process for future STS development programs. Either way, it would be possible to induce fruitful dialogue in the launch industry during the decision making process on future STS which is essential for the sustainable development of the launch industry.

4.3 Literature Study: Technology Forecasting and Forecasting Technology Paths

A number of students and practitioners have studied technology change but no agreement has yet been reached on whether technology change is predictable. It may be impractical to expect a unified view on this issue since the facts are matters of subjective.

4.3.1 Predictability of Technology

Some scholars have explicitly or implicitly discussed the predictability of technology change. Dosi (1984) doubted the predictability of the technology path *ex ante*. He argued that the possibility to compare and assess the superiority of one technological path over another is, a priori, doubtful given the innate uncertain nature of research activity, even leaving aside the market evaluation of the result. Rosenberg acknowledged the importance of the expectation but was skeptical about the predictability. As he stated, “since the technological future is, inevitably, shrouded in uncertainty, it is not surprising that different entrepreneurs hold different expectations" (Rosenberg 1976, p 523). The Intergovernmental Panel on Climate Change (IPCC) concluded that it is inappropriate to develop a model to predict technological change because of the uncertain nature of the process of technical change stemming from lack of knowledge on the outcome of cutting edge research and the complexity of institutional influence on the change (IPCC, 2000).

Samuelson (1965) recognized the existence of pay dirt[27] where the scientists sought innovation and hence denied the randomness of the innovation. Nelson and Winter (1977) perceived technology evolution as stochastic and established the conception of natural trajectory lead by institutional structure for innovation. Nelson and Winter are in some way admitting predictability as they argue that "if natural trajectory exists, following these may be a good strategy" (Nelson and Winter, 1977: 56). Sahal (1985b) has mixed views on the predictability. On the negative side, "chance determines which amongst many innovation avenues will be chosen in the course of development," and, on the positive side, "once the development is well along a certain innovation avenue, necessity prevails until another point connecting other innovation avenue is reached." He also introduced the conception of the momentum of technology which might infer some predictability of the technology.

Practitioners of TRIZ have a bolder attitude toward the predictability of technology change. They developed TRIZ Technology Forecasting (TF) methodology to predict and direct the evolution of technology *ex ante*. TRIZ TF is based on an ontology view as expressed in the axiom "the evolution of technical systems is governed by objective laws." But although they refer to this as an axiom, it is not well recognized yet by other students who study evolutionary economics in technology innovation. However, their approach expands the file of knowledge needed to handle the intractable subject of how to predict and direct technology evolution.

Predicting the future is similar to looking ahead in the dark under faint illumination. Similar to physical light, the light illuminating the future decreases its luminosity with increased temporal distance, just as the luminosity of physical light diminishes with an increase in spatial distance. Hence, one cannot discern the shape of the future if the light is too far beyond our reach. The adequacy of the luminosity also depends on the desire of the observer,

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[27] Samuelson's (1965) metaphor 'pay dirt' perceived a certain line of invention which scientists conceived as high as possible to get breakthroughs, choosing to pursue this area over other areas.

i.e., the luminosity might not be enough to read the characters of a book but it may be enough to discern whether the object is a book or a newspaper. Therefore if one was curious as to whether the future outcome would be a book or newspaper, one might say that the future is predictable. However, for those who would like to know the content of the book or the newspaper, then one might say it is unpredictable, even under the same luminosity

The argument surrounding the predictability of technology evolution is rooted in the world of metaphysics rather than science. We need to discuss the predictability of the knowledge creation from which the technology emerges and the social system within which the knowledge grows. These are matters concerning the free will of human beings, humans and society, determinism and free will or predictability and determinism, etc. However, the study of any of these subjects falls into a very different domain from the disciplines of the current study.

In reality, there are concrete interests in forecasting the future and hence a number of scholars as well as practitioners have developed and used methodologies and tools for technological forecasting. It is more pragmatic for this study to get insights from the disciplines for technological forecasting rather than searching for metaphysical answers to the root query. The term ‘technological forecasting’ has a broad meaning - a systematic way to predict the future in terms of anthropocentric and physiocentric change. Here, we narrow the focus of the study on the technology change, i.e. technology forecasting, and further focus in on forecasting the technology path.

4.3.2 Technology Forecasting

There are many methodologies to predict technology change. However, there are few with a baseline rationale, among them, human insight, wisdom of history, analogy and the morphology approach.

Human Insight

Delphi uses human insight, genius forecasting (Lenz: 1962, qtd. Ayres 1969) or the intuitive method (Ayres, 1969) to predict complicated technology change. Delphi is one of the most popular methodologies to be used for technological forecasting (Martino, 2003). The core of the Delphi methodology is that it relies upon human judgment of the technology change, similar to obtaining an expert opinion but with appropriate manipulation of the consulting process to minimize 'individual bias', and avoid "follow the leader or social compromise" (Wills, 1972) or the "extremely conservative trend" (Ayres, 1969) of the nominal committee approach. The method draws on a consensus opinion of expert panel members through repeated rounds of questioning to the panel members while incorporating feedback from earlier rounds of responses. Criticism also exists since there might be a lack of coherence in the resolution as the process of each individual judgment is in a black book. Some outcomes of the Delphi method could be self-exclusive (Patton and Sawicki, 1993) and there may be non-homogeneity in the level of expertise of the panel members but all have equal voting rights (Wills, 1972). Dransfeld et al. (2000) solved the problem of equal voting rights by introducing Bayesian weighting when combining responses to a Delphi questionnaire (qtd. Martino, 2003).

The Delphi method does not direct the process or ask any rationale for answers which could be the consequence of a belief, guessing, or a simplified adaptation of the other forecasting methodologies such as extrapolation, analogy, etc. There is therefore no homogeneity in the decision process amongst the panel members and hence it is just substituting the evident intractability of the forecasting with vague individual conjecture or beliefs rather than solving the intractable problem.

Wisdom of History

Wisdom of history means learning from history. One can rely upon the wisdom of history using the pattern of past technology change to predict future change. It is common to use past experience to guide future expectations (Ayres, 1969). Trend extrapolation is one of the typical methodologies - getting clues from the history of technology evolution. The S-curve approach is the most common application of this methodology. The S-curve approach uses the curve fitting methodology combined with insight into the exponential growth law of social and/or technological progress (Adams: 1958, Price: 1966, qtd. from Ayres 1969). Eventually the exponential phase of growth comes to an end due to saturation or imposition of constraints (Ridenour: 1951, Price: 1966, Holton: 1962, qtd. Ayres, 1969).

Moore’s law (1965), ‘the doubling of transistors every couple of years,’ has become a legend in the field of technology forecasting, especially for application of the extrapolation method. Moore’s law has fascinated practitioners in this field with its simplicity in expression and extraordinarily long endurance in time for a prediction with extraordinarily high accuracy. Originally he expected it to last for only one decade. However, surprisingly, the prediction is still valid 40 years later at the beginning of the 21st century and there is wide consensus that Moore’s law will last through to the end of this decade. However, criticism of Moore’s law also exists. Tuomi (2002) in ‘The Lives and Death of Moore’s Law’ pointed out that the empirical evidence of the last decades did not support Moore’s law. Tuomi (2002) argued that the prediction is the result of linear extrapolation from only five historical data points and is supported by a self-reinforcing phenomenon, as acknowledged in R&D activities of industry, and Moore's law has become a guideline to pursue in order to expedite or delay development. In addition, the law does not describe the technological evolution but only the change in complexity of the circuit itself. However the simplicity of the extrapolation methodology is not the flaw which weakens the methodology but the virtue which intensifies the usefulness of the methodology. The methodology washed out detailed quality factors and did not convey information on the complicated technology change mechanism. However, these might be the merits of the methodology rather than its demerits since knowing the mechanism of the technology change is neither a requirement nor a sufficient condition for technology forecasting. In addition, it is too much to expect that a prediction in social scientific law will have the same accuracy as that offered by natural scientific law. In regard to complexity, unless an invention is pursuing Rube Goldberg device[28]-like complexity, in general the more complex a product, the more advanced is its performance. A higher density of components in the circuit does not mean a qualitative technology change in the circuit. Rather, it means a quantitative technology change in product technology, such as the size of the memory, and is accompanied by qualitative technology change in the process technology to narrow the width of the circuit. The self-reinforcing phenomenon might contribute to the success of Moore’s prediction but it could not undermine the legend of Moore’s law since the mechanism of technology change is not as straightforward as Tuomi might argue.

Contrary to the Delphi method, this methodology does not need expertise for the technology system being studied, i.e. the forecasting process only needs the stochastic process to fit the

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[28] Accomplishing by extremely complex roundabout means what actually or seemingly could be done simply (adapted from Webster's Third New International Dictionary).

curve. This methodology saves forecasters not only from the effort of understanding and manipulating the intractably complicated technology evolution process, but also from the work involved in comprehending the system itself. S-curve theory is well recognized and utilized in various fields.

Analogy

There are two different types of analogy used for technological forecasting. One can predict a system's evolution by comparing two similar systems, one of which precedes the evolution of the other. Another is studying the regularity of evolutionary patterns by studying a number of known product technologies and applying the resulting pattern to predict the product technology of the unknown product technology being studied. The well-known S-curve and patterns and lines of technology evolution of TRIZ also fall into this category.

Forecasting using the first analogy type is simple to apply but the consequences are tremendous when it is applied appropriately. First of all, we do not need to understand the complicated internal mechanism to apply the methodology. For example, we can easily distinguish an ordinary male mallard from others by its noticeable glossy green head and white collar around the neck. However, it is very difficult to distinguish the sex of a white mallard because both sexes have the same color of feathers and beak - white and yellow. If we look at the ordinary mallard more carefully, then we can easily find another characteristic of the male mallard - the curl of the tail. Therefore, by analogy, one can tell the sex of a white mallard by the existence of a curl in the tail. For the analogy, firstly, we do not need to understand the gene process to determine the phenotype of the mallard, the tail curl. Actually we utilize the secret of the gene process to determine the sex of the white mallard without any understanding or even information on the underlying process. Secondly, we do not need to understand the functional mechanism of the curl to apply the methodology. There might be reasons for the emergence of the morphology of the tail curl of the male mallard, and it might have a particular function. However, we do not need to know these reasons and the function of the curl to predict the sex of a mallard. Assuming these two mallards are similar technology systems evolving in different time frames, then this method offers precise prediction once the appropriate precursor technology is available. However, it is not easy to find a precursor technology, especially in the case of breakthrough technology. Renz (1962) demonstrated that the change in speed trends of combat aircraft preceded that of transport aircraft (qtd. Ayres 1969).

With forecasting using the second analogy type, there are two different scopes of regularity. One is wide scope regularity to be found in most technology, as in the case of the pattern of technology evolution in the S-curve. These wide scope regularities show the quantitative change of the technology evolution but not the qualitative change of the technology. For example, it can show the pattern of increment in maximum velocity of a transportation system but not details of the technology to be incorporated to achieve the maximum velocity. The other regularity is narrow in scope, focussing on a particular technology, as in the line of the technology evolution in TRIZ which shows the qualitative change in a particular technology but from which it is difficult to extract a referable line of technology evolution. Clarke, SR (2000) stipulated over 350 lines of technology evolution which a TRIZ student uses for technology forecasting. S-curve theory and TRIZ Technology Forecasting (TF) will be discussed separately with Natural Trajectory and Innovation Avenue in Paragraph 4.3.3.

Morphology

The term morphology comes from the antique Greek *morphe* meaning shape or form. J. W. von Goethe (1749-1832) first represented morphology as a science (qtd. Steigerwald, 2002: 295). Goethe defined his new science of morphology as “the theory of form [Gestalt], formation [Bildung] and transformation of organic bodies” in his study of botany (qtd. Steigerwald, 2002: 295). Morphological study is widely applied in various disciplines which study form and structure and their transformation, such as in zoology, biology, metallurgy, diagnosis of disease, etc.

It was Zwicky who extended the process of morphological study to solve problems. As he put it, “The morphological method essentially is nothing more than an orderly way of looking at things and the methodology well suited to achieve a schematic perspective over all of the possible solutions of a given large-scale problem” (Zwicky 1948: 121). He applied morphology methodology to the study of astrophysics, for the development of jet and rocket propulsion systems, and to legal aspects of space travel and colonization (qtd. Ritchey 1998: 1). Ayres (1969) noticed that the Morphology method could be applied in the analysis of technological opportunities. Apart from the chance of using the scheme to anticipate actual inventions, there is at least a possibility of parametrically characterizing the optimum configuration for a particular mission or task, and one can devise an order of possible inventions in terms of their relative immediacy. Other things being equal, this exercise is not a forecast, *per se*, but it is useful for the initiation of further predictive activity. It is not surprising to see morphological methodology used in the process of scenario development for future studies since all feasible alternatives should be examined in order to develop robust scenarios, and morphological methodology is well matched to fulfil this requirement (Rhyne, 1995).

In order to avoid ambiguity in the terminology in this study, the Zwicky approach for morphological concept is referred to as 'morphological methodology' which focuses on the logical structural aspect of the morphology study, i.e. the orderly way looking at things. 'Morphology analysis' focuses on the content of the morphology study, i.e. analyzing the interrelationship among forms, formation and transformation of form. These are collectively referred to as the morphology approach.

A number of teachers introduce morphology analysis as a tool for technology forecasting. However, it is rare to hear reports of students who actually use the tool and even in such rare cases it is not used for forecasting technology. Foray (1990) performed a comprehensive morphological analysis of the technology trajectory of ferrous casting technology but this was an analysis of historical technology diffusion in France and Germany. Yoon and Park (2005) searched in a technologically undeveloped area using a morphological analysis of the keywords of patent claims in Thin Film Transistor-Liquid Crystal Display (TFT-LCD) technology. These facts can be understood as being for either one or both of two reasons: the tool is not appropriate to predict the future and/or the students are not well taught in the practical use of the tool. The latter is not evident but the former evidently contributes to the odd phenomenon.

There are innate limits in the morphology approach if one is seeking a complete tool for technology forecasting, i.e. the morphologically possible technology options increase exponentially as the number of elements of technology increases - these hinder the appropriate processing of all possible technology options. This might be a problem for those who use the methodology to forecast technology but it might be helpful for engineers or scientists who intend to screen out promising inventions which have hitherto been overlooked because of the limits of the routine heuristic approach[29] or by focussing on pay dirt areas in the innovation process. Secondly, even if the future technology is within the scope of the technology options predetermined by the morphology method, the morphology method itself would not give any hint as to what individual changes there would be or what the most feasible path would be. In other words, any technology options based on the morphology methodology and the technology paths thereof are indifferent to endogenous as well as exogenous factors. However, this characteristic can offer a good starting point for construing technology evolutionary paths which are independent of endogenous and/or exogenous factors.

The morphology method becomes a powerful tool especially when one has means to filter out the right answer but no means to induce the answer. Suppose that one needs to answer a question on the name of a city. One's memory may not be clear enough for direct recall of the answer; however, there still remains an image of the answer to filter the correct answer when somebody else replies to the question. Suppose the answer is L.A. One can subsequently mechanically build all the possible words using two alphabetical references and then easily filter out what the answer is from all possible combinations of the word. If one has a strong memory to filter out the characters separately, then the first character 'L' can be found on the 12th try and 'A' can be found on the first try, and it may take only a few second to find the answer. If one has a faint memory and hence only recognizes the answer collectively then one can find it on the 287th try by combining two characters - here one might construct the character in an orderly way and it might take few minutes to find the answer.

Similarly, if one does not have enough ability to draw the feasible technology evolution path but has the means for screening it from the candidate paths, then the morphology methodology is a good initiation tool to construct the feasible technology evolution path.

4.3.3 Forecasting Technology Paths

Scholars and practitioners have studied technology evolution, and a stack of knowledge has been accumulated in the field of technology change and prediction of the change. Since we

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[29] Nelson and Winter defined, "heuristic search process as an activity that has a goal, and a set of procedures for identifying , screening, and homing in on promising ways to get to that objective or close to it" (Nelson and Winter, 1977: 52-53).

are intending to study the possible technology evolution paths, the literature study focuses on forecasting methodology which contains the conception of the technology path, such as the S-curve theory, TRIZ TF (Technology Forecasting), theories for technology trajectory, etc. In particular, we will investigate the basic elements which constitute theory or methodology for forecasting technology paths including criteria to perceive the technology change, the source of change, the perceived governing rules or forces for change, the immunity of the governing rules or forces from exogenous factors, and, finally, the mapping methodology used to express the technology evolutionary paths.

S-curve Theory

Originally, S-curve fitting derives from the analogy of population growths in biology – looking at the embryonic growth and mature states - and was then extended to various fields, such as society, technology evolution, etc. The S-curve theory of technology evolution has a long history. Ridenour (1951) was perhaps the first one to look for mechanisms which explain the behaviour of technical trends and noted the exponential nature of the number of potential users of a new product and its finite upper limit (Ayres, 1969: 129). Mansfield (1961) suggested that the representation of temporal evolution for firms that have adapted a technology in an industry approaches a logical growth function, also known as the Pearl function (qtd. Nieto et al., 1998). Ralph Lenz (1962) analyzed technical improvement as biological growth and proposed using Pearl's (1920) formula to describe population growth as a function of time in a limited environment (Ayres, 1969:122-123).

S-curve theory arises by analyzing the technology growth as it follows a phenological model of the growth of yeast cells in a bottle. There are therefore some *post factum* explanations for the exponential increment in the progress, such as the bandwagon effect of the R&D resource allocation (Wills, 1972:109). Hartman (1966) viewed scientific progress in terms of information gain and assumed that the rate of increase of information is proportional to the total amount of information which already exists, to the probability that a scientist encountering a bit of information will react and create a new unit of information, and to the number of scientists (qtd. Ayres, 1969: 129:130).

In the S-curve theory, the technology change can be perceived in a quantitative way by tracing time phase performance increments. Wills (1972) was the one who clearly showed the S-curve fitting phenomenon as applicable to technology progress. He showed two discontinuity S-curves representing the progress of the lumens per watt for two competing homogeneity technologies: incandescent lamps and mercury vapor fluorescent lamps. A number of empirical studies are available for the S-curve in technology evolution, among them Foster (1982, a, b, 1986, a, b, c) and Becker and Speltz (1983, 1986) – (qtd. Nieto et al., 1998). Ayres (1969: 137) reproduced the data set of Acey Floyd (1968) and showed an S-curve shape on the speed trend of vehicles. Here the technology he showed was heterogeneous technology ranging from the Pony express to missiles.

The source of growth change could be group psychological such as the bandwagon effect of the resource allocation, R&D fund (Wills, 1972), the 'gold rush' phenomenon when a new discovery spreads out (Holton, 1962, qtd. Ayres, 1969) or the exponential increase of the research sources, such as researchers, in a new field (Ayres, 1969: 130), or economic returns as Perez and Soete (1988) argued that Wolff's law of diminishing returns on investment in incremental innovation can lead to an S-shape for the degree of technology maturity over time. The predictability of the S-curve theory comes from the common growth patterns of technology evolution, either the diffusion of technology or the increment in technology performance during the lifetime of the product. A typical growth pattern would be the initial learning stage begins, technological performance innovation increases slowly, then accumulated understanding accelerates the increments in technological performance, and finally the technology reaches its performance limit (Nieto et al. 1998). The extrapolation method is used to depict the quantitative change in technology progress from empirical data, *ex post*. On the other hand, the change can be predicted by locating the current technology on the S-curve and then studying the whole S-curve. As S-curve theory originates from the analogy of phenology and was based on empirical technology evolution, the curve is adapted for both endogenous and exogenous factors in technology change. The prediction of the technology change based on the S-curve is therefore supposed to be immune from exogenous change.

TRIZ Technology Forecasting

TRIZ was developed to improve the process of invention as the Russian abbreviation indicates – 'Theory of Inventive Problem Solving.' Genrich Altshuller developed TRIZ in 1946 through analyzing a number of patents (Clarke, SR., 2000) and its application has now been extended to the area of technology forecasting and further as a tool for directed evolution. The philosophical view of TRIZ Technology Forecasting (TF) is regarded as an ontological view since it starts with the axiom that "the evolution of technical system is governed by objective laws." During the evolution of the technical system, improvement of any part of that system, having already reached its pinnacle of functional performance, will lead to conflict with other parts and this conflict will lead to eventual improvement of the less evolved part, and this continuous self-sustaining process pushes the system ever closer to its ideal state (Shulyak, 2004). The methodological background of TRIZ TF is the combination of two disciplines learning from the wisdom of history and analogy since it elicits the reference object laws which govern evolution of the technology system through analyzing patents. The object laws would be patterns or lines of technological system evolution. TRIZ TF can be differentiated from the typical extrapolation as it keeps qualitative information on the technology during the forecasting process while the extrapolation methodology washes out the qualitative factors leaving only the quantitative factors and the shape of the fitted curve. This makes the TRIZ TF method different from other technological forecasting methodologies, linking the forecasting process to the problem solving process, i.e. creating the technology.

The TRIZ TF perceives the technology change in a qualitative way through predicting the evolution of technology options. As Fey and Rivin (1999) stated, the line of evolution for a varifocal lens system should be one rigid glass lens, a two-lens varifocal lens system, a multi-lens varifocal lens system, an elastometric varifocal lens system, a liquid varifocal lens system, a gas varifocal lens system, and a varifocal lens system using various fields. A continuum of potential evolutionary change in technology can be developed by mapping these steps for existing technologies to identify what steps are occupied and what steps remain for exploration (Mann, 2003: 782, Fey and Rivin, 1999: Para 4.4.4). This process uses TRIZ technology forecasting to produce a technology road map or scenarios which lead to further advancement of the technology forecasting process, i.e. guided or directed evolution.

The predictive power of TRIZ TF comes from patterns and lines of technology evolution. The patterns of evolution reflect stable and repeatable interactions between elements of technological systems, and between systems and their environment in the process of evolution (Fey and Rivin, 1999). The patterns of a technological system serve as soft equations describing the system's life curve in the evolution space. Hence, once the configuration of the current system is given then the configurations of the next stages in development can be reliably calculated using the patterns (Fey and Rivin, 1999). There are number of known patterns but no consensus has yet been reached on what patterns are generic in technology evolution. There are some patterns which are widely accepted, including evolution of the system towards ideality with increasing useful effects and decreasing harmful effects (Clarke, SR.: 2000, Petrov: 2002, Mann: 2003, Gahide: 2000), the evolution of the system according to the S-curve patterns (Fey and Rinvin: 1999, Mueller: 1999, Mann: 1999, Clarke, SR.: 2000, Gahide: 2000, Petrov: 2002), and an increasing complexity of the system followed by simplification (Clarke, SR.: 2000Gahide: 2000, Mann: 2003). The patterns of evolution delineate a general direction for further system transformation but cannot show the quality factors of the change, i.e. the details of technology transformation. The quality factor of the change could be traceable through the lines of technology evolution. Lines of technology evolution show progressive evolution steps to accomplish patterns of technology evolution. For example, as Fey and Rivin (1999) showed, there might be a line of technology evolution consisting of seven different evolution stages for a pattern of technology evolution - increasing flexibility, including stiff system, one joint, multi joint, elastomer, liquid, gas and field evolution. This line of technology evolution can be referenced to develop a line of technology evolution for a specific product technology.

TRIZ postulates that governing laws of technology evolution are determined by the intrinsic nature of technology. Here, this means intrinsic to the technology itself and hence much less widespread than the endogenous factors of the technology. At a glance, it looks as if the laws are isolated from the rest of the endogenous factors as well as the exogenous factors. However, in reality, the laws should be perceived in the form of patterns or lines of technology evolution which are induced from the patent study. This means that the laws are not isolated from the rest of the endogenous and exogenous factors of technology because the main purpose of the invention is to produce a better product to sell. Inventors therefore consider exogenous factors, such as institutional and cultural aspects, when they invent. In this regard, it is evident that the source of the technology change is influenced by exogenous factors. This seems to be contradictory to the ontological explanation of the governing laws of the technology evolution in TRIZ. However, it can be explained that the tide is induced by the gravity of the moon and the sun but the actual current shape of the tide is determined by the geographic configuration where the current flows. Here, the technology evolution representing the formation of the tide is induced by the gravity of the moon and sun, representing the exogenous factors. However, the shape of the current, representing patterns and lines of technology evolution, is determined by the geographic configuration where the current passes, representing the intrinsic nature of the technology. If we take the exogenous factors - the gravity forces of the moon and sun - as *status quo*, then the TRIZ's axiom, "the evolution of technical system is governed by objective laws," can be regarded as the primary cause of the change. This means TRIZ TF is quasi-indifferent to the exogenous factors, i.e. has quasi-immunity from the exogenous factors.

Natural Trajectory/Innovation Avenue

Nelson and Winter perceived technology evolution as stochastic and introduced the conception of natural trajectory: "there are certain powerful intra project heuristics that apply when a technology is advanced in a certain direction, and payoffs from advancing in that direction that exist under a wide range of demand condition" (Nelson and Winter, 1977: 56).

Sahal (1981) introduced the conception of technological guide posts to explain the role of the basic design of a machine which remains unchanged but influences subsequent technological advancement over a longer period of time. Sahal (1985b) further developed the Innovation Avenue conception through three case studies of technical progress in aircrafts, farm tractors and the computer industry. His notion of the avenue is the trajectory of a ball denoting object technology rolling down the valley of a hill or mountain, the topography of which can be represented by a wide variety of socio-economic forces. Once an avenue is selected, the ball can keep rolling on its own momentum until the next branch point is encountered.

In the Innovation Avenue, similar to the TRIZ TF, technology change is perceived in a qualitative way represented by technology options but also in a more generic way, such as digital or analogue form in computer technology, or track type or wheel type in tractor technology (Sahal, 1985b, 79). In Natural Trajectory, the technology change is perceived by the quantitative change in the performance characteristics of the technology, such as increasing the thrust-weight ratio of an aircraft engine or increasing the lift-drag ratio of airframes (Nelson and Winter, 1877: 57).

In the conception of Natural Trajectory, the source of the change might be payoff and the governing rules or forces to guide the evolution might be intra project ‘heuristic’ (Nelson and Winter, 1977: 56). Sahal (1985b) conceived the source of change as both endogenous and exogenous factors, and governing rules or forces for the technology evolution as ‘momentum’ of the technology. The theory of the trajectory or avenue admits semi-immunity of the technology trajectory from the exogenous factors. However, the degree of immunity can be interpreted differently in theory. The Natural Trajectory theory offers stronger immunity since the trajectory is based on ‘powerful intra project heuristics,’ which somehow implies the ontology conception. The innovation avenue offers weak immunity since the technology avenue is the path of a ball, technology, rolling in a valley of topography. The hill represents the exogenous factors. Hence, the technology has very limited immunity since the hill firmly constrains the direction of the ball, and the momentum of the ball cannot change the geography of the hill, allowing only temporary deviations from the water flow line which fully obeys the exogenous factors.

For the methodology representing the technology change, both Natural Trajectory and Innovation Avenue used the topology conception. For the Natural Trajectory, extrapolation technique is contemplated to depict the trajectory in characteristic space; for the innovation avenue, no method is presented to link the source of changes and the change of the evolution and hence it is not feasible to depict the avenue in any quantitative manner.

Comparative Analysis

Table 4-2 is a matrix comparing characteristics of the methodologies used to forecast technology paths. As shown in the table, the methodologies can be divided into two categories of study, temporal and spatial. The temporal study does not necessarily mean absolute time. It can mean sequential progress of the technology, as in the case of TRIZ TF. Spatial means either a mathematical coordinates system with each axis representing characteristics of performance over deficit trajectory of the technology evolution in natural trajectory, or, conceptual topology, the terrain of which represents the socio-economic forces which constrain the path of the ball rolling through the valley of the terrain in innovation avenue.

	Temporal Study		Spatial Study	
	S-curve	TRIZ TF	Natural Trajectory	Innovation Avenue
Perception of the Change	Performance	Specific Technology Options	Performance	Generic Technology Options
Source of Change	Group Psychology, Returns	Exogenous Factors (*status quo*)	Payoff	Endogenous & Exogenous Factors
Governing Rules or Forces	Growth Pattern	Patterns & Lines of Evolution	Heuristic	Momentum
Immunity from Exogenous*	Strong Immunity	Quasi-immunity	Semi-immunity	Semi-immunity
Mapping (Method)	Continuous Curve (Extrapolation)	Road Map (Analogy)	Trajectory (Extrapolation)	Topology (Intuition)

** Indicates immunity of the governing rules or forces from exogenous factors*

Table 4-1 Characteristics Matrix of Methodologies for Forecasting Technology Path

All the methods show technology change but the criteria to perceive the changes differ by methodology. Both S-curve and Natural Trajectory trace the technology change by means of measuring quantitative changes in the key performance of the technology. Both TRIZ TF and Innovation Avenue trace the technology change by means of identifying qualitative changes in the technology option to emerge. However, TRIZ TF is precise in capturing the change of the inner structure of the technology option, while the innovation avenue represents the technology option in a generic way.

The governing rules or forces direct the course of the future technology evolution path. Therefore, the predicting power comes from these factors. In general, the stronger the immunity the governing rules or forces have from the exogenous factors, the longer and more endurable the prediction will be. Here, we compared the immunity factors of the methodologies. However it is very primitive and subjective and so needs more study before asserting it. It also should be noted that high immunity is not the barometer for the superiority of a methodology but the barometer for robustness of the prediction which would usually be obtainable through the cost of decreasing the resolution of the prediction.

For mapping the paths, S-curve, Natural Trajectory and TRIZ TF show clear paths in the form of a continuous curve, a trajectory or a road map respectively. However, the Innovation Avenue method only shows conceptual paths. The elegant metaphor of the ball and valley in the Innovation Avenue method is good for understanding the relationship between the momentum of the technology and the constraints of the socio-economic forces but is not sufficient to project technology paths in a rigorous way.

In principle, we could not directly use these methods to construct possible technology paths for our study since the paths we are seeking are of a different nature from the path which is inducible from the existing methodologies. We need all physically possible paths which contain information on technology options for further tradeoff and the existing methodology does not meet this requirement. Both S-curve and Natural Trajectory only show selective paths on quantitative change in the performance characteristics. Both TRIZ TF and Innovation Avenue predict qualitative change in the technology. However, the latter is too generic a way to trade off, such as in analogue or digital technology; the former contains enough quality factors of the technology to trade off, but it only shows a single path, like a road map, and there is no room to trade off the path. However, there is much wisdom and knowledge to which we are indebted in developing our own methodology to construct possible technology evolutionary paths. Among these, the following two are the most important.

First, the proposed method should define its key elements, including criteria for perception of the change, source of the change, governing rules or forces with a definition of the immunity from exogenous factors, and method for the mapping.

Second, where the boundary of the existing methodology is, the proposed methodology is to be reinforced, including the firm definition of the immunity of the governing rules or forces from exogenous factors and a rigorous procedure for mapping the path.

4.4 Problems in Forecasting Technology

In this study, we do not intend to predict what the future evolutionary path will be but instead seek what the future evolutionary paths ought to be; hence, the task should be changed to determine how to construct the plausible evolutionary paths. Even though we do not intend to predict what the specific future evolutionary path will be, we cannot be completely free from the predicative task because the study objects, the technology evolutionary paths, should bridge different time horizons, the present and the future.

What the Problem is and How to Solve It

The intractability of technology forecasting comes from the nature of the technology evolution process, the complex links within and between the endogenous and exogenous factors and the innate uncertain nature of these factors. What Hughes (1986) termed ‘the seamless web’ and the intertwining of these factors (Mackenzie, 1987), is further exacerbated by the fact that these factors are dynamically evolving together through each other’s influence, making prediction even more difficult.

The surface of the problem in forecasting technology is the uncertain nature of the technology evolution. In order to solve the problem, we need to look into the root of the problem. The root of the problem is a complicated technology evolution mechanism with intertwining endogenous and exogenous factors of technology which interact and evolve together to amplify the uncertainty of each during the evolution process. We can divide the root of the problem into two parts: one is the intrinsic uncertain nature of both the endogenous and exogenous factors of technology evolution and another is amplified propagation of the uncertainty by the intersection of these factors throughout the evolutionary process.

For the first part, as we can see in the case of Dichloro-Diphenyl-Trichloroethane (DDT) and Chlorofluorocarbons (CFCs), and the sudden policy change in the US through Bush’s Vision for Space Exploration announced in January 2004, there is no theory or intelligent ability to predict these types of uncertainty[30]. There is no way to tell whether a technology will

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[30] The term used here is Knightian uncertainty. Knight (Knight, 1921: 233) divided uncertainty into two categories, risk and uncertainty, the former being the measurable uncertainty and the latter being unmeasurable.

experience this kind of sudden death or change. However, this kind of uncertainty is not something to be challenged but rather to be accepted.

For the second part of the problem, as Ayres (1969) noticed that "the problem of technology forecasting, where both types *endogenous and exogenous factors* exist, is clearly more complicated than where either one exists in isolation," (part in italic added by author), if we try to predict future technology change, it is a real problem. However, if we try to construe what the plausible future paths ought to be, then there might be some way to avoid the problematic amplified propagation of the uncertainty. If we can isolate these factors from each other then we can avoid the second problem.

We can separate these two types of factors during the process of studying the technology evolutionary paths by sequentially applying these two factors for the construction of the technology evolution path. First, develop physically possible evolutionary paths in consideration of the endogenous factors only, and then apply the exogenous factors to discern the sustainable paths from the physically possible paths for further trade off of the paths. By doing so, the undesirable complexity, as well as the problematic amplified propagation, can be avoided.

4.5 Theorizing for Proposed Methodology

We found a clue to handling the intractably complicated and uncertain technology evolutionary process. First, we must disintegrate the exogenous factors from the technology evolution mechanism, set them aside, and then develop feasible technology evolutionary paths, based on endogenous factor directives only, in order to construe exogenous factor impact free technology evolutionary paths. Here, we present the theoretical background and the structural scheme of the proposed methodology.

4.5.1 Theoretical Backgrounds

The proposed methodology relies on the disintegration of the endogenous and exogenous factors, so we will discuss the conceptual background of this methodology coupled with a definition of the two factors. Further, we give our perception of the source of the technology change upon which the proposed methodology is based.

The Ontological View and the Teleological View: Perception of Endogenous and Exogenous Factors

The terms endogenous and exogenous in economic theory are very slippery and subjective and no firm definitions have been established. Technology change can be regarded as an exogenous factor by neoclassical economists in production function theory, while those who study technology changes as the object of the study, as is the case here, can separate factors which affect the technology change, into two types - endogenous and exogenous. However, as Hughes (1986) conceived, in the interaction between technology and other contextual factors, such as social and political, where "disciplines, persons, and organizations in systems and networks take on one another's functions as if they are part of a seamless web," it is not simple task to determine the boundaries of these two notions.

Ayres (1969) categorized two fundamentally opposed ways of looking at the dynamics of technology change, the 'ontological' view and the 'teleological' view. The former view recognizes that invention and innovation are visible manifestations of a self-generation process, or an institution having dynamism, and have not only a life of their own but also almost a will of their own (Ogburn and Thomas: 1922, Bernhard Stern: 1927, qtd. from Ayres, 1969). Hence, once initiated, by whatever complex of prior causes rooted in history and culture, the subsequent growth of the science and technology must be understood primarily in terms of the response to scientific or technological opportunities or challenges, i.e. endogenous or intrinsic variables (Ayres, 1969). The teleological view is that invention and innovation are impersonal social processes determined by exogenous factors such as social or military needs or by the existence of an economic demand (Ayres, 1969).

In this study, we will follow Ayres conception, but will define the term in different way. We will use the term endogenous factors to refer to the technology itself as well as any personal, organizational or institutional entity, either real or conceptual, involved in giving birth to and sharing an interest in the fate of the technology. The term exogenous factors refers to any personal, organizational or institutional entity, either real or conceptual, which has an interest in the fate of the technology but which is not in the same boat with the technology. A program manager of a technology development project could be an endogenous factor since he/she has strong interest in the success or failure of the development, while senior management could be an exogenous factor because they might have some interest in the success of the development but could also kill the project in order to support a more promising program. The market, policy, and environmental constraints are considered as exogenous factors since they have an interest in the fate of the technology but are not supposed to share an interest with the fate of the technology. As Schumpeter (1942) perceived in his secular phrase, ‘creative destruction,’ the social economic system is ready to accept new innovative technology.

The proposed methodology adapts the ontological view in constructing a physically possible technology evolution path. Later, the sustainability of the path will be analyzed in consideration of the exogenous factors under the teleological view.

Source of Technology Change

We consider that the technology evolution process as a co-evolutionary process where the interwoven endogenous and exogenous factors interact and evolve together, similar to the co-determinism of Sahal (1985b). However, for the construction of the exogenous factor free evolutionary paths, the exogenous factors are set aside. Endogenous factors therefore become the only sources which govern the direction of the technology change. This is similar to the patterns of technology evolution in TRIZ TF, however the underlying rationale is different. The proposed methodology considers the endogenous factors only as a source of change for the procedural convenience of the study, not because the exogenous factors are not source of the change. TRIZ TF, on the other hand, considers that the exogenous factors induce the technology change but they are status quo and hence could not explicitly be treated as the sources of the change.

We share the conception of the patterns of technology evolution of TRIZ TF – the system evolves to improve its idealism with increasing useful effects and decreasing harmful effects as the primary source of the endogenous factors which induce technology change. In Chapter 3, we established the trilateral approach to conceive the product technology. We combine these two to end up with the endogenous source of the technology change – ‘technology evolves in such a way as to increase its performance and property as well as the efficiency of the structure of the product which embodies the technology.'

4.5.2 Scheme of Proposed Methodology: Exogenous Factor Impact Free Evolutionary Hierarchical Tree Methodology

It is proposed here to combine two disciplines, the morphology approach and an evolutionary approach, the so named Evolutionary Hierarchical Tree (EHT) to develop exogenous factor impact free technology evolution paths. We call this methodology the 'Exogenous Factor Impact Free Evolutionary Hierarchical Tree (EFIFEHT)' methodology.

The proposed methodology includes two steps and the sequential work to be performed is shown in Fig. 4-1.

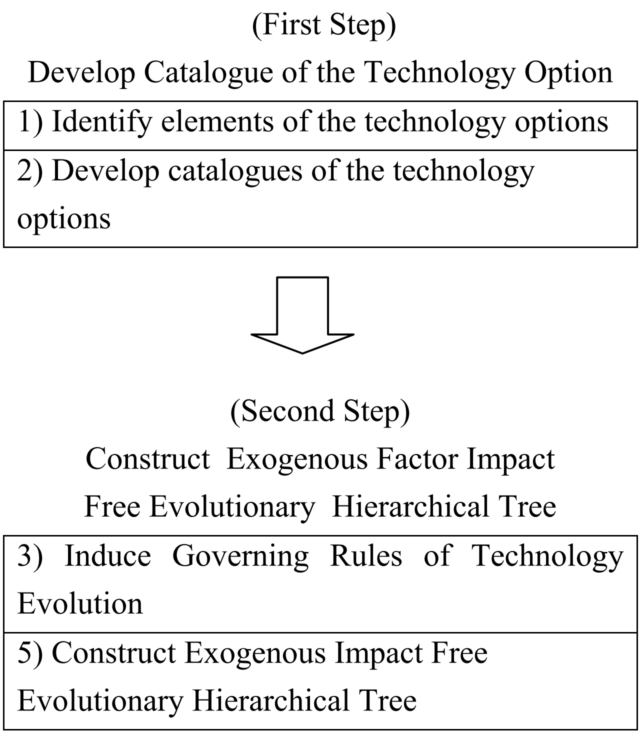

Fig. 4-1 Steps for the Construction of EFIFEHT

First step: in order to develop a catalogue of the technology options for a STS, we first define the elements of the technology options. Next, we identify feasible combinations of the elements by using the morphology approach to develop a catalogue of the technology options for the STS.

Second step: for the construction of EFIFEHT, we first induce rules which govern the direction of the technology evolutionary path by analyzing the influence of the endogenous factors on the heredity ranking of the elements of the technology on the one hand and the complexity growth patterns on the other. The evolutionary direction is determined by applying the governing rules to elements of the technology option of STS in the catalogue, and then topology. The evolutionary hierarchical tree will be used to depict the feasible technology evolutionary paths.

4.6 Exogenous Factor Impact Free Evolutionary Hierarchical Tree Methodology: For Space Transportation System Technology

As developed in the previous paragraph, the proposed EFIFEHT methodology includes two steps - the development of a catalogue of the technology options and the construction of EFIFEHT. We will apply EFIFEHT methodology to STS technology.

4.6.1 Developing the Catalogue of Technology Options for Space Transportation Systems

To develop a catalogue of technology options for STS, we first define the elements of the technology required to describe technology options for STS and then investigate all feasible combinations of the elements of the technology options by using the morphology approach.

4.6.1.1 Elements of Technology to Describe Technology Options for Space Transportation System

The elements of technology to describe the technology options for STS would be broad enough to describe all the possible technology changes of the STS with a reasonable number of the elements but detailed enough to include meaningful information to trade off the technology of the STS to be constructed by the elements of the technology. We will introduce two conceptions as the elements of the technology for this study – the operational option and the stage option.

Operational Option

The operational option of a vehicle is selected to describe the technology option of a STS because the operational option is a simple and broad notion giving only six different categories in which to classify all the technology options of STS while also giving information of embedded technology of the STS adapting the option.[31] The product

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[31] Horizontal landing could be obtained by a winged or lifting body or a combination of these two configurations. Similarly, vertical take off could be obtained by a pure rocket engine powered vehicle or a rocket based combined cycle engine configuration, but not by an airbreathing only configuration.

technology option, such as a winged body with cryogenic engine, could represent a technology option for a vehicle. However, we find that it is too difficult to define the technology option of a vehicle in this way because of the manifold nature of the product technology option and it is also an intractable task to elicit a product technology option, not only for the incumbent technology but also for the technology to be developed.

For the six operational options that are proposed for this study, all the terms are the same as the terminology which is widely used in the launch industry, except for the terms ‘vertical drop’ and ‘vertical landing.’ These terms, which are usually collectively termed as vertical landing in the industry, have been precisely defined for this study. For the convenience of the argument, we designated 6 characters to represent respective technology options. Since it is helpful in understanding the underlying technology of the operational option for the discussion of the proposed methodology, a brief review of the operational options is incorporated in Appendix C-1, Technology Options of a Vehicle: Operational Options.

Î: Vertical Take off and Vertical Drop (VTVD): Vehicle operational type which lifts off and drops in a vertical direction. For the descent of the vehicle, no controlled flight is anticipated.

I: Vertical Take off and Vertical Landing (VTVL): Vehicle operational type which lifts off and lands in a vertical direction. Soft landing is anticipated by controlled flight.

h: Vertical Take off and Horizontal Landing (VTHL): Vehicle operational type which lifts off vertically but lands in horizontal direction.

Ҹ: Horizontal Take off and Vertical Drop (HTVD): Vehicle operational type which takes off horizontally but drops in vertical direction. For the descent of the vehicle, no controlled flight is anticipated.

Ч: Horizontal Take off and Vertical Landing (HTVL): Vehicle operational type which takes off horizontally but lands in vertical direction. Soft landing is anticipated by controlled flight.

H: Horizontal Take off and Horizontal Landing (HTHL): Vehicle operational type which takes off horizontally and lands in horizontal direction like an airplane.

Stage Option

The operational option of a vehicle is useful in identifying the technology options for the single stage STS. However, if the STS is multistage, then we need another conception to identify the technology of each stage of the STS. We can call this the ‘operational option for a stage’ or simply ‘stage option.’ The conception of ‘stage option’ is important in understanding our proposed methodology, since it is the basic element of technology which defines the technology option of a STS and the technology evolutionary path to be expressed by the technology option of the STS.

We can identify the stage option with two factors - the operational options, as defined above, and the rank of the stage, such as first stage of the three-stage STS. For example, a three-stage STS, ‘HЧҸ’ can be interpreted as a technology option for a STS consisting of three stage options including HTHL first stage, HTVL second stage and HTVD third stage. Here, the order of the character denotes the order of the stage which the character represents, and the order of the stages is defined in accordance with the order of the engine burn, or, in the case of parallel burn or no burn, in accordance with the order of separation from the vehicle.

4.6.1.2 Catalogue of the Technology Options for Space Transportation Systems

All the possible technology options of STS, a catalogue of technology options of STS, could be developed by studying all the feasible combinations of elements of the technology expressed in the form of the stage option. However, an additional process is needed to reduce the number of combinations of elements to a reasonable number for further analysis. Hence, morphology analysis is used to screen the feasible combinations of elements by checking the self-contradictory combinations of the elements.

If we look into the physical constraints of the configuration of a STS, then the possible combination of elements for a STS can be reduced since all the stages of a STS are to be launched together. Once the take off type of the first stage is determined then the remaining stages should follow the same type. However, the landing type can be determined independently since each stage lands separately.

All the formations of STS can be divided into two families - vertical take off vehicles and horizontal take off vehicles. The morphology Table 4-2 shows the physically feasible formations of a three-stage STS. The vertical take off family includes three different first stages: VTVD (**Î**), VTVL (**I**) and VTHL (**h**). In addition, each first stage can be mated with three different second stages, and each second stage can be mated with three different third stages. Hence a total of 27 (3 x 3 x 3) different formations are feasible for vertical take off vehicle formations. The horizontal take off family consists of three different first stages, including HTVD (**Ҹ**), HTVL (**Ч**) and HTHL (**H**), and the feasible formations would be the same as for the vertical take off vehicle family. Accordingly, a total of 54 different formations are feasible for the three stage STS as opposed to the theoretical 216 types options (6 X 6 X 6). Similarly 18 different formations are possible for the two stage STS as opposed to the theoretical 36 types of options (6 X 6). For the single stage launch vehicle, there are 6 different type options. Accordingly, we can develop a catalogue of the technology options comprising 96 different types of options as presented in Appendix C-2, Catalogue for the Technology Options for Space Transportation Systems.

	Vertical Take off Vehicle Family									Horizontal Take off Vehicle Family								
1st Stage	Î			I			h			Ҹ			Ч			H		
2nd Stage	Î	I	h	Î	I	h	Î	I	h	Ҹ	Ч	H	Ҹ	Ч	H	Ҹ	Ч	H
3rd Stage	Î, I, h	Î, I, h	Î, I, h	Î, I, h	Î, I, h	Î, I, h	Î, I, h	Î, I, h	Î, I, h	Ҹ, Ч, H	Ҹ, Ч, H	Ҹ, Ч, H	Ҹ, Ч, H	Ҹ, Ч, H	Ҹ, Ч, H	Ҹ, Ч, H	Ҹ, Ч, H	Ҹ, Ч, H

Table 4-2 Morphological Table for Three Stage STS

4.6.2. Constructing the Exogenous Factor Impact Free Evolutionary Hierarchical Tree

In the previous section, we developed a catalogue of the technology options for a STS by using the morphology approach. If we simply apply the morphology method to construe the possible technology evolutionary path, then the number of evolutionary paths becomes too huge to analyze. This is shown in Appendix C-3, where a STS evolves from three stages and there are six different technology options for each - the possible number of paths would then be 2.723836 x 10^{412}. In order to construe possible evolutionary paths within manageable numbers, we need an approach that is more constrained in its application.

The direction of the technology change as determined by the endogenous factors alone is not random. There should be rules and here we induce the rules which govern the direction of the technology change and investigate a rigorous way of incorporating these rules in mapping the technology evolution path.

4.6.2.1 Governing Rules of Technology Evolution

We induce two rules which govern the direction of the technology evolution - heredity ranking of the elements of technology and complexity growth pattern, after articulating the state of the technology for the elements of the technology, here operational option and stage option, and the source of the change, here the source of the technology change as defined in the previous paragraph, ‘technology evolves in such a way as to improve its performance and property as well as the efficiency of structure of the product which embodied the technology.’

The heredity ranking defines the internal process of the product technology evolution by means of selecting the inner structure of the technology, i.e. directing which technology elements are followed down or phased out during the evolutionary process. The complexity growth pattern defines the external process of the product technology evolution by means of directing the outer structure of the technology, here, the number of stages of each generation of STS.

Heredity Ranking of Technology Elements

The heredity ranking determines which technology element is to be inherited by the next generation of STS during the evolution process. The heredity ranking of each technology element is evaluated by analyzing technology factors – the performance and property. Since the technology evolves in a way that increases the performance and property, it is evident that a technology element with a higher technological state would have high heredity ranking.

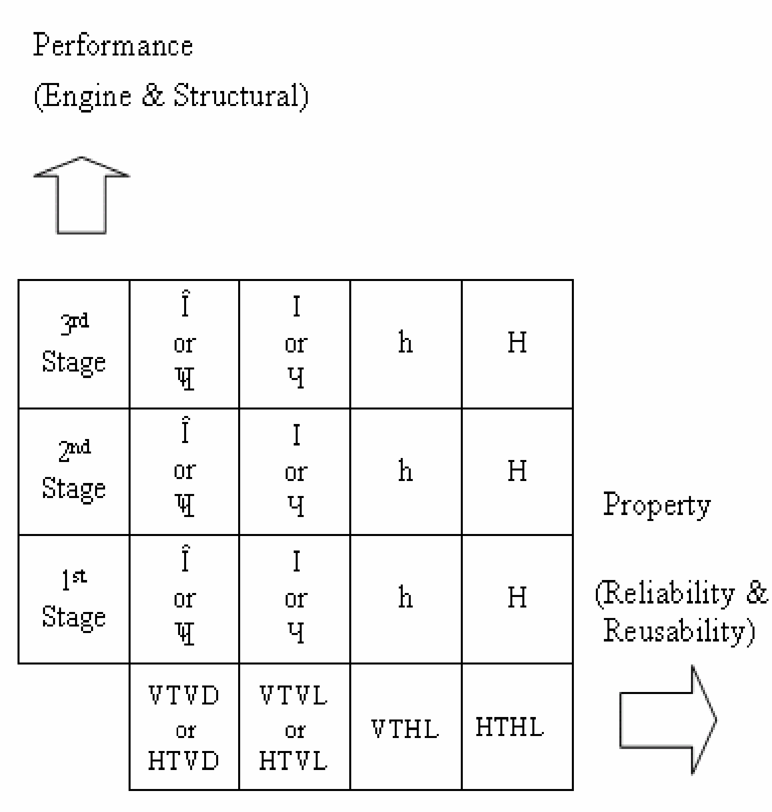
To determine the heredity ranking, we must evaluate the state of the technology of each operational option and stage option.

To differentiate the state of the technology among the elements of technology (stage options adopting a homogenous operational option), the performance factor will be reviewed since there is a noticeable advantage in adopting high performance technology, both in terms of engine efficiency and structural efficiency, in the upper stage rather than the lower stage. At the same time, there is no reason that the upper stage should be more reliable than the lower stage, and the same is also true for the reusability. For the last stage, there is a one to one exchange ratio between the vehicle dry mass and the payload, which means reducing 1 kg of the vehicle dry mass will increase the payload mass by 1 kg. The exchange rate is reduced more than an order of magnitude when it comes to the first stage and a similar effect is expected for engine efficiency (Chun, 2003).

To differentiate the state of the technology among the elements of technology (stage options adopting a heterogeneous operational option), the property factor will be reviewed since there is a rationale that discernible differences exist in the state of property factors among the heterogeneous operational options. However, there is no firm rationale to order the state of technology, in terms of performance, among the heterogeneous operational options.

The preliminary evaluation of the state of the technology is incorporated in Appendix C-4, Assessment of the State of the Technology of Operational Options and Stage Options.

Table 4-3 summarizes our review of state of technology of technology elements. In the table, the right hand direction denotes the order of the state of technology in property and the upper direction denotes the order of the state of the technology in performance. Both VTVD (Î) and HTVD (Ч̂) operational options are considered to be mutually homogeneous since there is not much difference between the options except for the operational option of the vehicle to be mated with. The same is true for both VTVL (I) and HTVL (Ч).

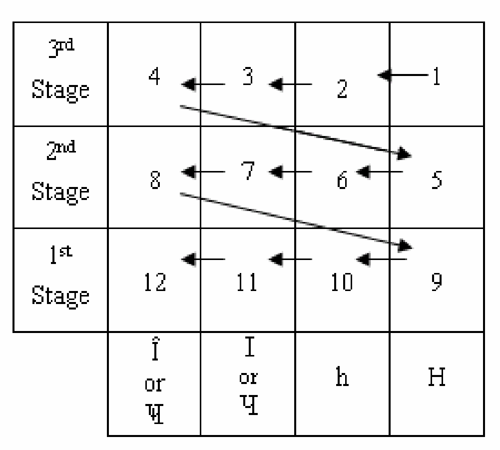


3rd Stage	Î or Ҹ	I or Ч	h	H
2nd Stage	Î or Ҹ	I or Ч	h	H
1st Stage	Î or Ҹ	I or Ч	h	H
	VTVD or HTVD	VTVL or HTVL	VTHL	HTHL

Table 4-3 State of Technology of Technology Elements

The preliminary evaluation of the state of the technology for the operational option showed that a STS of HTHL (H) operational option is supposed to have the highest value in vehicle reliability and reusability; a STS of VTHL (h) operational option is second and a STS of VTVL (I) and HTHL (Ч) operational option is next. A STS of VTVD (I) and HTVD (Ҹ) operational option has the least value in terms of the property of the vehicle. For the rank of the state of the technology in performance of different stages having homogenous operational options, it is evident that the higher the stage of the vehicle, the higher is the state of the technology it embodies.

It should be mentioned that the evaluated ranking of the technology state among the heterogeneous operational options is a very rudimentary one since almost all the existing launch vehicles fall into the VTVD (I) operational option and very few other cases are available (VTHL (h) Space Shuttle and HTVD (Ҹ) Pegasus/L1011 launch system). In order to minimize controversy in the rationale for ranking among the technology elements which have two different evaluation factors, we investigate ranking for possible appraisal strategies. Four different cases of heredity ranking appraisal strategy are defined and applied for the study.

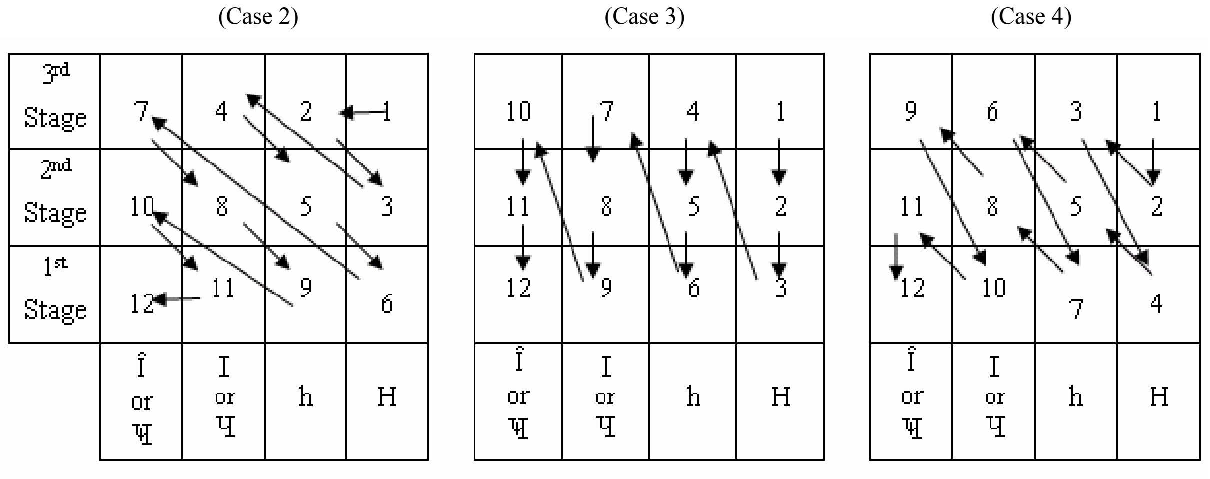


3rd Stage	4	3	2	1
2nd Stage	8	7	6	5
1st Stage	12	11	10	9
	Î or Ҹ	I or Ч	h	H

Table 4-4 Heredity Ranking of Technology Elements (Case 1: Performance as a Primary and Property as a Secondary Priority)

Table 4-4 shows heredity rankings of technology elements based on the appraisal strategy, with performance as primary priority and property as secondary priority. Each column of the table represents a specific operational option of the vehicle, from the right HTHL (H), VTHL (h), VTVL (I) or HTVL (Ч), and VTVD (Î) or HTVD (Ҹ). Each row of the table represents a stage in order, from the top, third stage, second stage and first stage of the vehicle. Heredity ranking is assigned to each element using the appraisal strategy. In case 1, the third stage operational option of HTHL (H) shows the highest heredity ranking, the third stage operational option of VTHL (h) shows the second highest heredity ranking, and others are as shown in the table.

Table 4-5 shows the heredity ranking of the other three cases. All cases show that the third stage operational option of the HTHL (H) has the highest heredity ranking while the first stage operational option of VTVD (Î) or HTVD (Ҹ) shows the lowest heredity ranking.



(Case 2)

3rd Stage	7	4	2	1
2nd Stage	10	8	5	3
1st Stage	12	11	9	6
	Î or Ҹ	I or Ч	h	H

(Case 3)

10	7	4	1
11	8	5	2
12	9	6	3
Î or Ҹ	I or Ч	h	H

(Case 4)

9	6	3	1
11	8	5	2
12	10	7	4
Î or Ҹ	I or Ч	h	H

Table 4-5 Heredity Ranking of Technology Elements (Case 2: Balanced Dominance with Performance Priority, Case 3: Property as a Primarily and Performance as a Secondary Priority, Case 4: Balanced Dominance with Property Priority)

Complexity Growth Pattern

We refer to two aspects, performance and property, from among three aspects which represent technology change in our proposed trilateral approach to determine the heredity ranking of the technology elements. There remains one aspect, the structural aspect, to gauge the technology change.

This heredity ranking governs the internal process of the technology evolution; however, we still need another rule to govern the external process of the technology evolution in the transformation of the structural aspects of the STS. In our evolutionary model this would be the number of stages of the STS.

There are three factors in the structural aspects - complexity, decomposability and architecture. As we discussed, these three factors are not mutually exclusive but rather they are closely interlinked. Here, we focus on complexity growth patterns to study the external process of the technology evolution for two reasons. First, these factors represent all the structural aspects of the product, interlinking with the components from different viewpoints and therefore any one of them can be expected to represent the whole external process of the technology evolution. Second, the complexity growth patterns are widely recognized among different disciplines and empirical cases exist of expendable STS subsystems which support these complexity growth patterns.

Hobday (1998) differentiated the dynamics of innovation in complex products and systems (CoPS) from mass-produced commodity goods. He argued that CoPS evolve with increasing complexity from one generation to another due to ever rising demands on performance capacity and reliability, with impingement on the simplification factor, e.g. modularization and standardization through time. TRIZ TF conceives the complexity growth pattern as an increase in the complexity of the product at the initial stage followed by simplification (Clarke, SR.: 2000, Gahide: 2000, Mann: 2003).

The expendable launch vehicle shows these patterns during the evolutionary process. Expendable launch vehicles evolve to increase performance; hence the increasing complexity of the vehicle, especially for engines with a high performance turbo pumps. However, newly developed launch vehicles show simplification patterns. RS-68 engines, which power the Evolved Expendable Launch Vehicle (EELV) Delta IV, reduced the part count drastically. A similar pattern is shown with the LE-7A and LE-5B rocket engines for the H-IIA (Maemura et al., 2002).

Fig. 4-2 shows a schematic representation of the dynamics of STS technology in the evolutionary space as developed in the previous chapter. The dotted line represents expendable vehicles, the VTVD (Î) or HTVD (Ҹ) conceptions, and the line arrow represents reusable vehicles, including first on the left, VTVL (I) or HTVL (Ч), second on the left, VTHL (h) and, lastly, HTHL (H). The arrow denotes the evolutionary trajectory of the vehicles.

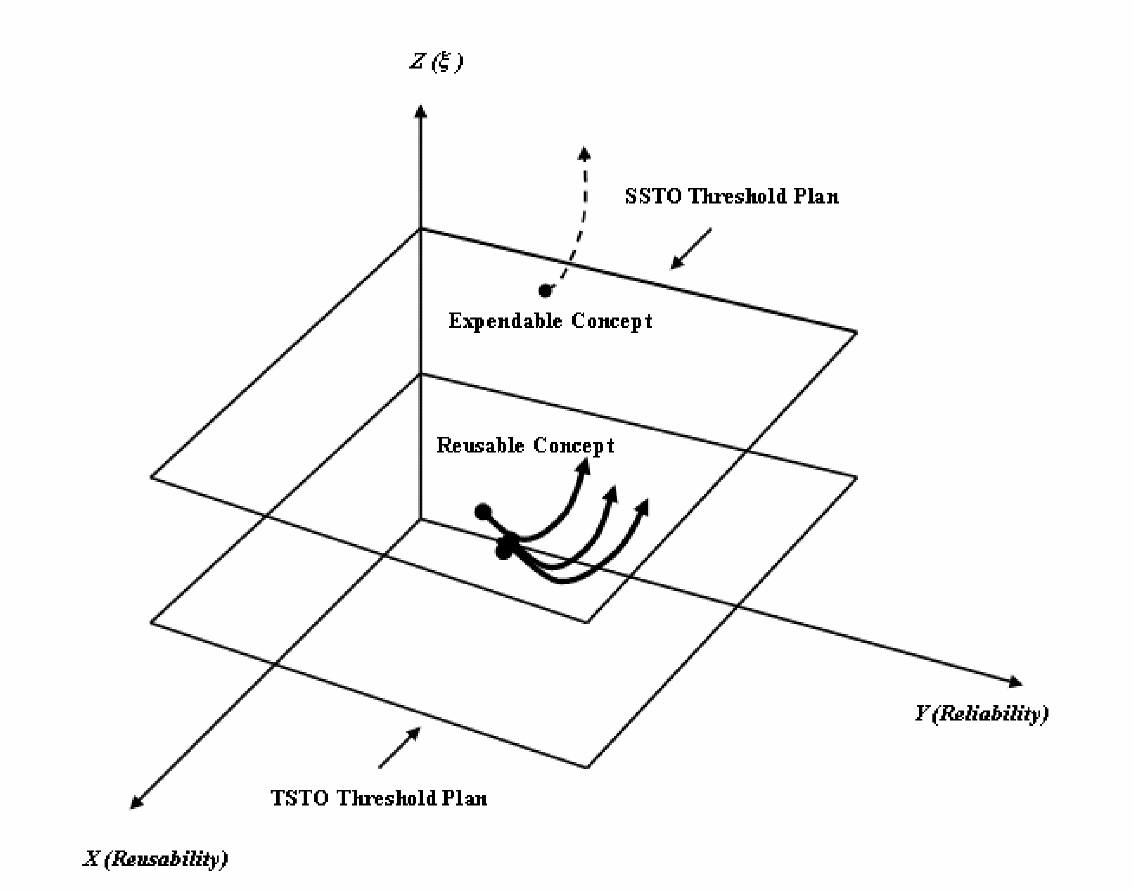


Fig. 4-2 Dynamics of the Space Transportation System Technology

The Z-axis scales the performance of the STS, taking into account both engine efficiency and structural efficiency. The Two Stage To Orbit (TSTO) or Single Stage To Orbit (SSTO) threshold plane denotes the state of the technology required, in terms of engine and structural efficiency, to build a TSTO or SSTO vehicle. As we discussed in the previous paragraph, the technology evolves to increase the performance. Once the technology path penetrates the threshold planes, there are then two possible scenarios: keep the number of stages or reduce the number of stages. Evidently the number of stages of the STS would not increase during the evolutionary process since this would provide no noticeable gains in performance but rather a loss in vehicle property, such as degradation of reliability due to increased critical operations such as engine ignition and stage separation maneuvering.

We can now narrow down our argument as to the way in which the external evolutionary process would occur, either decreasing the number of stages of the vehicle or keeping the number of stages the same. The question is then which one would match the complexity growth patterns, 'increasing complexity of the product at the initial stage, followed by simplification.'

Both ways seem representative of the complexity growth patterns. In the latter case, keeping the same number of stages of the vehicle, the complexity of the STS would increase in the beginning, followed by simplification as has been experienced by expendable launch vehicle technology.

In the former case, decreasing the number of vehicle stages, if we only consider the part count as the measurement of the degree of complexity, then the evolutionary pattern of decreasing the number of stages goes against the typical complexity growth pattern. However, if we look inside the structural changes of the STS, then we realize that the part count does not effectively represent the complexity of the multi-stage STS since each stage of the vehicle resembles another, functionally as well as structurally. Rather, reducing the number of stages requires integrated design and technology intensive design since the remaining stages should share the role which the lost stage carried out. The phenomenon of 'compensating the quantitative reduction by qualitative increment' would occur until the matured configuration of the vehicle emerged as Single Stage to Orbit (SSTO). Simon (1996) expressed that the complexity of a product is not necessarily proportional to the sum of the part counts but rather the interrelationship among the parts. Once the vehicle evolves to SSTO, then simplification of the vehicle structure would then follow with increasing modularity or standardization of previously customized components as argued by Hobday (1998).

For this study, we expect to see the external evolutionary process, decreasing the number of stages, because the staged vehicle architecture is the result of the limits of the technology and not the result of efforts to improve the product technology. This means there was no technology available during the embryonic era of the launch industry to build a single vehicle capable of reaching orbital velocity and thus the multi-stage STS emerged, not due to extrinsic constraints but due to intrinsic constraints of the technology such as limited engine and structural efficiency. Once these limitations are removed, then the evolution process would develop so as to increase the product technology in general. However, the multi-stage conception has inherited limitations in the development of the key property of the technology - the reliability of the vehicle - because of frequent critical operations such as ignition of the engine and separation maneuvering

4.6.2.2 Exogenous Factor Impact Free Evolutionary Hierarchical Tree: Mapping the Path

To express the change of the technology, and so the technology evolution path, topology is introduced, the so-called Evolutionary Hierarchical Tree (EHT), each node of which represents a technology option of for a STS.

For the mapping of the technology evolutionary paths, the technology option of the parent STS must first be selected and then the technology option of the next generation STS must be determined based on the heredity ranking. As the number of stages is reduced as the technology evolves to next generation, the lowest ranked heredity element of the technology, the stage option, is discarded. The initial number of stages of the technology option is three, and so the hierarchical tree will consist of three ranks.

For example, in the case 1 heredity ranking strategy, the first generation three stage STS, the technology option of which is H(9)H(5)H(1), Ч(11)H(5)H(1) and Ҹ(12)H(5)H(1) respectively, evolves to the second generation two stage STS, the technology option of which is H(5)H(1). The location of each character symbol represents the order of the stage, and the number in parenthesis denotes the heredity ranking of the stage option represented by the character in front of the parenthesis as defined in the previous paragraph. Ҹ(12)H(5)H(1) can be interpreted as a three stage STS consisting of a HTVD first stage, the heredity ranking of which is 12, a HTHL landing second stage, the heredity ranking of which is 5, and a HTHL third stage, the heredity ranking of which is 1.

Similarly, the first generation three stage STS, the technology option of which is H(9)Ч(7)H(1), Ч(11)Ч(7)H(1) and Ҹ(12)Ч(7)H(1) respectively, evolves to the second generation STS, the technology option of which is Ч(7)H(1). The STS, the technology option of which is H(9)Ҹ (8)H(1), Ч(11)Ҹ (8)H(1), and Ҹ(12)Ҹ(8)H(1) respectively, evolves to the STS, the technology option of which is Ҹ(8)H(1). The second generation two stage STS, the technology option of which is H(5)H(1), Ч(7)H(1) and Ҹ(8)H(1) respectively, evolves to the third generation single stage STS, whose technology option is H(1). It should be noted that the same technology option with the same heredity ranking does not mean the same technology. For example, the technology performance of the HTHL (H) conception with heredity ranking (1) differs from the one which is in the third stage and the one which is in single stage.

Fig. 4-3 shows the hierarchy tree of the example cases. Here, the location of the character represents the order of the stage - from the bottom, the first stage, second stage, and the third stage. As shown in the figure, the tree consists of nodes where each vehicle technology option is presented and the branches depict the relationship of the parent and child. From the bottom to the top, the first node shows the first generation of the technology option, the second node shows the second generation of the technology option, and the final node shows the third generation of the technology option respectively.

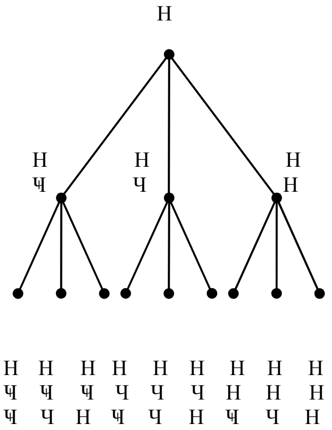


Fig. 4-3 Hierarchical Tree of Technology Evolution

The morphology of the hierarchical tree resembles the phylogenetic tree in biology. However, it differs in that the hierarchical tree shows converging patterns, while the typical phylogenetic tree shows diverging patterns as the evolution proceeds.

4.7 Exogenous Factor Impact Free Evolutionary Hierarchical Tree of Launch Vehicles

In accordance with the EFIFEHT methodology, as developed in the previous paragraph 4.6, we can construct exogenous factor impact free technology evolution paths. This evolutionary hierarchical tree shows what the possible evolutionary paths are but cannot show what the evolution path should be. Additional analysis into the plausibility of each path is therefore needed and will follow in the proceeding paragraph. In order to facilitate the tradeoff study, a preliminary review is made of the physical possibility, the morphological patterns of the tree and the patterns of the evolutionary paths.

There are two families of vehicles - vertical take off and horizontal take off - and four different hierarchy ranking strategies for each family. Hence, eight different evolutionary hierarchical trees are developed. The first four trees are for the vertical take off family and the remaining four are for the horizontal take off family. Later, the results of the review of the eight hierarchical trees will be consolidated into one hierarchical tree.

4.7.1 Evolutionary Hierarchical Trees of Vertical Take off Launch Vehicles

The vertical take off launch vehicle family is differentiated from the horizontal take off vehicle family not only by the vehicle configuration but also by the engine type on which it is mounted. The vertical take off launch vehicle needs a high thrust to weight ratio engine because the launch vehicle should be lifted by the thrust of the engine. Rocket engines can offer this high thrust to weight ratio. This family can be divided into three sub-family groups, according to the operational option of the destined launch vehicle in the evolution process: VTVD (Î), VTVL (I) and VTHL (h).

Case 1

Fig. 4-4 shows the evolutionary hierarchical tree of the vertical take off launch vehicle family based on the case 1 heredity ranking strategy with performance as primary priority and property as secondary priority. As shown in the figure, the pattern of branching is orderly, denoting that the evolution is straightforward; each of the three different vehicle types converges into next generation vehicle.

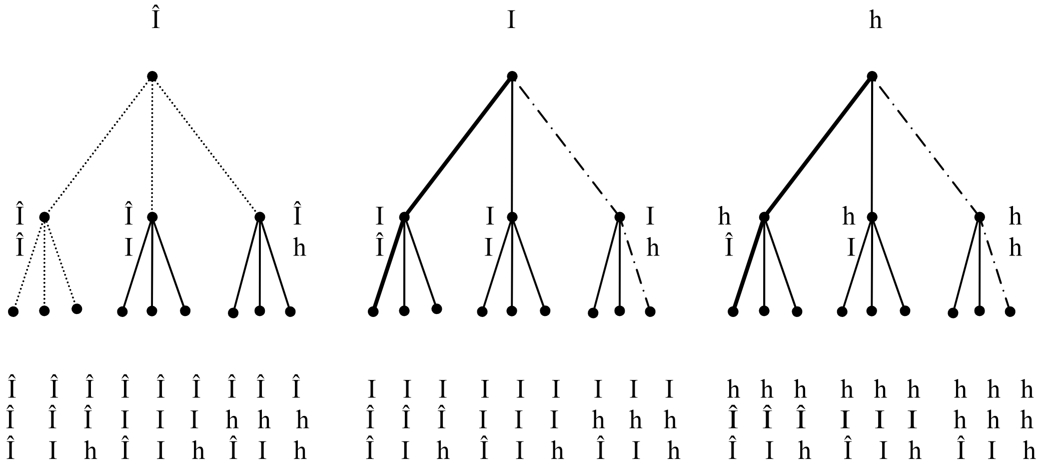


Fig. 4-4 Evolutionary Hierarchical Tree of Three Stage Vertical Take off Launch Vehicle Family (Case 1: Performance as a Primary and Property as a Secondary Priority)

There are two types of existing launch vehicles in this family, the first node from the left in the bottom line of the hierarchy tree, configuration ÎÎÎ, and all three stage VTVD Vehicles (Î). Most of the existing launch vehicles fall into this category. The ninth node from the right of the bottom line of the hierarchy tree, technology option ÎÎh, could be representative of the Space Shuttle, consisting of a VTVD (Î) first stage solid rocket booster, a VTVD (Î) second stage external tank, and a VTHL (h) third stage orbiter. The conception of DC-X, a VTVL (I) single stage vehicle, is represented by the node in the center of the upper line of the hierarchy tree. The X-33, a subscale version of Venture Star, a VTHL (h) single stage vehicle, is represented by the node on the right side of the upper line of the hierarchy tree.

The evolutionary branch represented by the dotted line is not likely to emerge because there are no noticeable returns expected in introducing a two stage VTVD (ÎÎ) or a single stage VTVD (Î) vehicle. The expected return might be an increment in the reliability. However, the improvement might be restrictive because this conception is an expendable conception and hence every flight of the vehicle is a maiden flight and thus exposed to the risk of poor workmanship and defective material in the production process, even with a highly improved product technology. Only limited improvement in the reliability of the vehicle is expected by reducing the number of staging operations and the technology options, ÎÎÎ, IÎÎ and hÎÎ are therefore expected to reach a dead-end evolutionary path. However, this does not mean that these vehicles should all be phased out. Instead, the launch vehicle ÎÎÎ continues its life since the political raison d'être, national security, exists. All 24 different types of the first generation evolve to 8 different types of second generation, and only 6 different types of second generations evolve into two different types of third generation. Accordingly, from amongst the 27 paths, nine paths are expected to lead to a dead-end.

In the VTHL (h) sub-family group, as shown on the right in the Fig. 4-4, the path marked with a dash-dot line, hhh→hh→h, shows the most sophisticated evolutionary path in terms of vehicle complexity and vehicle technology property to emerge during the evolutionary path. Vehicles in this path consist only of VTHL (h) type stages, the geometrical configuration of which is a complicated winged body or lifting body configuration and the subsystems of which include recovery systems such as landing gears and thermal protection systems. The conception of VTHL (h) also offers the highest property of the technology in reliability and reusability. The path marked with a bold line, ÎÎh→Îh→h, is the least sophisticated evolutionary path in terms of vehicle complexity and vehicle technology property to emerge during the evolutionary path. All the stages of the vehicle in the evolutionary path, except the core stage-VTHL (h) which is destined to evolve into an SSTO configuration, are of the expendable VTVD (Î) conception, the typical geometry of which is a standard cylindrical shape. The conception of VTVD (Î) also contains the lowest property of the technology in reliability.

Similarly, in the VTVL (I) sub-family group in the Fig. 4-4, the path marked with a dash-dot line, hhI→hI→I, shows the most sophisticated evolutionary path in terms of vehicle complexity and property of the technology to emerge during the evolutionary path. All the stages of the vehicle in the evolutionary path, except the core stage-VTVL (I) which is destined to evolve into an SSTO configuration, are VTHL (h) type stages, the geometrical configuration of which is a complicated winged body or lifting body configuration and the subsystems of which include recovery systems such as landing gears and thermal protection systems. The conception of VTHL (h) also offers the highest property of the technology in reliability and reusability. The paths marked with a bold line, ÎÎI→ÎI→I, show the least sophisticated evolutionary path, in terms of vehicle complexity and property of the technology, to emerge during the evolutionary path.

All the stages of the vehicle in the evolutionary path, except the core stage-VTVL (I) which is destined to evolve into an SSTO configuration, are of the expendable VTVD (Î) conception, the typical geometry of which is a standard cylindrical shape. The conception of VTVD (Î) also contains the lowest property of the technology in reliability.

Case 2

Fig. 4-5 shows an evolutionary hierarchical tree for a three stage vertical take off launch vehicle family based on the case 2 heredity ranking strategy, balanced dominance with performance priority. As shown in the figure, the branching pattern of the tree is disturbed somehow compared to case 1 but the pattern remains, i.e. the three sub-family groups show identical branching patterns. There is not much noticeable difference between this evolutionary pattern and that of Case 1.

All 25 different types of the first generation evolve to 8 different types of second generation; only 6 different types of second generation evolve to two different types of third generation. Accordingly, out of 27 paths, nine are expected to arrive at a dead end.

Similarly to case 1, the path marked with a dotted line is not a feasible path. The path marked with a dash-dot line is the most sophisticated path while the path marked with a bold line represents the least sophisticated path to emerge during the evolution in terms of vehicle complexity and property of the technology.

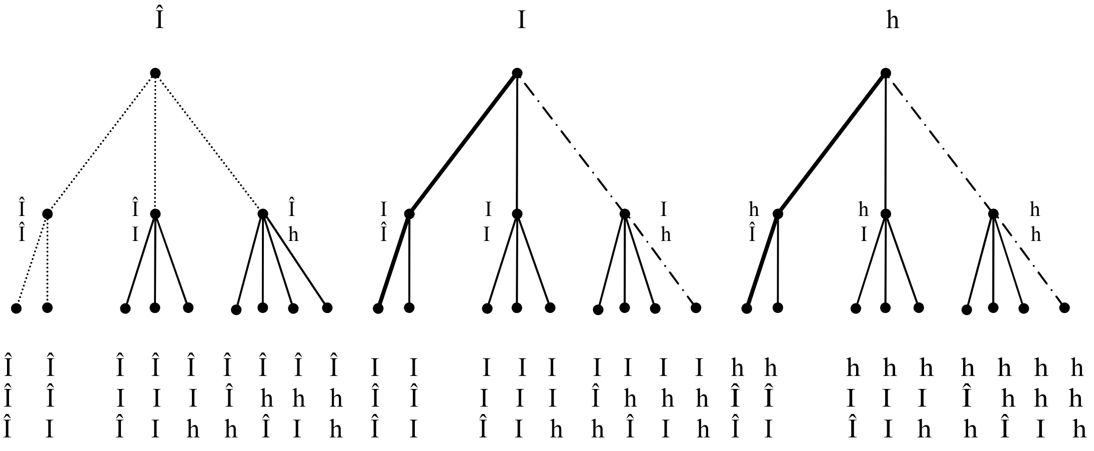


Fig. 4-5 Evolutionary Hierarchical Tree of Three Stage Vertical Take off Launch Vehicle Family (Case 2: Balanced Dominance with Performance Priority)

Case 3

Fig. 4-6 shows the evolutionary hierarchical tree for the three stage vertical take off launch vehicle family based on the case 3 heredity ranking strategy, property as a primary and performance as a secondary priority.

As shown in the figure, there is significant change in the morphology of the tree. The branching of the tree shows a different pattern compared to the first two cases. The most noticeable change is in the variation of the number of branches for each of the sub families. In the VTHL (h) sub-family group the branching increases drastically with 19 technology paths from a total of 27 diverging into the VTHL (h) SSTO conception. Contrary to this, the VTVD (Î) sub-family group reduces its branches from nine to one. These results could be expected since the heredity ranking is based on property priority in which the VTHL (h) has the highest ranking and the VTVD (Î) the lowest ranking. In this evolutionary strategy, only one path leads to a dead end, as marked with the dotted line.

In addition to the morphological change in the tree, new patterns of the evolution path also emerge. Among them, the VTHL (h) sub-family group, shown as the bold dash line evolutionary path in Fig. 4-5, hÎÎ→hÎ→h, shows the least sophisticated evolutionary path, similar to the bold line path ÎÎh→Îh→h. The two patterns are similar for all stages, except the core stage-VTHL (h) which is destined to evolve to the SSTO configuration, and consist of the least complex VTVD (Î) technology option. However, the evolution patterns differ from the former path, the core stage of which evolved from the lowest stage where the flight environment is benign compared to that of the SSTO vehicle. The core stage evolves, progressively increasing its capability both in acceleration and thermal protection, to meet the higher requirement needed to offer SSTO vehicle capability. The former path - the core stage - evolves from the upper stage where the flight environment is similar to that of the SSTO vehicle. The thermal protection capability of the core stage should therefore be almost the same as that of the SSTO vehicle since the core stage encounters a similar hostile reentry environment and hence progressive improvement is not permitted. We distinguish these two patterns as bottom up and top down evolution patterns respectively.

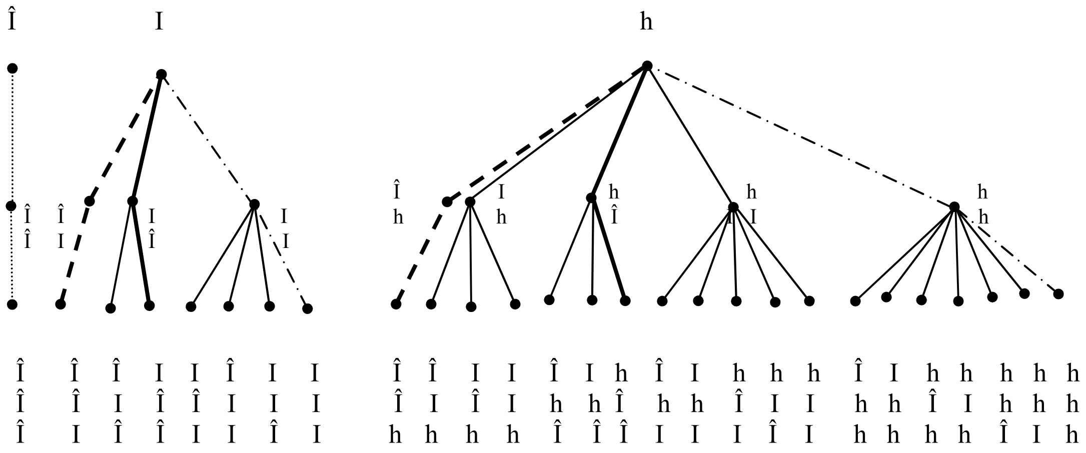


Fig. 4-6 Evolutionary Hierarchical Tree of Three Stage Vertical Take off Launch Vehicle Family (Case 3: Property as a Primary and Performance as a Secondary Priority)

Similarly, the VTVL (I) sub-family group, as shown in the center of Fig. 4-6, provides a sophisticated evolution path, III→II→I, marked with a dash-dot line, and a less sophisticated evolution path with both a bottom up approach, IÎÎ→IÎ→I, and a top down approach, ÎÎI→ÎI→I, marked in bold dash line and in bold line respectively.

Case 4

Fig. 4-7 shows the evolutionary hierarchy tree for the three stage vertical take off launch vehicle family based on the case 4 heredity ranking strategy, balanced dominance with property priority.

As shown in the figure, the branches of the tree show a similar pattern to the third case but are more orderly as the branches of each sub-family group become symmetrical. There are some changes in the branching within the individual sub-family groups but no branching changes appear between the sub-family groups. Only one path among the total of 27 arrives at an evolutionary dead end as marked with the dotted line. Here again, the bottom up evolutionary patterns appear as marked with the bold dash line. The same interpretation is valid for each different pattern of the evolution paths as marked with different types of lines.

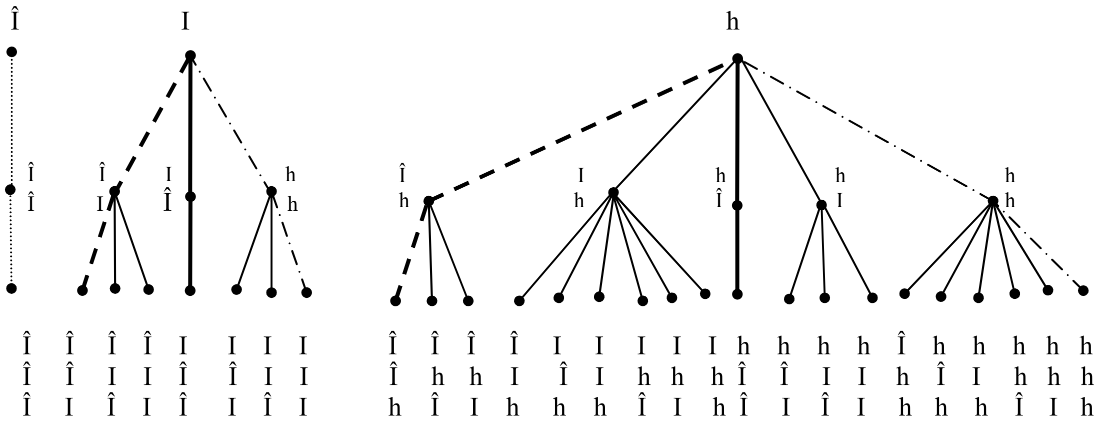


Fig. 4-7 Evolutionary Hierarchical Tree of Three Stage Vertical Take off Launch Vehicle Family (Case 4: Balanced Dominance with Property priority)

4.7.2 Evolutionary Hierarchical Trees of Horizontal Take off Launch Vehicles

The horizontal take off launch vehicle family typically uses airbreathing engines for atmospheric flight. The vehicle also needs rocket engines to accelerate to orbital velocity since there are limits on the maximum velocity achievable using airbreathing engines. This family can be divided into three sub-family groups according to the operational option of the destined launch vehicle in the evolution process: HTVD (Ч), HTVL (Ч) and HTHL (H).

In general, the pattern of the hierarchical tree for the horizontal take off launch family is the same as that of the vertical take off launch vehicle but the number of feasible evolutionary paths is much different. Many more dead end evolutionary paths are found in the horizontal take off launch vehicle family than in the vertical take off launch vehicle family.

Case 1

Fig. 4-8 shows the evolutionary hierarchical tree for the three stage horizontal take off launch vehicle family based on the case 1 heredity ranking strategy, performance as a primary and property as a secondary priority.

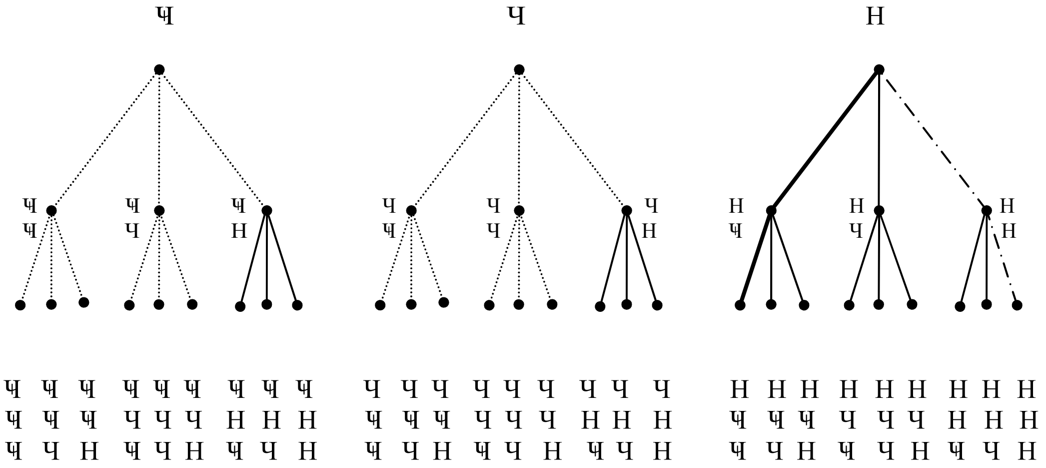


Fig. 4-8 Evolutionary Hierarchical Tree of Three Stage Horizontal Take off Launch Vehicle Family (Case 1: Performance as a Primary and Property as a Secondary Prority)

As shown in the figure, the pattern of the tree branches is the same as that of the vertical take off launch vehicle family tree as analyzed in the previous paragraph. However, only one sub-family group, the one converging to the HTHL (H) SSTO launch vehicle, shows feasible paths for SSTO technology evolution. The other sub families, converging to HTVD (Ҹ) SSTO and HTVL (Ч) SSTO launch vehicles cannot show any feasible path for SSTO technology evolution. As seen in the figure, the vehicle exclusively composed of HTVL (Ч) or HTVD (Ҹ) could not offer feasible paths since this type of launch vehicle should have at least one stage with a geometrical configuration which is suitable for producing a lifting force for horizontal take off. Hence it might be impractical for all the stages to drop or land vertically. The lifting body or winged shaped stage may free fall or vertically land using retrofit thrust, rotary wings or a parachute, but it is absurd for a lifting shape vehicle to free fall or to take on additional mass to provide retrofit burn capability, redundant rotary wings or parachutes. In aviation technology, this type of conception of Vertical Short Takeoff and Landing (VSTOL) aircraft exists. For example, the Harrier, a deflected turbojet VSTOL, and the Ospray, a tilt rotor airplane, are capable of taking off horizontally and landing vertically to increase the operability of the vehicle. However, for the launch vehicle, this conception might be too costly to justify the extra mass of the vehicle. The reasonable way to make this combination of technology options feasible is by using an external system, such as a catapult or a maglev system, to accelerate the vehicle to a velocity high enough to produce a centrifugal force equivalent to the earth's gravity force for horizontal take off of the vehicle. However, the feasibility of this kind of system relying only on centrifugal force for horizontal take off is highly questionable from a technical as well as economical point of view. Accordingly, only nine of the 27 theoretically possible paths are practically feasible.

There is one operational launch vehicle which might be categorized as falling within the horizontal take off family. The Pegasus air launcher system, HЧЧЧ , consisting of an HTHL (H) first stage L-1011 aircraft carrier, and three additional three HTVD (Ч) stages. There are also some experimental vehicles which can be categorized in this vehicle family, among them, the X-43A experimental vehicle launch system, HЧЧ, consisting of an HTHL (H) B52 mother ship, an HTVD (Ч) booster rocket and an HTVD (Ч) experimental X-43A.

The evolutionary path marked with a dash-dot line, HHH→HH→H, shows the most sophisticated vehicle evolutionary path to emerge in terms of vehicle complexity and property of the technology in reliability and reusability. Vehicles in the path all consist of HTHL (H) type stages, the geometrical configuration of which is a complicated winged body or lifting body configuration and the subsystems of which include recovery systems such as landing gears and thermal protection systems. Since the vehicle flies through an atmospheric dense area at a high Mach number coupled with a sharp leading edge, active cooling might be required for the leading edge and the airbreathing engine may also require variable geometry for the engine inlet. All these are the factors which increase the vehicle complexity. The path marked in bold line, ЧЧH→ ЧH→H, is the least sophisticated evolutionary path to emerge in terms of vehicle complexity and property of the technology in reliability and reusability. All the stages of the vehicle in the evolutionary path, except the core stage-HTHL (H) which is destined to evolve to the SSTO configuration, are of the expendable HTVD (Ч) conception.

Case 2

Fig. 4-9 shows the evolutionary hierarchical tree for the three stage horizontal take off launch vehicle family based on the case 2 heredity ranking strategy of balanced dominance with performance priority.

As shown in the figure, the pattern of the tree branches is the same as that of the vertical take off launch vehicle family tree, as analyzed in the previous paragraph. However, as discussed above, only one sub-family group, converging to HTHL (H) SSTO launch vehicle is feasible for this family, hence only 9 paths among the total 27 technology paths are feasible.

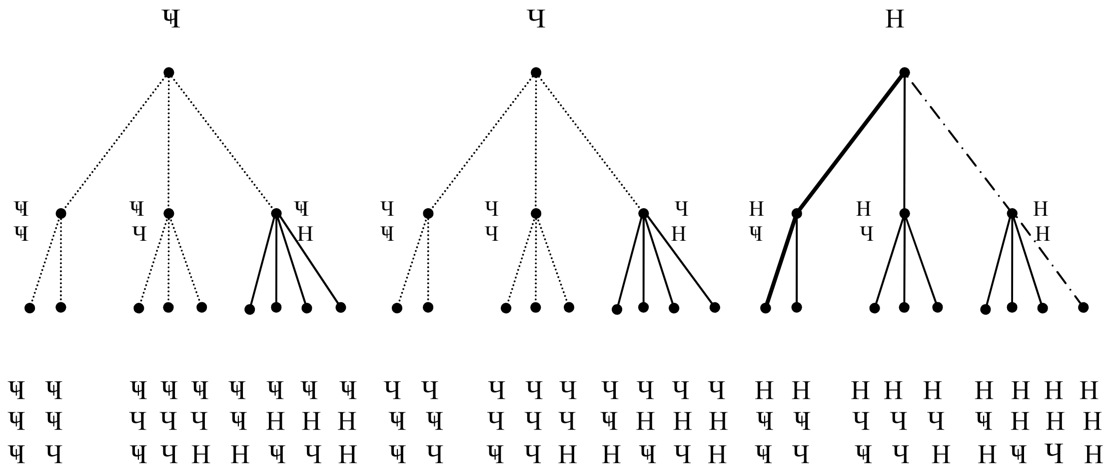


Fig. 4-9 Evolutionary Hierarchical Tree of Three Stage Horizontal Take off Launch Vehicle Family (Case 2: Balanced Dominance with Performance Priority)

As with case 1, the evolutionary path marked with a dash-dot line, HHH→HH→H, is the most sophisticated path and the evolutionary path marked in bold line, ҸҸH→ҸH→H, is a top down evolutionary pattern.

Case 3

Fig. 4-10 shows the evolutionary hierarchical tree for the three stage horizontal take off launch vehicle family based on the case 3 heredity ranking strategy with property as a primary and performance as a secondary priority. The pattern of the tree branches for the horizontal take off launch vehicle family is the same as that of the vertical take off launch vehicle family, as analyzed in the previous paragraph. However, the number of practically feasible branches is 19 branches out of the total 27 theoretical branches.

In this hierarchical tree, as with that of the vertical take off launch vehicle family, we can see a new pattern of evolutionary path, the least sophisticated, so-called bottom up evolutionary path (HҸҸ→HҸ→H) marked with a bold dash line. We also can see similar least sophisticated top down evolutionary path, ҸҸH→ҸH→H, as marked with a bold line. The evolutionary branch marked with a dash-dot line is the most sophisticated path, HHH→HH→H.

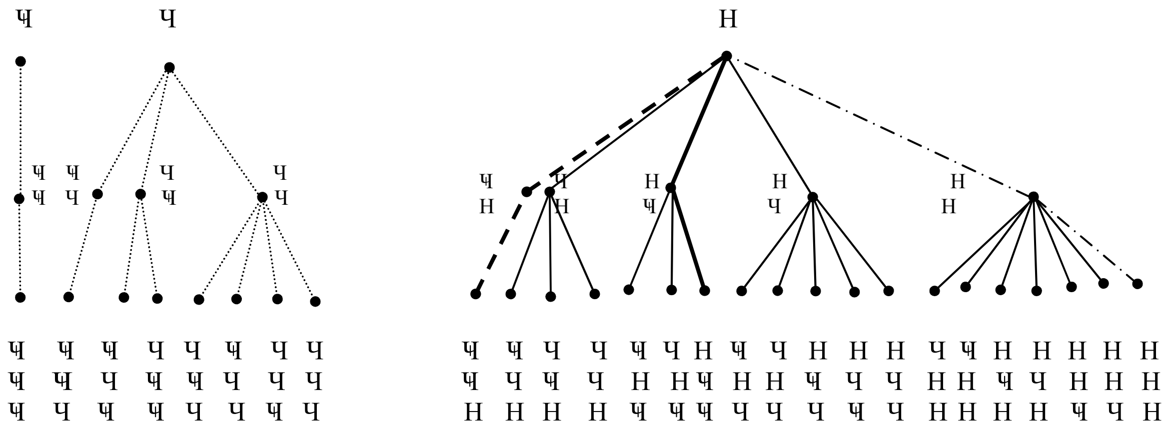


Fig. 4-10 Evolutionary Hierarchical Tree of Three Stage Horizontal Take off Launch Vehicle Family (Case 3: Property as a Primary and Performance as a Secondary Priority)

Case 4

Fig. 4-11 shows the evolutionary hierarchical tree for the three stage horizontal take off launch vehicle family based on the case 4 heredity ranking strategy, balanced dominance with property priority.

The pattern of the tree branches for the horizontal take off launch vehicle is the same as that of the vertical take off launch vehicle family tree as analyzed in the previous paragraph. However, the number of feasible branches of the technology paths would be 19 out of 27 theoretical branches.

Here, similar to case 3, we can see the top down evolutionary path marked with a bold line, ЧЧH→ЧH→H, and the bottom up evolutionary path marked with a bold dash line, HЧЧ→HЧ→H. The evolutionary branch marked with a dash-dot line is the most sophisticated path, HHH→HH→H.

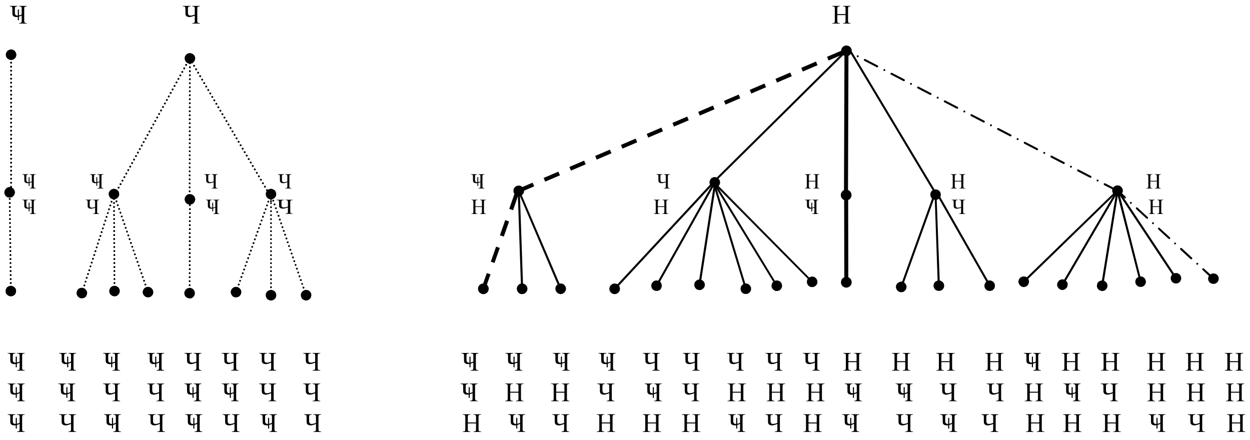


Fig. 4-11 Evolutionary Hierarchical Tree of Three Stage Horizontal Take off Launch Vehicle Family (Case 4: Balanced Dominance with Property Priority)

4.7.3 Consolidated Evolutionary Hierarchical Tree

To trade off of the evolutionary paths we do not need to analyze all the evolutionary paths. It is enough to review representative paths in terms of the complexity and the property of the technology, such as the most sophisticated path (dash-dot line) and the least sophisticated paths, both the top down evolutionary path in bold line and bottom up in bold dash line.

Fig. 4-12 shows the consolidated evolutionary hierarchical tree for launch vehicles. As seen in the figure, the culmination of the evolutionary tree is an HTHL (H) SSTO launch vehicle. However, it should be noted that the tree does not and could not show what would be the technology lock in or dominant design, but only shows exogenous factor impact free, feasible technology evolutionary paths which have been developed using the predetermined heredity ranking and growth patterns of complexity.

The real technology evolution path would be different than the typical path shown in the consolidated evolutionary path. However, it can be categorized as one of the nine representative evolutionary paths as shown in Fig. 4-12. So this consolidated evolutionary tree can be used not only for the tradeoff of the future evolutionary path as case of in this chapter but also for the evaluation of the past evolutionary path as in the case of the next chapter.

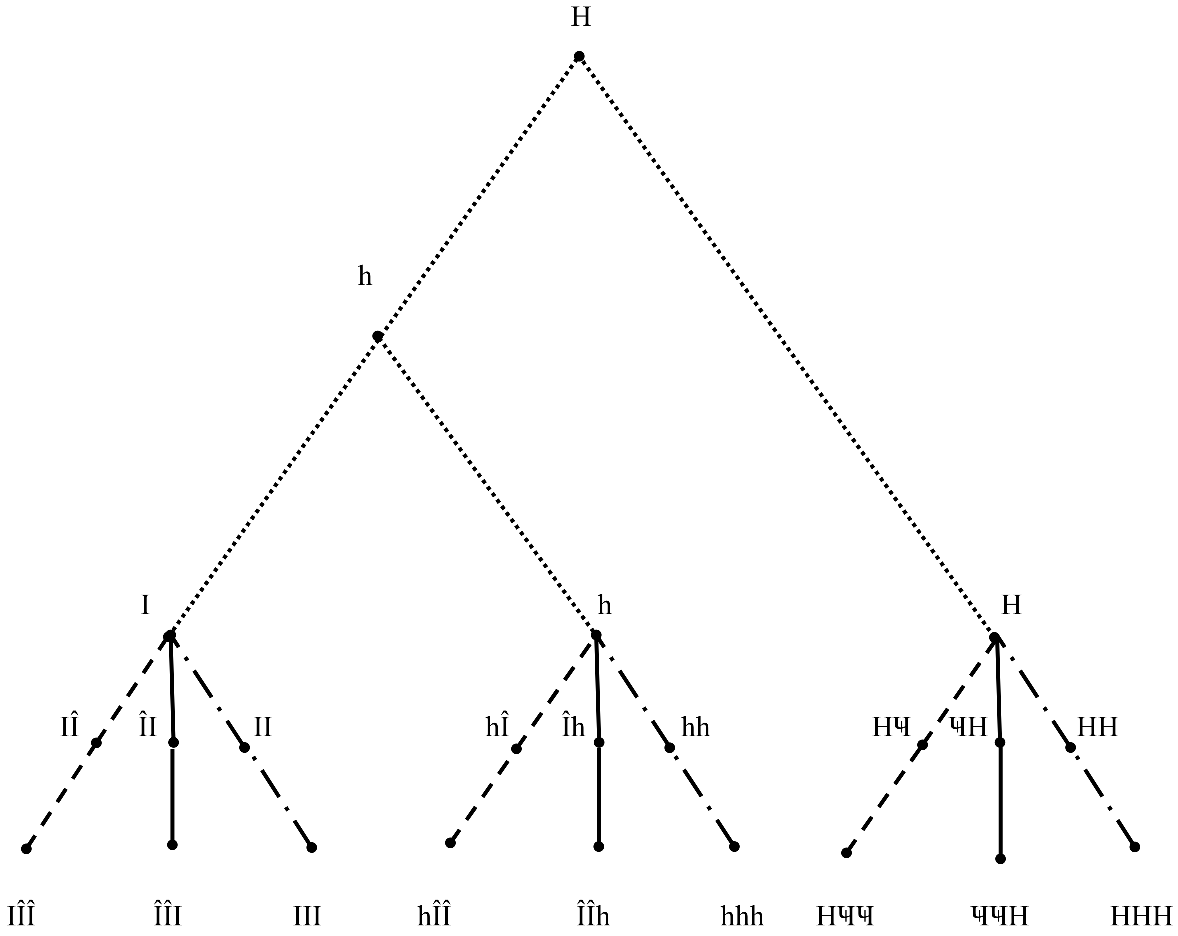


Fig. 4-12 Consolidated Evolutionary Hierarchical Tree for Launch Vehicles

4.8 Trading off Technology Evolutionary Paths

In the previous section, we constructed a feasible exogenous factor impact free technology evolution path for a STS in the form of the evolutionary hierarchical tree, any branch of which could represent the technology evolutionary path. In this section, we will trade off the evolutionary paths by means of screening the sustainability of the paths in consideration of the exogenous factors and selecting a plausible path in consideration of the evaluation factor, to be developed based on Knowledge Oriented Policy (KOP).

4.8.1 Sustainability of Technology Evolutionary Paths

History says that the superiority of a technology is neither a requirement nor a sufficient condition for its sustainable development. This is the reason why we need to screen the sustainability of technology paths using exogenous factors.

To analyse the sustainability of the paths, we do not need to see all the exogenous factors; we will only focus on the exogenous factors which are critical to the sustainability of the paths, including politics, market and environmental constraints.

The meaning of sustainability as used in this chapter is different than that used in Chapter 2. In Chapter 2, we implicitly used the term to express growth power of the market or industry. In this chapter, we use the term to express fitness of a technology option against the environment imposed by the exogenous factors.

Sustainability analysis is carried out for three representative technology options, VTVL (I), VTHL (h) and HTHL (H).

Politics

STS technology is one of the most politically sensitive technologies because of its dual use characteristic. Launch vehicle technology is heavily indebted to military missile technology. The first man-made satellite, Sputnik 1, was launched using R-7, Inter Continental Ballistic Missile (ICBM) technology on October 4, 1957. The first US satellite, Explorer 1, was launched by a Jupiter C vehicle which uses the first stage of the ballistic missile Redstone.

From the technical point of view, there is not much difference between a launch vehicle and an ICBM. Both have the capability to accelerate payloads to very high orbital, or near orbital, velocity. The difference is that launch vehicles have orbital maneuvering capability to insert a payload to a serviceable orbit while ICBMs lack this capability.

Because of the high similarity between these two vehicle technologies, the Missile Technology Control Regime (MTCR) restricted the proliferation of technology not only for rocket systems, including ballistic missile systems, but also for space launch vehicles and sounding rockets capable of delivering a payload of at least 500 kg over a range of at least 300km.

Governments influence the evolution of the technology path by directly funding vehicle development or procuring of launch vehicles, what Hobday (1998) explained as 'user push' or 'demand driven' innovation. Hence policy change is crucial for the evolution of STS technology. As experienced in the USA, the current new political initiative in space activity, Vision for Space Exploration, changed the priority of the policy for STS technology development from the next generation Reusable Launch Vehicle (RLV) to expendable heavy launcher to carry a Crew Exploration Vehicle (CEV) while cancelling or reducing the equivalent in up front investment for the development of reusable concepts.

The dual-use role is inherent in the nature of STS technology and places this technology in a highly politically sensitive environment, a factor which sometimes increases the uncertainty of the technology evolution. It is well-known that the Shuttle could have had enough cross range capability to return to the launch base after a military mission involving only one orbital revolution. In such a case, the cross range distance would exceed 2,040 km, compensating for the distance of the Earth's rotation during the orbital flight, in order to enable the Shuttle to return to the launch base. However, this requirement would rule out the ballistic capsule configuration and straight wing concept. The Shuttle would have had a larger payload bay to accommodate a huge military payload which effectively would have eliminated the lifting body design configuration.

It is certain that the future STS technology evolutionary path will be highly susceptible to the dual role mission. The dual role mission is sensitive to a vehicle's capability for responsiveness - how quickly the vehicle can prepare for a new mission after returning from a current mission - and the flexibility both in the payload capability and in capability to operate from multiple launch sites or air bases (RAND, 1997).

The VTVL (I) conception might be least attractive for the dual role mission since it might have limited cross range capability precluding return to the launch place after one orbital revolution. The VTHL (h) and HTHL (H) conceptions might allow return to the launch place after a one-revolution mission flight with appropriate cross range capability. According to the reliability and reusability of the two concepts as analyzed in Appendix C-4, the HTHL (H) conception might need less time for inspection and corrective actions than the VTHL (h) conception. Hence, the HTHL (H) concept is expected to offer higher responsiveness than the VTHL (h) conception.

For flexibility of the vehicle, the VTHL (h) conception offers variously configured payloads because the high value of Küchemann's τ enables a high payload bay, while the inverse is true for the HTHL (H) conception (Czysz, 1999). However, HTHL (H) is more flexible when it comes to the selection of the launch base since it is probably operable from airbases. Hence, these two conceptions can be considered as having a comparable flexibility.

Market

In this study, we argued that there is a potential for a big market in public space travel which would lead to sustainable development in the launch industry. The accommodation of this market is therefore evaluated for each technology option. However, this does not mean to deny the sustainability of the other technology options that could not be accommodated in this market since they could continue to support other market segments.

The public space travel market is sensitive to both the price as well as the reliability of the service (CSTS, 1994). It is evident that the VTVL (I) vehicle could not effectively serve the public space travel market because it is less competitive in reliability than other technology options. In order to evaluate the price competitiveness of the VTHL (h) and HTHL (H) conceptions, an in-depth cost analysis may be needed. However, this is neither a simple task nor is it within the scope of this study. Setting this price competitiveness aside, the HTHL (H) conception would be a more attractive conception than the VTHL (h) for the public space flight market with its superiority in reliability and the passenger friendly take off mode.

Environmental Constraints

Launch vehicle operations have various influences on the environment. Among them, the atmospheric change becomes the prominent issue since, during the process of a launch vehicle operation, a huge amount of chemical energy from the propellant changes to kinetic energy.

This is accompanied by undesirable environmental changes such as the emission of greenhouse gases and ozone depletion. In regard to the greenhouse effect, as the IPCC (1999) greenhouse effect study showed, only negligible impact might be expected by launch vehicles, since even the aviation industry, which suppose to have a far greater impact on greenhouse gases than the launch industry, showed limited greenhouse effect. Accordingly, rocket emissions might be within the permissible range for the greenhouse effect.

Regarding ozone depletion, it is widely accepted that the environmental impact of a launch vehicle is not serious because of the limited amount of launch activity. However, as the launch industry grows, environmental issues will become a more serious subject (Ross and Zittel: 2000, WMO: 2002).

Studies on the environmental impact of launch vehicles to date have focused on the solid rocket motor because of the striking impact of Hydrogen Chloride (HCl) emissions on ozone depletion. However, other emissions, such as Nitric Oxide (NO), Water Molecule (H_2O), Aluminium Oxide (Al_2O_3) or soot, might cause serious ozone depletion if the number of launches increased drastically.

Nitric Oxide (NO) is known as an ozone producer at low altitude (20-25 km) but an ozone depleter at higher altitude (Brühl et al., 1992, Roger et al., 2000, and Kinnison et al., 2001). However, the extent to which Nitric Oxide (NO) affects ozone concentration is dependent on the external atmospheric composition and the density of the Chlorine (Cl) released from Chlorofluorocarbons (CFCs) since there are titration reactions between the two ozone depleters producing Chlorine Nitrate ($ClNO_3$) and HCl both of which do not react with ozone (Brühl et al., 1992). What makes the prediction more difficult is the assimilation of the Earth's atmospheric system - ozone is continuously produced and destroyed in the natural atmosphere and hence this could act as a buffer against any changes in the disturbance caused by anthropogenic activity.

Water is a life friendly substance in general, but in certain specific circumstances this is not always true. Air is not harmful to the human body in general but a cc of air in a vein might cause loss of life. Water is not harmful for the Earth's system in general but when it is injected into upper atmosphere, in the upper stratosphere and the mesosphere, then it act as an ozone destroyer by enhancing the catalytic ozone destruction cycles involving odd hydrogen[32] (Brühl et al, 1992). Water vapor emitted from liquid hydrogen combustion will produce contrails which cause significant perturbations of Ozone and temperature in the stratosphere (Brühl et al, 1992).

It is evident that solid rocket motors are not affordable for the sustainable development of the industry in the long run. Liquid propellant engine technology might be affordable for the sustainable development of the launch industry but an in-depth study is needed to verify this, which is beyond of the scope of this study. Here, only a very preliminary assessment can be provided based on the literature study. Table 4-6 summarizes the potential ozone reactive species by fuel type.

	Kerosene	Liquid Hydrogen (LH_2)
Airbreathing Engine	H_2O, NO, (Soot)	H_2O, NO
Rocket Engine	H_2O, NO, (Soot)	H_2O, NO

( ): Soot is a possible source of the ozone depletion (WMO, 2002).

Table 4-6 Potential Ozone Reactive Species by Fuel Type

Both kerosene fuel rocket engines and Liquid Hydrogen (LH_2) fuel rocket engines produce H_2O and Nitric Oxide (NO), but the kerosene fuel engine produces soot, which is a suspected source of ozone depletion, while the LH_2 fuel engine produces a higher quantity of H_2O than the kerosene fuel engine. Both engines are supposed to produce a lesser quantity of Nitric Oxide (NO) than the airbreathing engine because Nitric Oxide (NO) is not produced in the combustion chamber since no Nitrogen (N_2) is charged in the chamber. Only a limited quantity of Nitric Oxide (NO) is produced in the after burning area, where the downstream flow of the mach disk, a strong normal shock, is subsonic with high temperature and pressure in which ambient nitrogen can be transformed into Nitric Oxide (NO) through the Zeldovich

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[32] Catalytic ozone destruction cycles involving odd hydrogen.

$$\begin{array}{l} H + O_3 \rightarrow O_2 + OH \\ OH + O \rightarrow O_2 + H \\ O_3 + h\nu \rightarrow O + O_2 \\ \hline 2O_3 \rightarrow 3O_2 \end{array} \quad \text{and} \quad \begin{array}{l} OH + O_3 \rightarrow O_2 + HO_2 \\ HO_2 + O \rightarrow O_2 + OH \\ O_3 + h\nu \rightarrow O + O_2 \\ \hline 2O_3 \rightarrow 3O_2 \end{array}$$

mechanism[33]. The area of barrel shock also allows Nitric Oxide to form; however, the total mass flow flowing through the mach disk and barrel shock is known to be negligible, in the order of about 10 % (Lohn et al., 1999).

The airbreathing kerosene fuel engine and the airbreathing LH2 fuel engine both produce H_2O and Nitric Oxide (NO), but the kerosene fuel engine also produces soot, which is a suspected source of ozone depletion, while the LH_2 fuel engine produces a higher quantity of H_2O. Both airbreathing engines produce a higher quantity of Nitric Oxide (NO) than rocket engines, since the Nitrogen (NO_2) in the air mixes to produce Nitric Oxide (NO) in the chamber through the Zeldovich mechanism where the temperature reaches to about 2,760° C at Mach 8 flight (National Academy Council, 1998). In addition to the emission impact, a quantity of Nitric Oxide (NO) will be produced in the region after the strong shock wave during ascent as well as reentry of the vehicle, where the temperature of the air increases and the Zeldovich mechanism works.

The VTVL (I) and VTHL (h) conceptions might have similar characteristics when it comes to ozone depletion impact because both conceptions are supposed to use rocket engines.

Supposing that the fuel type is the same, then the HTHL (H) conception has higher ozone depletion impact than the VTHL (I) or VTHL (h) conception because:

The HTHL (H) conception vehicle produces more Nitric Oxide (NO) than the VTVL (I) or VTHL (h) conception vehicle since The VTVL (I) or VTHL (h) vehicle have a limited Zeldovich process in exhaust fumes and in the rear region of the strong shock wave to be produced during reentry flight while the HTHL (H) vehicle produce Nitric Oxide (NO) in the combustion chamber of airbreathing engine and in the rear region of the strong shock wave to be produced during the ascent flight at high Mach speed in dense atmospheric area as well.

A firm assessment of the ozone depletion impact of the HTHL (H) conception using LH_2 fuel in the middle atmosphere is not available. However, the SÄNGAR launch vehicle study

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[33] Highly temperature-dependent chemical reactions for the formation of NO.
O2 = O + O
O + N2 = NO + N
N + O2 = NO + O

(Brühl et al., 1992) and various High Speed Civil Transport (HSCT) studies can be referred to since, in these studies, the vehicle uses an airbreathing engine with liquid hydrogen propellant. The SÄNGER study showed only minimal global ozone depletion in the case of 24 launches per year. The calculated ozone depletion by the HSCT differs depending on the simulation model. The IPCC (1999) estimated that the effect on column ozone (at 45° N Latitude) in 2050 of a combined HSCT and subsonic fleet would be –0.4 % relative to current aircraft and –1.5 % relative to a 2050 subsonic only fleet. If the quantity of the emission is the same, the ozone depletion impact of the HTHL (H) conception is supposed to be more serious than that of HSCT since most of the airbreathing flight corridor passes through the region where Nitric Oxide (NO) acts as an ozone depleter.

4.8.2 Plausibility of Technology Evolutionary Paths

In the previous section, we carried out the first step of the tradeoff of the technology evolutionary paths, the evaluation of the sustainability of the technology paths. Here, we will perform the second step, selecting plausible evolutionary technology paths from amongst the sustainable paths. There are not many referable methodologies available for the selection of plausible paths. The golden rule for selecting competing investment opportunities, cost and benefit analysis, cannot provide the answers needed because the path is a notional as opposed to a physical path and therefore it is not suitable for quantifying the resources required to build it or the benefits obtainable from it.

There are some studies quantifying the value of multi-generation product technologies based on the real options theory. Baldwin and Clark (2000) value modularity of a product by using real options approach to capture multi-generation effects. Ishii and Yang (2003) discern two types of modularity value - static value referring to the value realized in a single generation and the dynamic value over multiple generations - and propose real options and portfolio theories as a promising approach to minimizing risk and maximizing profits. However, the option value they discussed is for a specific product in consideration of the multi-generation effects and not for all multi-generation products. There should be new criteria for the selection of the plausible technology evolutionary path.

4.8.2.1 Evaluation Criteria for Technology Evolutionary Paths

In order to gain insight for the selection of the evaluation criteria for technology evolutionary paths, we will review the evaluation criteria for similar existing conceptions both technology roadmapping and scenario analysis.

Similar Conceptions

There are some conceptions which discuss the plausibility of technology paths *ex ante* - technology roadmapping and scenario analysis. We will briefly look at these conceptions in order to gain insight into the selection criteria for our case.

Roadmapping

Technology roadmapping is a widely used tool within industries. Commonality exists between the technology path we are discussing and the technology road map. Both are useful for decision-makers who intend to select a technology option today in consideration of a longer vision of technology evolution. However, the approaching attitude is different. Technology roadmapping is a passive approach since it explores what the future would be, especially relationships between evolving and developing markets, products and technology over time (Phaal et al., 2004) or elicits the best decision today in consideration of the product life cycle (Petrick and Echols, 2004).

Companies use technology roadmapping to enhance the sustainability of new product development decisions (Petrick and Echols, 2004) or to their survivability in turbulent environments by providing a focus for scanning the environment and identifying potentially disruptive technologies (Phaal et al., 2004).

Scenario Analysis

The term scenario is borrowed from the theater world, meaning the description of scenes. This technique was introduced in strategic decisions on defense and security in the 1950s and has since spread to private companies in preparing for the uncertain future business environment.

Different interest groups apply this methodology for problem solving in relation to future uncertainty when a firm definition is not available. Different groups share the same basic understanding, i.e. the scenario does not aim to foresee the future, but to show how different interpretations of the driving forces of change can lead to different possible worlds (Wigert, 2004). The scenario can be viewed as a linking tool that integrates qualitative narratives or stories about the future and quantitative formulations based on formal modelling. The scenarios are images of the future, or alternative futures; they are neither predictions nor forecasts (IPCC, 2000).

There are similarities in the attitude toward the future between our evolutionary hierarchical tree and the scenario methodology. Both methodologies are intended to make an intelligent decision to open the future evolution of a system by studying feasible paths or scenarios. The difference is that the EFIFEHT methodology we have developed is based on exogenous factor impact free evolution paths and hence there is a need to examine the influence of exogenous factors on the paths in order to conduct the tradeoff. However, the scenarios are an image of a future system, i.e. the scenarios reflect the endogenous factors as well as the exogenous factors and hence the scenario is expected to show an image of alternative futures. Scenarios can be used to analyze how current problems could develop in the future, such as the greenhouse effect or the space debris scenarios.

Evaluation Criteria for Similar Conceptions

The selection criteria for the road map and the scenario are clear. If a company uses roadmapping for their new product design then the sustainability of the product might be based on selection criteria rather than immediate profit loss evaluation. For the scenario, it depends upon the problems the scenario user encounters. If it were the greenhouse effect scenario, then the degree of warming of the Earth would be the evaluation criteria. On the other hand, if it were the space debris scenario, then the risk of the loss of the space system owing to the space debris becomes the evaluation factor.

Evaluation Criteria for Technology Evolutionary Paths

As seen in the roadmapping and scenario approaches, the criteria for evolution differ according to the objects to be evaluated and are closely related to the characteristics of the object. In order to determine the selection criteria of the technology evolutionary paths of launch vehicles, we therefore first investigate the characteristics of the technology and the industry. The nature of STS technology has two aspects - the intrinsic nature of the technology, the complex system technology, and the extrinsic nature of the technology, the dual use technology.

A Complex System Technology: Intrinsic Nature

A launch vehicle, as a complex system, is a highly customised, engineering effort-intensive good, which requires a wide range of in-depth technological disciplines in design, manufacture and operation. The dynamics of innovation in the complex system are likely to differ from mass produced commodity goods (Hobday, 1998). Avadikyan et al. (2005) explained the notion of complexity refers to the features, the variety of the components of the technology (breadth of the knowledge) and to the necessary competencies for integrating these components and the competencies to develop product technology close to the technological frontier (depth of the knowledge)[34]. In a very highly complex system and in a knowledge intensive sector, the opportunity for learning and positive feedback offers a major contribution to path dependence (Arthur, 1994) and reinforces the competence of the incumbents.

A Dual Use Technology: Extrinsic Nature

With regard to the latter, launch vehicle technology is a typical dual use technology which has largely relied upon public funding for its development as well as its use. It is a common phenomenon that most of launch vehicles of the space faring nations or any components thereof are derivatives of military missiles. The economic consequence of a dual use technology might be the formation of a critical mass of specialists and the improvement of workforce skills - a pattern of spin off (Bach et al. 1992). Contrary to the positive effect on

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[34] The parts in parenthesis are added by the author.

efficiency of resources, both human and monetary, the fluidity of the knowledge, and so the regenerative ability of the knowledge, is seriously undermined by the institutional constraints on the transfer of the technology across the national boundary which is induced by the dual use concerns.

A Knowledge Intensive Area: Need for Knowledge Oriented Policy

We have looked at both prominent aspects of the nature of launch vehicle technology but it is still hard to induce any criteria or norm which we can refer to for evaluation of the plausibility of the technology evolution path. Cohendet and Meyer-Krahmer's (2005) study on incentive policy in the knowledge based economy can provide a clue for the problem we encounter. As the Knowledge Based Economy (KBE) emerges and grows, there is an increasing need to think in terms of Knowledge Oriented Policy (KOP). Since the launch vehicle industry is a typical knowledge intensive industry involving both in-depth as well as a wide breadth of knowledge, if we look into both prominent aspects of the dual nature from a knowledge-oriented point of view, we can find that:

1. First, for the STS technology with its intrinsic nature of complex system technology, the creation of knowledge becomes crucial for the sustainable development of the technology since the depth and breadth of knowledge required to build such complex system with high standards of performance as well as property is enormous.

The efficiency of knowledge creation, and hence the learning capability, is therefore the key determinant of the competitiveness of a national industry or a firm. As Nonaka (1991) stated, "in an economy where the only certainty is uncertainty, the one sure source of lasting competitive advantage is knowledge."

Since the technology is "knowledge related to some physical object" as Howells (1995) noted, or, in our definition, the product technology is the formation of the material and knowledge into an artifact to manifest desired performance, deeper knowledge yields higher performance as well as property of the technology by which the competitiveness of a firm or a national industry is critically influenced. The performance is a key determinant of the price competitiveness while the properties, such as reliability of the product, are a key determinant of non-price competitiveness for the launch vehicle (Weigel, 2002).

Learning, as the means of knowledge creation, prevails throughout the life of the product technology, from the research activity (Atkinson, 1969, Rosenberg 1982) and production-learning by doing (Arrow, 1962) to operation-learning by using (Rosenberg, 1982) in this industry.

As Rosenberg (1982) investigated, learning by using is significant for industries where the degree of the system complexity is high. It is highly probable that learning by using plays a major role in improving product technology through feeding back the operation experience into the process of the product design to enhance embodied knowledge, i.e. product technology, or improving the efficiency of the vehicle operation by accumulation of disembodied knowledge in the operation and maintenance of the launch vehicle. The embodied knowledge impact is applicable to both expendable and reusable launch vehicles but the disembodied knowledge is mostly appropriate for reusable launch vehicles. This is because there is a wide range of areas to be improved in refurbishment of the reusable vehicle to restore its launch capability for repeated launches whereas this does not apply to expendable launch vehicles (the Space Shuttle experiences over 140,000 direct hours per flight for restoring the reusability of the vehicle[35]). With learning by doing, the expendable launch vehicle offers more chances of learning than the reusable launch vehicle with its increased production number. Only 5 units of the Space Shuttle have been produced so it is very difficult to benefit from learning from repetitive production.

2. Second, the STS technology with its extrinsic nature of dual use technology, has limit fluidity in crossing national boundaries and this lack of fluidity precludes any virtue of non-exclusive codified knowledge in this industry on a worldwide scale. The STS technology heuristic requires a high standard of documentation during the process of research, production and use, and therefore a large portion of the knowledge is produced in the form of non-exclusive and non-rival knowledge.

Romer (1990, 1993), Cohendet and Meyer-Krahmer (2005) categorized an economic form of knowledge, knowledge expressed in codified statements (“string of bits”), as the prototype of

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[35] Excluding the effort for Space Shuttle Main Engine (SSME) and for Solid Rocket Motors (SRM), adapted from http://space.com/businesstechnology/technology/armor_tps_020130-1.html viewed 15 June 2004.

non-exclusive and non-rival goods[36], which exhibit a completely public character, if one renders such goods subject to appropriation, which is almost always possible. However, even with fluent knowledge in codified form in the launch industry, the geo-political constraints induced from the concerns of the dual use of the technology strictly controls the appropriation of the knowledge produced, especially for the transaction of the knowledge across national boundaries in the name of an international regime, such as the Missile Technology Control Regime (MTCR) and a national security control system including an export license control system. Hence, the appropriation of the knowledge is highly restrictive, especially to foreign entities, and this induces a non-optimal situation for technology transfer. Each entity therefore needs to develop the competency in this technology area by itself, rather than benefiting from spillover from external knowledge creation activity, more precisely, foreign activity. This situation, coupled with national political raison d'être for creation of the knowledge in this field, justifies the sub-optimal individualized knowledge creating process from a worldwide point of view on the one hand, and makes optimization of the knowledge creating process more imminent at the local national level on the other hand, i.e. efficient learning process in the industry of a particular country becomes more important.

3. As we reviewed above, it is evident that both prominent aspects of the nature of STS technology are well recognized in reinforcing the importance of knowledge creation in the launch industry. We can therefore define the launch vehicle industry as 'a learning industry' in which the creation of knowledge is crucial for the construction of a sound launch industry.

Accordingly, we can elicit the learning capability as the evaluation factor throughout the evolutionary path. This also links well to another insight that future RLV programs could be considered as investment processes where the development of the technology, together with the process of learning, is the prime interest, until such time as the technology is mature enough to build a launch vehicle whose service price and reliability are at a level which enables the potentially huge non traditional markets to materialize for sustainable development of the launch industry, such as space power or public space flight.

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[36] A non-rival good is a good that is infinitely expandable without being diminished in quality, so that it can be possessed and used jointly by as many as care to do so, and a good is non-exclusive if it is impossible or very costly to exclude individuals from benefiting from the good. Adapted from Cohendet and Meyer-Krahmer (2005).

The efficiency has a multifaceted meaning. Economists intend to measure the efficiency in terms of monetary values by studying the relationship between the value of the end and the value of the means. Engineers may use the term as a measure of the ratio of energy consumed for useful work to total input. The definition of efficiency might differ according to the characteristics of the object being measured.

In this study, we use two factors to analyse the efficiency of learning, including facility of the learning and efficiency of knowledge creation and preservation. The former tells us whether the learning process is a logical way to obtain the knowledge, step by step from a low level to a high level, while the latter tells us the degree of reusability of the knowledge during the evolutionary process. If we adapt these norms as criteria to measure the efficiency of the construction process of the technology evolutionary path, then the path leading to an incremental learning process, minimizing the loss of knowledge through enhancing the reusability of the knowledge during the evolution process, becomes the plausible evolutionary path.

It should be noted that the plausibility of incremental learning does not deny the usefulness of radical innovation, should it happen, and in which case the incumbent knowledge becomes obsolete (Henderson and Kim, 1990). Rather, it denies the inappropriate introduction of radical conceptions of technology options without a supporting accumulated level of knowledge or breakthrough of the technology. As with the Shuttle program, the radical conception of the technology option- the reusable conception of the orbiter - without radical innovation or an accumulated level of knowledge to support the conception, causes prohibitive burdens. The Shuttle requires a huge number of direct man-hours to restore the launch readiness (about 140,000 hours), and this effectively eradicates the virtue that the radical conception might have.

4.8.2.2 Evaluate Plausibility of the Evolutionary Paths

In the preceding sections, we elicited possible evolutionary paths and then screened the paths according to their sustainability. HTHL (H) showed the highest level of fitness and therefore the highest sustainability but there is a critical issue to be clarified - the environmental constraints. The VTHL (h) conception was second in terms of general fitness but showed highest fitness in environmental constraints. VTVL (I) showed the lowest level of sustainability. Hence, this study will trade off the evolutionary paths for both the HTHL (H) and VTHL (h) conceptions. Since their evolution patterns resemble each other, we will investigate HTVL (h) only. However, the analyzed result is also extendable to the case of the HTHL (H) evolution.

As elicited previously, there are three prominent evolutionary paths for the VTHL (h) vehicle family:

hhh→hh→h - this path is defined as the most sophisticated evolution path and it also can be defined as the most knowledge intensive path since all the stages of the vehicles in the evolutionary path are of a VTHL (h) technology option. This option is the most sophisticated knowledge intensive one in terms of the breadth and depth of the knowledge to be involved to materialize the technology option which has the most complicated structure with the highest property of the product.

Since three evolutionary paths converge to a destined technology option, VTVL (h) SSTO vehicle, it is evident that a knowledge intensive path loses the knowledge most amongst the three paths during the evolutionary process; hence, the path is the lowest in efficiency of learning. At first glance, it looks like it offers facility of learning. However, if we look more closely, the level of knowledge to build the initial vehicle is still high in some critical areas such as the thermal protection system. In terms of requirements at the technology level, there is not much difference between the thermal protection system of the third stage of the initial vehicle and that of the single stage of the destined vehicle. The third stage of the initial vehicle will be exposed to almost the same reentry environment as that which the single stage vehicle will experience. In this type of vehicle, the most demanding requirement is the Thermal Protection System (TPS) for reentry. If the technology advancement and the embodied knowledge of the vehicle are not high enough to accommodate the hostile reentry conditions, then it should be paid for in another way, i.e. high operational cost resulting in the cost of excessive refurbishment man hours for the TPS (about 40,000 direct man hours per flight[37] in case of Shuttle orbiter) for every flight. In this regard, *ceteris paribus*, the facility of learning for the path can be evaluated as the lowest one.

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[37] Adapted from http://space.com/businesstechnology/technology/armor_tps_020130-1.html viewed on 15 June 2004.

hÎÎ→hÎ→h and ÎÎh→Îh→h – these two paths are less knowledge intensive evolutionary paths since each path contains the least number of VTHL (h) technology options and a maximum number of VTVD (Î) technology options which are less sophisticated, so less knowledge intensive in terms of the breadth and depth of the knowledge involved to materialize the technology option which has a less complicated structure with the lower property of the product.

With the top down evolutionary pattern, ÎÎh→Îh→h, the amount and level of the knowledge needed to construe the path is less than that for the knowledge intensive path. This is because the vehicles in the path contain the least number of knowledge intensive VTHL (h) technology options and a maximum number of VTVD (Î) technology options which have the lowest technology property and least complexity and hence require the least degree of depth and breadth knowledge. The path experiences the least amount of knowledge loss during the evolution since the phasing out stage has the least knowledge intensive configuration, VTVD (Î), and hence offers an efficient learning path. However, the path does not offer a facile path for learning since, as we reviewed in the case of the knowledge intensive path, the third stage of the first generation encounters a similar reentry environment as the SSTO vehicle which is too demanding to manage based on current knowledge.

The bottom up evolutionary pattern, hÎÎ→hÎ→h, similarly to the top down evolutionary pattern, could offer an efficient learning path since the phasing out stage has a less knowledge intensive configuration, VTVD (Î). It also offers a facile learning path since the core stage evolves from the lowest stage vehicle for which the flight environment is least hostile. The core stage could therefore progressively increase its capability in acceleration as well as in thermal protection as the technology frontier extends.

4.9 Conclusions

In this chapter, we investigated the main theme of this study, ‘tradeoff for the evolutionary paths of the Space Transportation System (STS) technology.’ In order to discuss the theme, there are two fundamental issues that need to be addressed: how to predict or construct the technology evolutionary path and how to evaluate the plausibility for the path.

The first is the most intractable problem involving the uncertainty of the technology evolution as a result of the innate uncertain nature of the endogenous and exogenous factors involved in the technology evolutionary process, and the complicated technology evolution mechanism which intertwines both the endogenous and exogenous factors which interact and evolve together to amplify the uncertainty. The second issue is also not easy to handle since the existing methodologies based on the cost and benefit analysis are no longer useful to evaluate the technology evolutionary path, which is not a physical but a notional one for which any investment or return appraisal is not appropriate.

For the problem of predicting the evolutionary path, since our objective is to seek what the evolutionary paths ought to be and not to predict what the future technology path will be, we can somehow avoid the intractable task of predicting the technology path.

We introduced a new conception, the so-called ‘Exogenous Factor Impact Free Evolutionary Hierarchical Tree’ methodology, to represent a technology evolutionary path which is purely endogenous factor directed. The core of this methodology is disintegrating the exogenous factors from the technology evolution mechanism to develop physically possible technology evolution paths based on endogenous factors only. The exogenous factors were then applied to the physically possible paths to screen out the sustainable evolutionary paths. Finally, a plausible technology path was selected by evaluating the sustainable paths.

For the rigorous way of mapping the paths, we introduced governing rules of the product technology evolution: heredity ranking or ‘weeding out’ of the elements of the technology which direct the internal process of the technology evolution by means of designating which elements of the technology are inherited by the next generation, and complexity growth patterns which direct the external process of the product technology evolution by means of directing the outer structure of the product technology represented by the number of stages in each generation.

For the evaluation of the paths, we noted two aspects of the nature of the STS technology: the intrinsic nature, a complex system technology, and the extrinsic nature, a dual use technology, which induce key characteristics of the STS technology from which the evaluation criteria of the technology evolutionary path is elicited.

We introduce new evaluation criteria, facility of learning and efficiency of knowledge creation and preservation based on evaluation of the key characteristic of the launch industry, a ‘learning industry’ where the Knowledge Oriented Policy (KOP) is essential. Both the intrinsic and extrinsic nature of the STS technology require efficiency of learning during the technology evolution. In regard to the intrinsic nature, the complex system technology, this is a knowledge intensive area where the efficiency of knowledge creation is crucial when considering the breadth as well as the depth of the knowledge. With the extrinsic nature, the dual use technology, efficiency of learning is important where the lack of fluidity of the technology transfer across the border of the country is evident.

Accordingly, we first developed a physically possible exogenous impact free technology evolutionary path using the EFIFEHT methodology, and carried out a sustainability review to find that:

1. HTHL (H) conception shows the highest sustainability considering both political and market factors but is least preferable for ozone depletion impact.

2. VTHL (h) conception shows the second highest level of sustainability in terms of political and market factors but is better than HTHL (H) in ozone depletion impact.

3. VTVL (I) conception shows the least sustainability in terms of political and market factors.

Finally, we evaluated the plausibility of the sustainable evolutionary path in consideration of two factors - the appropriateness of the accumulation process of the knowledge from a lower to higher level, and the amount of knowledge lost during the evolution process which is derived based on the evaluation criteria ‘facility of learning and efficiency of knowledge creation and preservation’ to find that:

1. The bottom up evolutionary pattern, hÎÎ→hÎ→h or HÎÎ→HÎ→H offers economic learning as well as a facile learning process,

2. The top down evolutionary pattern, ÎÎh→Îh→h or ÎÎH→ÎH→H offers economic learning but not a facile learning process.

3. The sophisticated evolutionary pattern, hhh→hh→h or HHH→HH→H offers neither economic learning nor a facile learning process.

Since environmental concern is still an open issue for both the VTHL (h) and HTHL (H) conceptions, it is highly desirable to perform an in-depth environmental impact study before any decision is made on investment for the next generation launch vehicles.

In the following Chapter, the technology evolutionary path of the US Reusable Launch Vehicle (RLV) will be analyzed based on the evaluation methodology we developed in this Chapter.

Chapter 5

A Case Study: *What is the Efficiency of the U.S. Reusable Launch Vehicle Technology Evolutionary Paths?*

> *On 14 January 2004, US President Bush announced "The Vision for US space exploration - human and robotic missions to Moon, Mars and beyond." On 4 October 2004, Brian Binnie concluded his second official suborbital flight in SpaceShipOne to win the X-prize.*

These two events are not at all comparable in terms of the amount of money involved in realizing their respective visions. The government initiative requires more than hundreds of billions of dollars over several decades to realize its vision while the purely private initiative of the suborbital conception requires only hundreds of millions of dollars.

When we look deeper under the surface of these two events, we find totally different stories. The former could be compared to spending gold for the luxurious funeral of an Emperor while the latter could be compared to spending a nickel to buy milk for a new born baby.

We will investigate what is the underlying story that has led to a long list of casualties in US Reusable Launch Vehicle (RLV) Programs.

5.1 Introduction

In the previous chapter, we looked at the main theme of the study, 'how to trade off technology evolutionary paths', in order to discuss the main argument of the study, 'What is the efficiency of the U.S. reusable launch vehicle technology evolutionary paths,' and to investigate the root cause of consecutively unsuccessful Reusable Launch Vehicle (RLV) programs.

The Space Transportation System (STS) is a very complex system and there is a mechanism for purposely selecting technology options, as Hobday (1998) explained in his theory of Complex Products and Systems (CoPS). This might be an opportunity for a wise approach in determining the technology option and the evolution path thereof.

However, historically, RLV programs in one of the countries at the forefront of RLV technology have left a long casualty list of programs. Each program has its own reasons for turning into a casualty. However, we need to know more than just the surface reason in order to avoid recurrence of such undesirable consequences in future RLV development programs. We presupposed that the sub-optimal lock-in in the technology evolutionary path was the root cause of these undesirable consequences. To examine this presupposition, our study will perform the following steps:

First, a historical study of RLV development programs with a preliminary analysis for each program, from their birth to their death, through a literature survey.

Secondly, an investigation of technology evolution paths for RLV technology using the Evolutionary Hierarchical Tree (EHT).

Finally, an analysis of the efficiency of the RLV technology evolutionary paths.

In addition to the analysis of the evolutionary paths, some strategic issues relating to the plausibility of RLV evolutionary paths, such as criticism of suborbital activity, the components technology priority strategy, etc., are also investigated in order to induce a recommendable RLV development strategy for the sustainable development of the launch industry.

5.2 Background: Policy, Activity and Motivations

US RLV policy and actual activities have shown high fluidity in the past decade, and it is only in very recent years that the industry has come to recognize the strategic deficiency in past RLV development programs yielding undesirable consequences.

Policy

On 5 August 1994, the Clinton administration established a national space transportation policy whereby they introduced the national two-track strategy of maintaining and improving current expendable launch vehicles and developing and demonstrating the next generation of reusable space transportation systems. The Department of Defense (DoD) was designated to manage the first track and NASA was designated for the second track (Fact Sheet-White House, 1994,a,b). A decade later, on 21 December 2004, the Bush administration authorized a new space transportation policy giving priority to military missions for access to space and focusing on launch vehicle technology capability for responsiveness and heavy lift capability for "Vision for US space Exploration - human and robotic missions to Moon, Mars and beyond (Vision for Space Exploration)" (Fact Sheet, 2005). Under the new policy directive, the RLV initiative is effectively transferred from NASA to the DoD.

NASA is supposed to focus on developing a heavy launcher for Crew Exploration Vehicles (CEV), which ought to be expendable, while the DoD is supposed to continue their RLV activities under the National Aerospace Initiative (NAI) focusing on the key technology for a launch vehicle which is highly responsive, so highly reusable.

Activity

In January 2004, President Bush announced his Vision for Space Exploration. This vision would seem to be a final finishing blow to enthusiasm for RLV program initiatives which is already weakened by a long list of casualties in RLV development programs - casualties such as DC-X, X-33, X-34 and X-38, coupled with the cooling down of the boom in the Low Earth Orbit (LEO) telecommunication satellite launch market triggered by the downturn of Iridium.

In another world, on 4 October 2004, a manned private rocketplane, SpaceShipOne, concluded its 2nd suborbital flight to win the 10 million-dollar X-prize, a feat which might open the door to new RLV evolutionary paths.

If we just take a snap shot image of these developments, Bush's new initiative calls for billions of dollars worth in new space transportation system development programs for expendable heavy launchers and Crew Exploration Vehicles (CEVs) which might need state of the art technology, while the private rocketplane only expended tens of millions of dollars using technology which is behind the technology frontier. However, in terms of the dynamics of technology evolution, the rocketplane has a highly dynamic potential for evolution while the expendable heavy launcher and CEV program is simply returning to the old path in terms of earth to orbit launch vehicle technology.

Motivations

The U.S. RLV activities and the political environment have experienced turmoil in these early years of the 21st century. It is only in very recent years that the industry has recognized any strategic deficiency in the past RLV programs. In reaction to the costly series of RLV program failures, debate was initiated in Congress on strategic issues such as the 'tops-down'[38] and bottoms–up approaches in 2001 during the hearing on "Space Launch Initiative: A Program Review". The current suborbital private initiative has also induced fruitful debate on the strategic issue of technology evolution of the suborbital launch vehicle.

We presupposed that the root cause of the long list of casualties in U.S. RLV programs was the sub-optimal lock-in in the technology path. This issue is coupled with the current turmoil in the RLV industry and increasing interest in strategic issues relating to RLV programs. It is therefore constructive for the launch industry since it induces fruitful dialogue during the decision making process for future RLV programs which is helpful for the sustainable development of the launch industry.

5.3 Scope, Process, and Definitions

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[38] The original term used is 'top-down' approach, we refer it as 'tops-down' approach in order to avoid confusion with the conception of 'top down' approach we studied in Chapter 4, the definition of each tem is provided in the paragraph 5.3.

We will carry out a preliminary analysis of each RLV program by means of a literature study and further analyze the efficiency of the RLV evolutionary path by studying the Evolutionary Hierarchical Tree (EHT). For the case study, we will first define the scope of the case study, and the process and key terminology used.

5.3.1 Scope of the Case Study

For this study, we are focused on earth to orbit RLV technology. The suborbital reusable vehicle technology is also reviewed since a suborbital vehicle has certain technology in common with orbital vehicles and has itself the potential to evolve into an orbital vehicle. However, Space Transportation System (STS) for beyond Earth orbit, such as a Crew Exploration Vehicle (CEV), or in Earth orbit, such as an Orbital Maneuvering Vehicle (OMV) or vehicles which have a specific mission such as a Crew Return Vehicle (CRV), are not investigated in this study. This is because the economic impact of these vehicles is not comparable to that of the earth to orbit launch vehicle. As the Augustine report (1990) aptly expressed "the most fundamental building block without which there can be no future space program is the transportation system which provides our access to space. All spacecraft and mission architectures are constrained by the characteristics of the vehicles that lift them into orbit. When things are going well in space transportation, the space program seems to flourish; when space transportation is troubled, the entire space program languishes and any other error seemingly is magnified." The focus of our interest in this study is therefore on the sustainable development of Space Transportation System (STS) technology to lead sustainable development of the space industry. In particular, our focus is on a launch vehicle operable from the Earth's surface to earth orbit since reaching the earth orbit is the prerequisite for any space activity in the earth orbit as well as beyond.

In order to study the technology evolutionary path for a launch vehicle, we can refer to the launch vehicle technology embodied in operational launch vehicles. However, if we only study the successful operational launch vehicle technology then we cannot learn from the failures. We have therefore extended the scope of this study to include RLV programs which have been cancelled or which did not even demonstrate technical feasibility. In other words, we will investigate all the contemplated RLV technologies and analyze the efficiency of the technology evolutionary paths thereof.

5.3.2 Process of the Case Study

The process of the case study is shown in the Fig. 5-1. For the case study, we first identify the study object – determine what the contemplated technology is. If we define it too strictly, then there will not be many cases available to carry out meaningful case studies. However, if we define it too loosely, to include conceptual studies, then it will also reduce the credibility of the study since it would seem as if we were analyzing fairy tales.

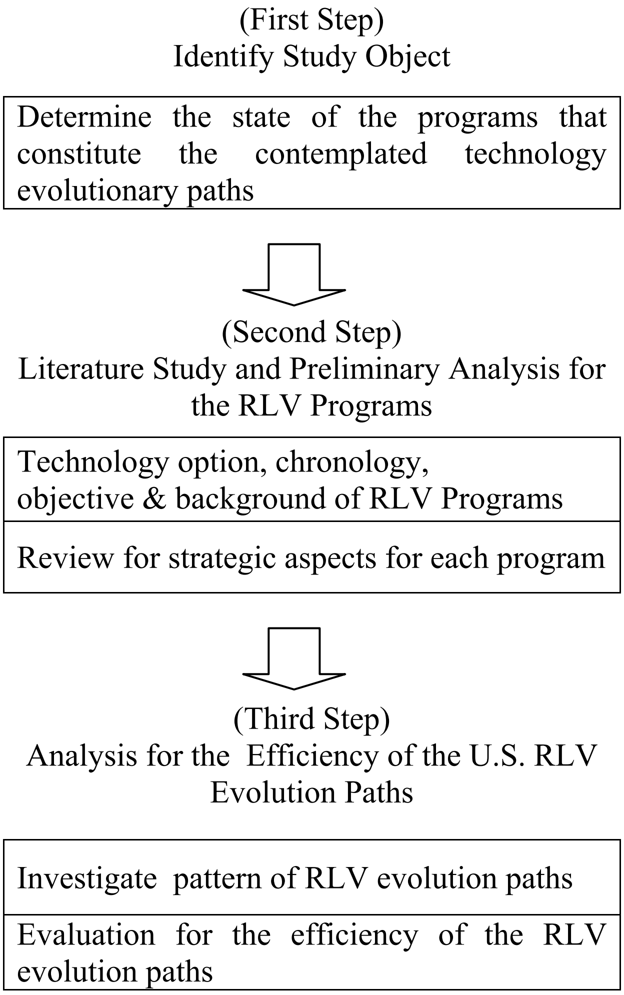

Fig. 5-1 Procedure for the Analysis for Efficiency of Reusable Launch Vehicle Technology Evolutionary Paths

Once we have determined the state of the technology development from which we can constitute the technology evolutionary paths to be contemplated, we then perform a literature study to archive data for the analysis, including data on the technology options for the launch vehicles, chronology, etc. Preliminary analysis of the strategic aspects of each program can then be performed.

By studying RLV programs at the individual level, we can see the reasons why a program has succeeded or failed. However, it is very difficult to see the dynamics of the technology evolution and to get an overview of the patterns relating to the contemplated technology evolutionary paths. We will therefore investigate the patterns of RLV technology evolution paths by using the Evolutionary Hierarchical Tree (EHT) for RLV technology and then analyze the efficiency of the RLV technology evolutionary paths.

5.3.3 Definitions

In addition to the study object, what the contemplated technology is, for the efficiency of argument, we will define the conceptions which are frequently used to explain the main argument.

Contemplated Technology:

There might be controversy in regard to what is meant by contemplated technology in the state of the technology development. From the beginning, hundreds of technology options emerge and then the number of options converges as the program proceeds. It is usual to develop launch vehicle technology step by step through a phased development approach (PDA), in order to minimize the amount of loss in case of the program failure. There are typically four steps: Phase I: base research and test, Phase II: focusing on technology demonstration, Phase III: vehicle system demonstration, and Phase IV: operational vehicle development.

Phase I	Perform laboratory research and testing of system concepts and component technology to explore evolutionary or revolutionary system concepts and component technology.
Phase II	Technology demonstration through selected flight demonstration or ground demonstration focusing on tested technology.
Phase III	Combine the component technology into a system demonstration X-vehicle to demonstrate integration technology as well as the real operability of the component technology.
Phase IV	Develop a mission capable vehicle based on the proven technology and system demonstrations.

Table 5-1 Phased Development Approach for Technology Development and System Integration (Adapted from Rasky et al., 2003)

Table 5-1 shows a summary of the phased development approach. For this study, we will investigate only the technology options which reached Phase III - the so-called contemplated technology.

For any RLV program which does not follow this Phased Development Approach (PDA), the technology option embodied in a product either as a technology demonstrator or operational vehicle will be studied. However, we do not investigate whether the technology embodied in the vehicle is mature enough to obtain the desired performance or not since our study is intended to investigate the efficiency of the envisaged technology evolutionary paths but not the actual technology paths consisting of demonstrated technology in economical or technological terms.

Technology Option of a Launch Vehicle:

In this study, to describe the technology option of a launch vehicle we used two elements – the operational option and the stage option. The former shows the patterns of vehicle take off and landing such as Horizontal Take off Horizontal Landing (HTHL), while the latter shows the operational option of a stage in a vehicle with the order of the stage in a STS. For example, the technology option of Space Shuttle can be expressed using these two elements, as Vertical Take off Vertical Drop (VTVD) first stage two Solid Rocket Booster (SRB), VTVD second stage External Tank (ET) and Vertical Take off Horizontal Landing (VTHL) third stage orbiter.

Bottom up approach:

A notion introduced in this study. A pattern of STS technology evolution, introducing the reusable conception in the lower stage of the STS, and then progressively increasing the flight regime of the reusable stage to evolve into a fully reusable Single Stage To Orbit (SSTO) vehicle step by step as the component technology frontier and the system technology evolve. Typically, this pattern of evolution starts from a vehicle configuration consisting of a reusable booster coupled with expendable upper stage, so, it can be regarded as a booster first approach. It could offer low risk in terms of technology development because the evolution is initiated from a less demanding technology option which is usually within the reach of component technology frontier.

Bottoms-up approach:

A strategy recognized by US Industry. A strategy for STS technology development focussing on the increment of the technology frontier of the component technology in order to reduce technical risk for the development of the STS by reducing the technology gap between the component technology frontier and the level of the technology needed to build a robust STS. This can be regarded as ‘component technology priority strategy,’ Top down approach:

A notion introduced in this study. A pattern of STS technology evolution introducing the reusable conception at the upper stage of the STS and then increasing the delta velocity of the reusable stage to evolve into a fully reusable SSTO vehicle. Typically, this pattern of evolution starts from a vehicle configuration consisting of a reusable orbiter coupled with expendable lower stages. It can be regarded as an orbiter first approach. The technical risk of this approach is high because the orbiter would be exposed to a hostile thermal load as well as dynamic pressure during the reentry. The level of technology needed to build the orbiter is therefore high and hence the technology gap between the technology required to build the orbiter and the component technology frontier is still large.

Tops-down approach:

A strategy recognized by US industry (the original term is 'top-down' approach, however we refer it as 'tops-down' approach in this study in order to avoid confusion with the 'top down' approach). A strategy of STS technology development focussing on exploring the optimal technology option of the STS for designated missions and then developing the component technology to materialize the technology option of the vehicle. This can be regarded as a 'technology option of the vehicle priority strategy,' or simply called 'vehicle architecture priority strategy,'

5.4 Literature Survey: Preliminary Analysis for the Reusable Launch Vehicle Programs

We can categorize the RLV programs into either mission oriented programs or technology demonstration programs. The former is a mission capable launch vehicle the technology option of which construes the technology evolutionary path of the STS technology, while the latter is focused on demonstration of the STS technology and hence there is no specific reasoning for the technology option of the demonstrator vehicle other than to facilitate a designated technology demonstration. Therefore, it is more useful to investigate what technology option of a launch vehicle would evolve from the demonstrated technology. We will investigate this technology option separately as a potential technology option.

5.4.1 Mission Oriented Reusable Launch Vehicle Programs

Seven RLV programs can be categorized as mission oriented: X-20, Space Shuttle, Pegasus/L1011 Launch System, DC-X, X-33, SpaceShipOne and the X-37 program. All these programs are for the development of orbital launch vehicles, except for SpaceShipOne which is a suborbital vehicle. All programs were also initiated by the government, except for the Pegasus/L1011 launch system and SpaceShipOne.

5.4.1.1 X-20 Program

X-20, Dyna-soar (a nick name), is a single-pilot manned spaceplane - a Vertical Take off Horizontal Landing (VTHL) reusable vehicle to be launched on the top of the expendable Titan II for suborbital missions and Titan III for orbital missions.

Chronology

Air Research Development Command (ARDC) Headquarters issued System Development Directive 464L directing the implementation of the Dyna-soar program on 21 December 1957. The Air Force awarded three contracts for the Dyna-soar program on 29 September 1961. The Dyna-soar glider was designated as X-20 on 26 June 1962. The X-20 program was cancelled on 10 December 1963.

Objective and Background

The origin of the Dyna-soar conception comes from the German Sänger-Bredt Silverbird intercontinental skip-glide rocket bomber. From the beginning, the program had a narrow mission - a manned space bomber mission. However, when the program became formal, the mission became broader. In the secret DD form 613 (R&D project card) dated 23 August 1957, it was given the confidential name of ‘Hypersonic Glide Rocket Weapon System’ or the unclassified name of ‘Hypersonic Strategic Weapon System’ (Godwin, 2003).

DD form 613 directed a three-phase approach for the Hypersonic Glide Rocket Weapon System-Dyna-soar. Dyna-soar I was to be a hypersonic research vehicle, boosted to the velocity of 5.5 km/sec and to an altitude of 100 km by a single stage and the velocity and altitude were to be increased by adding one more stage. Dyna-soar II was to be a manned hypersonic reconnaissance vehicle and the production version of the Phase I vehicle was to be boosted to 52 km altitude with the velocity of 5.5 km/sec. The pilot would monitor the operation of reconnaissance systems, and the vehicle would have interim nuclear weapons delivery capability. Dyna-soar III, was to be a fully-fledged manned, hypersonic, global, strategic bombardment and reconnaissance system. The vehicle would be accelerated to near orbital velocity at about 7.6 km/sec at 90 km altitude by a multi stage expendable launch vehicle.

Mission Blurred and Cancellation of the Program

The program goal was to develop a manned spaceplane capable of controlled reentry flight for military missions such as bombardment. However, the technology was not mature enough to produce such a vehicle and the program therefore needed to be carried out in a phased approach. From the beginning, focus was placed on the technology development and verification. The Dyna-soar I was being developed to determine the military potential of a hypersonic boost glide type weapon system, provide a basis for such development, and to research characteristics and problems of flight in the boost glide flight regime up to and including orbital flight outside of the Earth's atmosphere.[39] The program then became more research priority oriented as suborbital exploration of hypersonic flight became the primary objective and military applications were designated as only of secondary importance by the Director of Defense for Research and Engineering on 13 April 1959. At the initiative of the Air Force which disagreed with these changes, the program was revised into a three step plan on 21 July 1960 which included military missions such as reconnaissance and satellite intercept missions in orbit, and full operational military vehicles. Again, on 23 February 1962, McNamara confined the objective of the program to the development of an orbital research system to demonstrate reentry and landing of a spaceplane. In response to McNamara's direction, on 18 June 1963, the Air Force Systems Command (AFSC) redefined the program incorporating military missions including testing of reconnaissance and satellite. On 14 November 1963, the Director of Defense for Research and Engineering recommended to the Secretary of Defense the cancellation of the X-20 program and its replacement with the

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[39] Adapted from Memorandum of Understanding (MOU) between National Advisory Committee for Aeronautics (NACA) & USAF, "Subject: Principles for Participation of NACA in Development and Testing of the Air Force System 464L Hypersonic Boost Glide Vehicle (Dyna Soar I)" 20 May 1958.

Gemini-serviced space station. Finally, McNamara cancelled the X-20 program on 10 December 1963.[40]

The program was initiated as a military mission, primarily for the purposes of bombardment from the hypersonic manned reentry vehicle. Later, this mission was eliminated and the program was only aimed at in orbit military missions such as reconnaissance and spacecraft inspection. However, for in orbit missions, space station projects such as the Manned Orbiting Laboratory (MOL) project could offer more space and longer mission duration at lower cost and therefore the X-20 program lost its raison d'être.

There might be a number of reasons for why the objective of the program was to swing like a pendulum between military mission and research priority. However, the circumstances suggest that national security policy, especially in relation to the strategy of 'Mutual Assured Destruction (MAD)' which McNamara advocated during the 1960's, heavily influenced the elimination of the strike mission for the X-20 program. In order to keep the balance of MAD, the US forces needed to maintain sufficient second strike capability, even after receiving a massive surprise attack. To maintain second strike capability, it is more effective to keep weapons in a silo or in a submarine in order to increase the chances of those weapons surviving. The X-20 glider may be efficient for enhancing first strike capability as it can deliver strategic weapons with enough accuracy to penetrate difficult targets. However, it is a very expensive manned system and much more vulnerable to enemy attack than a submarine which can be dispatched in the vast sea or an Inter Continental Ballistic Missile (ICBM) which can be kept underground. In fact, McNamara had a long shopping list of munitions of this kind, including the Minuteman ICBM and the Polaris Submarine-Launched Ballistic Missile (SLBM) missiles, which could enhance the second strike capability more economically than a manned strategic bomber which is expensive and more vulnerable.

A Top down Approach

The technology option of the X-20 vehicle is a reusable orbital plane mated with expendable lower stages, i.e. an orbiter first approach. This configuration is similar to that of the Space

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[40] Adapted from http://www.astronautix.com/craft/dynasoar.htm, viewed on 17 June 2005.

Shuttle built in the 1970's and is almost same as the Orbital Space Plane (OSP) which was planned to be built in the first decade of the 21st century.

5.4.1.2 Space Shuttle Program

The Space Shuttle system is an operational launch vehicle consisting of three stages: the first stage-Vertical Take off Vertical Drop (VTVD) two Solid Rocket Boosters (SRB), the second stage-Vertical Take off Vertical Drop (VTVD) an External Tank (ET), and the reusable third stage-Vertical Take off Horizontal Landing (VTHL) Orbiter Spacecraft.

Chronology

President Nixon announced the development of a reusable Space Transportation System (STS), the Space Shuttle, on 5 January 1972. The National Aerospace and Space Administration (NASA) selected a contractor to construct the Shuttle orbiter on 9 August 1972. The rollout of the orbiter Enterprise took place on 17 September 1975 and the first flight on 12 to 14 April 1981. The 100th launch of the Space Shuttle took place on 12 October 2000 (Dick and Garber, 2004).

Objective and Background

The President's Science Advisory Committee (PSAC) issued a report in February 1967 discussing "The Space Program in the Post-Apollo Period," and addressing future launch vehicles. In the longer range, studies were to be made of more economical ferrying systems, presumably involving partial or total recovery and reuse (PSAC, 1967, qtd. Heppenheimer, 1999: 100).

In September 1969, the Space Task Group (STG)[41] issued a report, "The Post-Apollo Space Program: Directions for the Future," drafting an overall plan for the future U.S. space program in response to Nixon's request. In this report, the Shuttle is defined as a STS that can carry its payload into orbit and then return and land as a conventional jet aircraft (STG, 1969:

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[41] President Nixon established a Space Task Group (STG) in February 1969 to draft an overall plan for the next decade of the U.S. space program. The STG was chaired by Vice President Spiro Agnew, with the members of Secretary of the Air Force, NASA Administrator and the President's Science Advisor as chairman of the PSAC (Compton, 1989).

1). The Shuttle was supposed to reduce space mission costs by introducing the concept of reusability and serving as a ferry for both passengers and cargo to and from the space station module, as well as supporting a spectrum of both Department of Defense (DoD) and NASA missions (STG, 1969: 14-15).

The lack of budget[42], resulting from the lack of the support from the White House and Congress for the ambitious NASA program after Apollo, which contained a short term plan for Space Shuttle and space station and a long term plan for Moon and Mars missions, forced NASA to put the space station program on the shelf and focus on the Shuttle program. However, this in turn caused a dilemma in the justification for the Shuttle program since the Shuttle had been promoted as a service for the space station (Woods, 2003: 24). Accordingly, NASA needed more payloads to justify the huge investment for Shuttle development and the program mission was therefore changed to serve as a transport for government payloads, for both NASA and the Air Force, as well as commercial payloads. NASA needed Air Force support for their payloads as well as Congressional approval. In a testimony before the Senate space committee in March 1971, the Secretary of the Air Force stated: "…the Air Force will provide a strong recommendation that Shuttle development be authorized. When the operation system is achieved, we would expect to use it to orbit essentially all DoD payloads …" (qtd. Heppenheimer, 1999: 234). In return, NASA was expected to give priority to Air Force requirements in the Shuttle design, including the payload capacity and size of the cargo bay, and the shape of the wing to accommodate longer cross range requirement.

Air Force Requirements

When the Shuttle program emerged, no high-resolution electronic camera technology was available and hence a reconnaissance satellite would use an optical camera to capture images. It therefore took time to get the image of the surveyed area from the retrieved films. As evidenced in the Six-day war in the Middle East in 1967 and the Soviet invasion of Czechoslovakia in 1968, existing reconnaissance satellites were not well suited to swift battle maneuvers since they had been designed to follow the slow development and deployment of missiles and other strategic weapons (Heppenheimer, 1999:213). For quick access to the film

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[42] NASA requested 4.2 billion dollars including over 250 million for space station and shuttle for FY-1971, but got appropriation of only 3.27 billion dollars including 110 million for space station and shuttle (Heppenheimer, 1999: 174, 180).

images, two methods are feasible. The first is to use a manned orbital laboratory with an onboard photo interpreter to take, develop and analyze the photos. The second is to use a one-round mission spacecraft like Space Shuttle, launch the spacecraft above the target area, take a photo, and then return to the launch place for image processing (Heppenheimer, 1999:214).

Since the Earth rotates as the spacecraft is orbiting the Earth, the spacecraft should have cross range capability of about 2,040 km in order to return to the same launch place. This is distance of the Earth rotating for 90 minutes equivalent to the time of one revolution of the spacecraft in low Earth orbit. Using the Shuttle to retrieve a satellite in orbit during a once around mission is an intriguing idea. It might be possible to snatch an adversary's satellite using the Shuttle but such a mission would need to be completed before the adversary realizes their satellite is missing (Heppenheimer, 1999:215). In order to obtain the long cross range capability, the orbiter would need a delta-wing which has a higher lift to drag ratio than the straight wing originally envisaged by NASA. However, the change imposes both a high heating rate and a high total heat load which call for a double dose of additional thermal protection. The resulting Shuttle would be heavier, so more costly (Heppenheimer, 1999: 217). The Shuttle also needed a payload capacity of 18.3 X 4.6 meter and 30 tons in order to accommodate the growing Air Force reconnaissance satellite in lengths and weight.

The tight budget, coupled with large payload capacity requirements, could not offer the development of the reusable Two Stage To Orbit (TSTO) vehicles which NASA originally envisaged. In May 1971, the Office of Management and Budget (OMB) proposed to limit NASA's spending to a peak of 3.2 billion dollars with Shuttle spending rising not higher than a billion dollars per year (Heppenheimer, 1999: 331).

Orbiter First or Booster First

With the budget constraint to develop the fully reusable launch vehicle there are two alternative methodologies which can be examined for development of a vehicle: reusable booster first (bottom up approach) and reusable orbiter first (top down approach). It was Von Braun, former director of the Marshall Space Flight Center, who insisted on the reusable booster first approach (Mayers, 1970, qtd. in Woods, 2003: 21) and this was echoed by Thompson, a former X-15 test flight engineer. The basis for the booster first approach was that NASA had some tremendous gaps in the knowledge and experience required to design a successful shuttlecraft, and developing the booster would not only provide a proof of concept for a reusable booster but would also provide the next logical step to building the reusable orbiter (Thompson, 1970, qtd. Woods, 2003: 23). Mayer, the Associate Administrator for Manned Space Flight, believed that the orbiter first approach was the logical path to take because "it focuses all the attention on the toughest technology problem" (Woods, 2003: 22).

The reason why the booster first approach could not gain credibility is not clear but there are perhaps two reasons which induced the orbiter first preference, the first based on cultural aspects of NASA pursuing technological excellence and the second based on economical aspects of the technology options.

Garber (2001) explained the reason why the Space Shuttle has wings based on the social construction of technology theory. The goals of the Shuttle program and the engineering rational can explain the choice of the current Shuttle wings. However, as Garber argued, there would be reasons beyond the engineering rational for the selection of a winged Shuttle configuration. He suggested that this could be attributed to social factors, more precisely, cultural factors. The US generally, and NASA more specifically, have cultures favoring innovation over incremental modification, and the aeronautical training background of many, if not most, aerospace engineers in the late 1960s and early 1970s, combined with the relatively long tradition of spaceplane concepts, might have led the Shuttle designers to favor winged concepts. Here, Garber focussed on NASA's cultural aspects in determining the reason for a winged configuration. However, this explanation is also valid for the selection of the orbiter first conception. In terms of the technology excellence required, the bottom up approach - the booster first strategy - is not comparable to that of the top down approach - the orbiter first strategy. The dynamic pressure as well as the thermal load for the orbiter was much higher than those for boosters and the technology for the orbiter had not yet been developed, while the technology for boosters had already been demonstrated by the X-15 program.

For a review of the economic aspect, we should look back to the knowledge available at the end of the 1960s and early 1970s when the Shuttle decision was made. At this time, there was no knowledge available on the performance of the Shuttle, including the high operational costs which would be incurred by huge refurbishment efforts. If we set aside this unexpected high operational cost for the orbiter, then it is hard to deny the economic excellence of the orbiter first approach over the booster first approach. The orbiter first approach, especially with respect to the Thrust Assisted Orbiter Shuttle (TAOS), can reduce the operation cost by increasing the reusability of the system as well as reducing the development cost by half of the original development cost for the fully reusable two stage conception. The TAOS conception, consisting of a small orbiter with an expendable external tank and recoverable Solid Rocket Boosters (SRB) could reduce the development cost of the launch vehicle by reducing the size of the orbiter by removing the volumetric propellant tank from the orbiter and skipping the first stage winged booster. The expendable external tank has a simple structure and hence the cost of throw away material could be minimized. However, the booster first approach could not promise noticeable launch cost savings since it would throw away expensive upper stages which contain complicated engines and control systems. In addition to the high recurring cost of the throw away hardware, it still needs to observe a high non recurring cost to amortize a significant amount of development cost for the new launch system comprising of a reusable booster and expendable upper stages.

To achieve technology excellence is a dignified goal but it also incurs high technical risk. The orbital first approach is based on the assumption that there will be successful development of component technologies, including long life engine technology, on board systems for automated check out and highly reusable thermal protection systems. There are no strong arguments on this assumption either from the Office of Management and Budget (OMB) or Congress since this kind of technological appreciation is beyond the capability of the OMB and Congress. They may rely upon the opinion of the special committee or the hearing procedure. However, it is also difficult to expect that the experts of the committee or hearing procedure could find firm evidence to give a decisive recommendation against the appreciation of NASA since there is almost always a lack of knowledge in this early stage of a program. Even supposing that any decisive knowledge which might nullify the appreciation of NASA exists, in the cases presented either NASA overlooked the critical knowledge or acknowledged it but then disregarded it during the process of their decision making. However, this is hardly likely to occur since NASA itself is the congregation of experts and there is no reason they should disregard the hard evidence once they have acknowledged it. The Flax Committee, which reviewed the Shuttle program on behalf of the White House, only questioned the credibility of the NASA estimation on the operation cost: “The operating cost estimates of $5.5 million per flight for the shuttle, within narrow limits, must be considered to be a very rough estimate at this time, particularly for the early years of Shuttle operation. The actual value will depend upon the time between overhaul of equipment not yet designed, refurbishability of thermal protection system materials not yet out of the laboratory, and on the feasibility of operating in the Shuttle in an "airline" mode radically different from all past experience in space operations.” (Heppenheimer, 1999: 371)

In technological appreciation of highly advanced complex systems development programs like RLV programs, the entity proposing the programs becomes the real final decision-maker regardless of its hierarchical position in the decision system. It is therefore the responsibility of a proponent of the program to assess the technology risk and the impact of a failure in the technology development for the program they proposed. If the proponent overlooks this from the beginning, then there is no authority with the required expertise which can screen the wrong decision, as the case of the Shuttle demonstrated.

Break Through Conception without Technological Break Through

NASA selected the orbiter first approach, which was accompanied by a large technological gap between the available technology and the required technology. Such a gap can be filled either by a series of progressive improvements or by a sporadic break through. However, the top down approach eliminates the possibility of filling the gap by incremental innovations. In this regard, the orbiter first approach, top down approach, has innate deficiencies.

First, the approach relies upon break through technology but this occurs rather through random uncertain events than through a predictable scheduled event.

Second, occasionally, the break through could happen, but time is still needed to integrate such technology into the operational system since the launch vehicle is a complex system. For example, even with a localized break through in material technology for the thermal protection system or rocket engine, time is still needed to integrate it into the product. In order to improve the system level performance, there still remain a number of subsystems which need to be improved to accommodate the localized break through technology. However, these improvements can be obtained through continuous product design improvement. Moreover, even when the hardware improvements are completed, there is still a need for time to benefit from the improvement. Even if the hardware could offer 100 consecutive mission flights without refurbishment, it takes some time to become convinced, i.e., time is needed for learning by using.

White Elephants

The Shuttle program top down approach resulted in a ‘break through conception without technology break through.’ Such lack of radical innovation casts a long gloomy shadow over the life time of the launch vehicle.

The current Shuttle experience of incurring a huge number of man-hours for inspection and refurbishment of the main engine and Thermal Protection System (TPS) suggests that the technology is not mature enough to develop an operable reusable orbiter. The Shuttle needs 40,000 man-hours for the inspection and restoration of the orbiter TPS alone, from a total of about 140,000 hours to restore it for launch readiness. This is excluding the effort required for refurbishment of the Space Shuttle Main Engine (SSME) and Solid Rocket Booster (SRB).

The direct cause of the Columbia accident is that a large piece of insulating foam separated from the external tank, struck Columbia on the underside of the left wing and damaged the thermal protection system of the vehicle resulting in the loss of the vehicle during reentry (CAIB, 2003). In reality, the root cause was the incomplete product technology for the insulation foam which produced a shower of debris over the orbiter during the nominal take off operation. The technology causing the shower was not acceptable for a vehicle which operates in an extreme environment and where any malfunction of the vehicle can cause disastrous failure resulting in the loss of precious human lives.

In “The Space Shuttle: NASA's White Elephant in the Sky", O'Leary (1973) argued that the Shuttle would become a white elephant due to the uncertainty of the recurring cost. The Shuttle fleet, like a white elephant with its high operation cost, effectively deprived NASA of resources and prevented the effective allocation of their resources in the long run to the preparation of the next generation of RLV programs.

5.4.1.3 Pegasus/L-1011Launch System

The Pegasus launch system is an operable launch vehicle consisting of four stages: a reusable Horizontal Take off Horizontal Landing (HTHL) first stage-L-1011 aircraft, a Horizontal Take off Vertical Drop (HTVD) second stage (the first stage of the Pegasus), a HTVD third stage (the second stage of the Pegasus), and a HTVD fourth stage (the third stage of the Pegasus).

Chronology

The Program was initiated in 1987 and the first launch was conducted on 15 April 1990.

Objective and Background

The Pegasus launch system program is a private initiative. The unique feature of the Pegasus launch system is its horizontal takeoff using a carrier aircraft as the first stage of the launch system.

There might be controversy over whether the Pegasus launch system is a reusable system or not. However, it should be regarded as a reusable launcher since the L-1011 aircraft not only provides the base for Pegasus but also accelerates the vehicle as the first stage of the launch system. The Pegasus/L-1011 launch system is categorized as a partially reusable launcher by the Federal Aviation Administration (FAA) under safety approval regulations for RLV operations (FAA, 2002b).

The primary objective of the program is to reduce the cost of putting small payloads into low earth orbit. Since the launch vehicle takes off from a runway and the first stage of the vehicle, the L1011 carrier, can change its direction, it could launch its payload into any desired inclination (Air Force Fact Sheet, 2005).

Bottom up Approach

Contrary to the government initiated programs, the Pegasus/L-1011 program adapts the philosophy of the bottom up approach and is still in service for the small payload market.

5.4.1.4 DC-X Program

The DC-X was an experimental vehicle, 1/3 of the size of a planned DC-Y Vertical Take off Vertical Landing (VTVL) Single Stage To Orbit (SSTO) launch vehicle.

Chronology

The first flight was on 18 August 1993 to a height of 46 meters, and eight flights had been completed by July 1995. The maximum altitude reached was about 2,500 m, and on the eighth flight, the aeroshell cracked on a hard landing.[43] NASA developed the DC-XA, an upgraded version of the DC-X, including a Russian built aluminium-lithium alloy cryogenic oxygen tank using a graphite-epoxy composite for the liquid hydrogen tank and a graphite/aluminium honeycomb for the inter tank, and an improved reaction control system. The DC-XA first flight was on 18 May 1995 and it completed a total of four flights including the last flight on 31 July 1996. The maximum altitude reached was 1,250 m on the fourth flight. The vehicle was destroyed because one of the four landing gears failed to deploy and caused the vehicle to turn over after landing and explode. (X-33 Fact Sheet # 6, 1999)

Objective and Background

The DC-X program was designated by the Strategic Defense Initiative Organization (SDIO) as an operation demonstrator to develop an operational SSTO launch vehicle from scratch. It was then changed to a technology demonstrator by NASA.

Program Cancelled with the Fading Out of the 'Brilliant Pebbles'

The 'Brilliant Pebbles' system was intended as a countermeasure against massive missile attacks from the former Soviet Union. Since the DC-X was sold by linking it to Brilliant Pebbles, once the strategic relationship between the United States and the Soviet Union changed in the late 1980's, as confirmed by the Malta Summit in December 1989, the fate of the DC-X also changed. In January 1991, the Bush administration changed the focus of its Strategic Defense Initiative (SDI) from countermeasures against a massive missile attack to a

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[43] Adapted from http://www.astronautix.com/ls/dcx.htm, viewed on 17 June 2004.

system known as Global Protection Against Limited Strikes (GPALS). Accordingly, the required number of Brilliant Pebbles was reduced to one fourth of the original 4,000 units. The raison d'être for the DC-X SSTO therefore became no longer valid (X-33 Fact Sheet # 4, 1999).

The DC-X program was moved to the Advanced Research Projects Administration (ARPA) in September 1993 by H.R. 2401 of the House Armed Service Committee. Later, in 1994, the program moved to NASA in compliance with the policy change designating NASA to lead technology development for reusable space transportation systems such as SSTO concepts and the DoD to lead the improvement of and technology development for expendable launch vehicles.

5.4.1.5 X-33 Program

The X-33 is a half scale prototype of the VTHL SSTO Vehicle - VentureStar, designed to test a range of technologies such as thermal protection systems, advanced engine design and lightweight fuel tanks made of composite material.

Chronology

NASA issued a Cooperative Agreement Notice (CAN) for the X-33 program on 12 January 1995. It contracted for the design, construction and test-flight of the X-33 on 30 August 1996. The failure of the X-33 composite material liquid hydrogen tank # 2 occurred during the cryogenic and structural load testing on 3 November 1999. The technical problems delayed the first flight until October 2003, about four and a half years after the original March 1999 first flight date (Li, 2001a: 7). NASA announced that the X-33 program would not receive Space Launch Initiative[44] (SLI) funds on 1 March 2001 (NASA News Release. 2001).

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[44] Space Launch Initiative (SLI) was a NASA program introduced in February 2001 to develop technologies and identify options for future space transportation systems, performing the critical analysis necessary for NASA to eventually proceed with full-scale development of a new reusable launch vehicle system (NASA Facts, 2003).

Objective and Background

The objectives of the X-33 program are to demonstrate the technical, operational, and business feasibility of a privately financed and commercially operated SSTO RLV. The X-33 program consists of three Phases. Phase I is for defining the vehicle, the business investment and the operational planning to provide a basis for an administrative decision on whether to proceed to Phase II. Phase II is for the design, construction and flight demonstration of the X-33 to support the decision to proceed with Phase III. Phase III is for full-scale operational vehicle development (NASA News Release, 1995).

The X-33 program pursued the goals and guidelines of the National Space Transportation Policy issued in August 1994. Firstly, under this policy, NASA is supposed to be the leading agency for technology development and demonstration of the next-generation of RLV. Secondly, the policy provides that the objective of NASA's technology development and demonstration effort is to support government and private sector decisions to the end of the decade on development of an operational next-generation RLV. Thirdly, the policy provides for focus on research into technologies to support a decision to proceed toward a sub-scale flight demonstration which would prove whether the concept of SSTO is feasible. The decision to design and build the X-33 grew out of NASA's 'Access to Space' study which was commissioned by the NASA administrator on 7 January 1993. The study attempted to develop a comprehensive model for a launch system that would serve the needs of NASA, the DoD and the commercial launch industry (X-33 Fact Sheet # 2, 1998).

Technical Problems

The X-33 program has experienced technical difficulties in developing the advanced technologies required for key components of VentureStar, including the composite liquid hydrogen tanks, engines and the thermal protection system. The first major technical problem arose during the fabrication of the composite liquid hydrogen tank. The conical shape of the tank needs a bonding process to combine its component sections but difficulties were encountered in bonding two lobes onto a y-shaped joint in the left-hand tank (Li, 1999). The second major technical problem occurred while fabricating one of the exhaust ramps for the linearspike rocket engines. Impurities in the brazing material caused the layers of one ramp to detach during the process (GAO, 1999). The third technical problem occurred during fabrication of the thermal protection system. The thermal protection system is composed of individual heat-resistant metallic panels which are made by bonding together several layers of heat-resistant material. A high rejection rate was experienced during the bonding process (GAO, 1999). The second and third problems related to the production and hence those were dealt with relatively easily by improving the production process. The composite liquid hydrogen tank problem was a more critical one engaging premature technology. The failure of the tank during the cryogenic and structural load testing eventually caused the cancellation of the program since using composite material for the tanks to reduce vehicle weight is one of the key success points for the development of a SSTO launch vehicle and the investigation into the cause of the failure revealed that the composite technology was not mature enough for such use (NASA News Release, 2001).

Top down Approach

For the X-33 decision, similar to the Space Shuttle decision, 'the technology excellence and the economic factors' became the rationales for the top down approach, as shown in the Cooperative Agreement Notice (CAN). The goal of RLV technology such as the X-33 is a SSTO launch vehicle because past studies indicate that it has the best potential for achieving the lowest cost access to space while acting as an RLV technology driver.

According to the technical and operations technology requirements in the CAN for the X-33 program, NASA seemed to be aware of the possible operational problem of the vehicle based on the 'top down' approach. However, it could not have been aware of the innate problems of the 'top down' approach and therefore, they did not reconsider the approach. Instead, NASA only tried to avoid the problem of reusability and efficiency of the operation by tightly controlling these key success factors during the development. The specific technical and operations technology requirements for the X-33 include: (1) a minimum of fifteen X-33 flights under main engine rocket power; (2) a minimum of two X-33 flights that meet or exceed Mach 15; (3) the demonstration of a seven day turn around from landing to reflight over a minimum of three consecutive flights; and (4) the demonstration of a two day turn around from landing to reflight at least once (Dailcy, 1999).

There were debates on focussing the RLV development program on the SSTO concept. NASA's tactics to solve development risk for the revolutionary development is a phased technology maturation program for the SSTO concept that periodically pauses along the way to evaluate its progress. If at any of the designated evaluation points the Administration decides that insufficient progress is being made, the pursuit of SSTO can be called off to consider RLV concepts and possibly draw from past SSTO technology development where applicable (OTA, 1995: 52). This tactic also encounters criticism in that the SSTO is a revolutionary goal and pursuing it with vigour then having to break off that pursuit in favor of other RLV concepts may also lead to an inefficient and sub-optimal result (OTA, 1995: 52).

Program Failure

With the technical difficulties, the program experienced cost overrun, schedule delay, and degradation of the performance of the vehicle. Resolving the technical problems increased both industry and government cost. As of March of 1999, Lockheed Martin estimated that industry's contributions to complete the X-33 cooperative agreement had increased by 76 million US dollars, from 211 million US dollars to 287 million, and that the NASA civil service personnel working on the program also increased from 95 million US dollars to 113 million, which was not included in the agreed fixed contribution of NASA for the program of 912 million US dollars (GAO, 1999 and Li, 1999). The test vehicle's first flight was delayed by 16 months, from March 1999 to July 2000 and performance objectives were revised including reduction of the flight speed objective from Mach 15 to Mach 13.8, and reduction of the number of test flights from a minimum of 15 flights to 5 flights (GAO, 1999).

Despite the reconciliation efforts, the failure of the composite material liquid hydrogen tank 2, which occurred during the cryogenic and structural load testing on 3 November 1999, seriously damaged the fate of the program. Finally, on 1 March 2001, NASA announced that the X-33 program would not receive SLI funds. The Center Director of the NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama, stated: "We have gained a tremendous amount of knowledge from these X-programs, but one of the things we have learned is that our technology has not yet advanced to the point that we can successfully develop a new reusable launch vehicle that substantially improves safety, reliability and affordability" (NASA News Release, 2001).

Bottoms-up not Bottom up

It took about 37 years from the implementation of the X-20 program in 1964, and an expense of more than billions of US dollars[45], before the US industry became aware of the deficiency of the underlying strategy, the top down approach. NASA reconfigured the SLI Program by employing a new strategy that emphasizes development of launch vehicle component technologies, as opposed to starting with a launch vehicle concept as in the case of the X-20, Space Shuttle and X-33. In developing the Shuttle and X-33, NASA selected a particular design and then sought to develop the technology necessary to realize that particular design. NASA's new focus is to raise the Technology Readiness Levels (TRL)[46] of 'high – risk' technologies to determine what kind of vehicle might be built. In short, SLI's 'bottoms-up' approach is the opposite of the 'tops-down' approach taken in the X - 33 (Hearing Charter, 2001).

NASA did not define the terminology of 'tops-down' and 'bottoms-up' approaches but the meaning can be clearly understood from their work under the SLI. In SLI, NASA intended to improve the component technology of the launch vehicle before determining whether full-scale launch vehicle development would be feasible. This contrasts with what they call the 'tops-down' approach. The technology option of the launch vehicle is defined first and then the component technology is developed as needed in the course of the development of the specific technology option of the launch vehicle. The NASA conception of the 'bottoms-up' approach shares the goal of the conception of the 'bottom up approach' as both conceptions are aiming to avoid the adaptation of a technology option of the launch vehicle which requires far less mature component technology. However, the underlying philosophy is different. The 'bottoms-up' approach is a strategy seeking a logical way to determine the technology option of a launch vehicle by considering the frontier line of the component technology and selecting a vehicle technology option which is within the reach of the component technology frontier during the development of the launch vehicle, i.e. a strategy applicable to a single generation of launch vehicles. The 'bottom up' approach is a strategy seeking a logical way to determine

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[45] X-33 program cost reached to 1.5 billion dollars, X-20 also is billions of dollars program (figure for X-33 adapted from Pielke, Jr. and Byerly, Jr., 1992).

[46] Technical Readiness Levels (TRL) is a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology, has been used on and off in NASA space technology planning for many years ranging from first level corresponding basic principles observed and reported to nine corresponding actual system 'flight proven' through successful mission operation (adapted from Mankins, 1995).

launch vehicle options by considering the evolution path of the launch vehicle technology and selecting an option which offers the most plausible technology evolution path, typically introducing reusability from the lower stage, which is less demanding to develop, then increasing the flight envelope of the reusable stage step by step, i.e. a strategy applicable to multiple generations.

The industry was aware that there is deficiency in the top down approach but it seems as if they were only aware of one aspect of the problem - the technology gap between the technology needed to build a specific technological vehicle configuration and the technology frontier of the component technology. However, the industry failed to see the overall aspects of the top down approach in the line of the technology evolutionary path. Accordingly, NASA might have avoided a tops-down approach but continued another top down approach program, the X-37/Orbital Space Plane (OSP).

5.4.1.6 SpaceShipOne Program

The SpaceShipOne system is a research rocket vehicle to develop a suborbital launch vehicle consisting of two stages: a reusable HTHL first stage, turbojet powered White Knight aircraft, and a reusable HTHL second stage hybrid rocket motor powered SpaceShipOne rocket vehicle[47].

Chronology

The Program began in April 2001. The White Knight, a carrier aircraft for the SpaceShipOne suborbital vehicle performed its first flight on 1 August 2002. The suborbital vehicle-SpaceShipOne was rolled out on 18 April 2003. The first captive flight with the mated carrier aircraft-White Knight and SpaceShipOne occurred on 3 May 2003. The first powered flight of SpaceShipOne was for 15 seconds engine burn time on 17 December 2003. The first flight exceeding 100 km altitude was completed on 21 June 2004. Competition flights for X-prize were performed on 29 September and 4 October 2004 to win the prize.

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[47] The US Commercial Space Launch Amendment Act, H.R. 3752 dated on 4 March 2004, designed to enable the development of public space travel, defined a ‘suborbital rocket’ as a rocket-propelled vehicle intended for flight on a suborbital trajectory whose thrust is greater than its lift for the majority of the powered portion of its flight.

Objective and Background

The SpaceShipOne program is a privately funded program, the primary goal of which is to participate in the X-prize competition, a $10 million prize to stimulate the space tourism industry through promoting competition among the entrepreneurs and rocket experts in the world for the development of reusable suborbital launch vehicles.

The ultimate goal of the program is to demonstrate aircraft-like operations in a spacecraft to explore the new space transportation market, space tourism. SpaceShipOne is not an operational vehicle but a proof-of-concept vehicle which is scalable for operational vehicles.

Suborbital Vehicles

SpaceShipOne is not the first reusable suborbital launch vehicle. There were the suborbital conceptions of the X-15 program in late 1950s to 1960s and the X-34 programs in the late 1990s. From a technical point of view, SpaceShipOne is far less advanced than X-34 or even X-15 which flew higher than 100 km in 1963, 41 years before the flight of SpaceShipOne. Table 5-2 provides an overview of the technical specifications for suborbital launch vehicles or rocketplanes. All the suborbital vehicles use conventional turbojet aircraft as their mother ship for air launch.

	HTHL First Stage		HTHL Second Stage		Maximum Velocity (Altitude)[48]	Rollout
	Vehicle (Material)	Engine	Vehicle (Material)	Engine		
X-15	B52 (Aluminium)	Turbojet	X-15 (Inconel x)	Liquid Rocket	Mach 6.7 (108 km)	1958
X-34	L1011 (Aluminium)	Turbojet	X-34 (Composite)	Liquid Rocket	Mach 8* (76* km)	1999
SpaceShipOne	White Knight (Composite)	Turbojet	SpaceShipOne (Composite)	Hybrid Rocket	Mach 3.5 (112 km)	2003

** Based on design performance, no flight data is available since the program was cancelled before flight test.*

Table 5-2 Suborbital Launch Vehicle or Rocketplane Programs

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[48] Data from, 5 August 2005 < http://www.astronautix.com/lvs/x15a2.htm>, 9 August 2005. <http://www.fas.org/spp/guide/usa/launch/x-34.htm>, and 29 October 2004 <http://www.scaled.com/projects/tierone/logs-WK-SS1.htm>

The maximum velocity of SpaceShipOne is only Mach 3.5 but it can reach an altitude as high as the X-15 rocketplane the maximum velocity of which is about Mach 6.7. The difference is in the flight path angle for these two vehicles. The flight path angle of the X-15 is not very big and it increases its altitude in a smooth pattern. SpaceShipOne, on the other hand, has a flight path angle of about 60° when a rocket engine burns and this increases to an almost vertical angle so as to reach the highest altitude possible.

The noticeable difference between these two vehicles also relates to the thermal load encountered during the flight. As the speed of the aircraft increases, the molecules of air are pushed out of the path of the aircraft; some are accelerated to the speed of the aircraft and undergo a change in kinetic energy, and this energy is imparted to the molecules in the form of heat, where the air temperature is proportional to the square of the velocity. At Mach 6 this heat energy raises air temperature to about 1400° C within a thin layer of air near the leading edges of the wing and tail and cockpit canopy, etc. (Stillwell, 1964). The heat-energy flow into the skin from the high temperature air increases at an approximate ratio of the cube of the velocity (Stillwell, 1964). Thus, at Mach 6.7, the X-15 absorbs about seven times more heat than that which SpaceShipOne encounters at Mach 3.5 (this assumes that loss of heat energy from the aircraft by radiation from the structure back to the outside is small, in actual, in the case of the X-15; at higher temperatures, radiation becomes a predominant feature which aids in cooling the structure) (Stillwell, 1964). The temperature of the leading edge of the wing of the X-15 reaches 718° C at mach 6, which is far beyond the endurance capacity of the aluminium. However, Incornel X, an alloy of nickel and chrome successfully withstands the high temperature. Heat flow is also a function of air pressure and the stiff flight path of SpaceShipOne enables the vehicle to remain for less time at atmospherically dense low altitude and so reduces the thermal load during the ascending flight. During the reentry flight, the peculiar shape of the rear part of the wing and tailboom hinge upward to create dynamic pressure from the vehicle far behind its center of gravity making the vehicle highly stable, like dropping a shuttlecock. The drag also effectively decelerates the vehicle to reduce the maximum heat rate of the vehicle. Accordingly most of SpaceShipOne is constructed from conventional graphite-epoxy composite material.

A few selected areas use high-temperature epoxies and hotter sections are protected by a simple ‘trowel-on’ ablative thermal protection layer (Sweetman, 2004). Hybrid rocket burning solid fuel with oxidizer is not new technology, but it is less complex than liquid rocket engine technology since it skips the fuel pump. They are safer than liquid rocket engines and more efficient than solid rocket motors.

A Bottom up Approach

The flight regime of the suborbital vehicle is similar to the reusable booster, and the suborbital vehicle would increase the flight regime as the technology evolves, to become a reusable orbital vehicle. It could therefore also be regarded as a technology evolution pattern of the bottom up approach.

5.4.1.7 X-37 Program

The X-37 is a technology demonstrator for the Orbital Space Plane (OSP), a VTHL reusable vehicle to be launched on the top of the expendable Delta IV or a comparable rocket.

Chronology

NASA contracted the construction of one X-37 in July 1999. The first captive flight test of X-37 by the White Knight aircraft took place on 21 June 2005.

Objective and Background

The X-37 is a 120 % scale version of the US Air Force Research Laboratory's X-40 vehicle, a low speed approach and landing phase flight test vehicle, for a Space Maneuver Vehicle (SMV). The X-37 will demonstrate technologies for the operation of in orbit maneuvering and reentry such as non-toxic, storable propellant propulsion and power; advanced thermal protection system materials and structures; materials, structures and components for long-duration exposure to the space environment; advanced flight control systems; and algorithms for autonomous in-space, reentry and landing maneuvers. In addition to the X-37 vehicle, there would be two more technology demonstrators for the OSP including the Demonstration of Autonomous Rendezvous Technology (DART) flight demonstrator and the Pad Abort

Demonstrator (PAD) - a full scale platform for testing and assessment of crew escape technology.

A Top down Approach

In November 2002, NASA revised the second generation RLV program - SLI, to serve two emerging programs, an OSP program and a Next Generation Launch Technology (NGLT) program. NASA seemed to be elaborating their bottoms-up approach by combining it with a tops-down approach, i.e. simultaneously launching a component technology priority NGTL program and a launch vehicle program, X-37/OSP (NASA Facts, 2003).

The OSP is a mission oriented launch vehicle development program to serve the crew escape and transfer function for International Space Station (ISS). In deciding on OSP, NASA reviewed several options for future RLV development: (1) to make the decision in 2006 to concurrently build a new RLV-two stage booster to replace Space Shuttle and a crew transfer vehicle to deliver crew and cargo, (2) to develop an OSP to be flown on top of an existing expendable launch vehicle and to delay RLV booster development, (3) to develop a prototype RLV booster and build a common RLV prototype booster with the Department of Defense, with an operational booster and OSP to be developed later, and (4) to seek breakthrough technology such as hypersonic propulsion and withholding RLV development indefinitely. The decision was made to proceed with option 2 - to develop an OSP for crew rescue and crew transportation to and from ISS (Gregory, 2003).

The first option is the most sophisticated approach since there is a need to develop both reusable lower and upper stages. The second option is a top down approach - develop a reusable upper stage first, as with the Space Shuttle program. The third option is the bottom up approach – the strategy to develop a reusable lower stage first. The fourth option is a component technology priority approach.

NASA selected the top down approach for the OSP technology configuration. The selection is based on criteria and information from the complementary studies (Gregory, 2003). However, it can also be explained by the path dependency or technology momentum, with reusable orbiter technology as the main contributor to the decision.

NASA later withdrew the OSP program and transferred the X-37 to the Defense Advanced Research Project Agency (DARPA) on 13 September 2004 because NASA needed to focus on the transportation system for the Crew Exploration Vehicle (CEV).

5.4.2 Technology Demonstration Reusable Launch Vehicle Programs

There are three technology demonstration programs: X-15, X-34 and X-43.

5.4.2.1 X-15 Program

X-15 is a manned hypersonic research rocket aircraft consisting of two stages - a reusable HTHL first stage, the turbojet powered B-52 aircraft, and a reusable HTHL second stage liquid rocket powered X-15 rocketplane.

Chronology

The National Advisory Committee for Aeronautics (NACA) proposed the X-15 program to the Air Force and Navy on 9 July 1954. It contracted the development of three X-15 research aircrafts in September 1955 and contracted the development of the XLR-99 rocket engine to power the X-15 in February 1956. The first X-15 rollout occurred on 15 October 1958 and the first powered flight on 17 September 1959. The first flight to Mach 6 was on 9 November 1961 and the first flight above 91.4 km was on 17 July 1962.

Objective and Background

In order to maintain supremacy in the air, the NACA launched the X-15 rocketplane program, in cooperation with the Air Force and Navy, to make exploratory flight studies on the problems that might be encountered in space flight, such as aerodynamic heating, stability, control, and physiological problems of hypersonic and space flight (Dryden, 1956).

During the spring of 1952, the NACA Committee on Aerodynamics directed the initiation of studies on the problems that are likely to be encountered in space flight and the methods to be used such as laboratory techniques, missiles and manned aircraft. Accordingly, the NACA proposed to construct an aircraft capable of a speed of 2 km per second and an altitude of 76 km. Because of the magnitude of the anticipated cost of the program, the NACA needed the DoD's cooperation and therefore proposed the X-15 program to the Air Force and Navy. It discovered that the Air Force Scientific Advisory Board had been making a similar proposal to the Air force Headquarters and the Office of Naval Research, and these independent coinciding actions made for early acceptance of the NACA proposal by the Air Force and Navy, and eventually led to the X-15 program (Dryden, 1956).

Research Achievements

The X-15 program was to demonstrate man's ability to control a high-performance vehicle and the problems associated with lifting reentry (Stillwell, 1964).

The X-15 program, through its 199 flights, unveiled tremendous knowledge in the area of hypersonic flights including aerodynamics in the boundary layer and turbulence and aerothermal characteristics in the hypersonic air flow and their thermal and aerodynamic influence on the vehicle, the vehicle stability and control during exit from and reentry to the atmosphere, and man machine integration and pilot psychology (Stillwell, 1964). In addition to the original objective, the X-15 rocketplane carried out various experimental packages such as horizon definition and insulation that were to bear fruit in the navigation equipment and thermal protection used on the Saturn launch vehicle.[49] The X-15 program also provided data for the development of the Space Shuttle (NASA History Fact Sheet, 2001).

A Bottom up Approach Familiar Technology

The X-15 program is not a mission oriented launch vehicle program; it seeks knowledge in hypersonic flight and therefore the vehicle configuration of the X-15 is not optimized for a specific mission. However, the technological options it took, the two stage reusable vehicle including HTHL first stage and the HTHL second stage, became a model for later programs seeking a similar flight envelope for the launch vehicle, including the X-34 vehicle capability for Mach 8 velocity and SpaceShipOne capability for suborbital flight higher than 100 km.

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[49] Adapted from Encyclopedia Astronautica. Viewed on 5 August 2005, <http://www.astronautix.com/craft/x15a.htm>.

The flight regime of the X-15 might be close to the reusable booster which contributes to the bottom up approach once it is mated with the expendable upper stage. The technology to be demonstrated by the X-15 is therefore familiar with the bottom up approach technology evolutionary path.

5.4.2.2 X-34 Program

The X-34 is a technology testbed demonstrator consisting of two stages: a HTHL first stage L-1011 aircraft and a HTHL second stage X-34.

Chronology

NASA issued a Cooperative Agreement Notice (CAN) for the X-34, a reusable booster, on 12 January 1995. It contracted the design, construction and test-flight of the X-34 on 28 August 1996. Rollout of the X-34 reusable booster occurred on 30 April 1999 and the first captive carry flight was conducted on 29 June 1999. On 1 March 2001, NASA announced that the X-34 program would not receive SLI funds.

Objective and Background

In 1993, the Marshall Space Flight Center conducted a low cost launch vehicle study to assess alternatives for reducing the cost of launching small payloads into low earth orbit. The aim was to be able to launch 227 kgs into orbit at a cost of 5 million US dollars or less and to foster the development of cheaper launch vehicles by purchasing launch services and supporting joint venture activities in which a company and NASA would share the provision of resources required to develop a specific launch system (X-33 Fact Sheet # 6, 1999).

Initially, the X-34 program was chasing two rabbits, both the reusable launcher technology demonstrator and the real operable launch booster for commercial service. In regard to the latter, the X-34 was to serve small satellites of up to 1,134 kg, and consisted of three stages: a large B-747 aircraft (or L1011 aircraft), a fully reusable rocket-powered booster (X-34) and a small expendable orbital vehicle. For the former mission, the X-34 was to demonstrate autonomous ascent, reentry, and landing and consisted of composite structures, reusable liquid oxygen tanks, a durable thermal protection system, and rapid vehicle turn around (X-33 Fact Sheet # 7, 2000). However, as the design progressed, it became evident that the size, weight and the cost of the booster had grown and therefore it became difficult to achieve the goal of both technology demonstrator and commercial launcher. The initial activity under the CAN therefore ceased in the last quarter of 1995 (X-33 Fact Sheet # 6, 1999).

NASA redefined the goal of the program and removed the commercial service mission from the project concept, and launched a new X-34 program, focusing on smaller project technology demonstration objectives by issuing a NASA Research Announcement, a call for bids, on 27 March 1996. The X-34 was to have a performance capacity with speeds of up to Mach 8 and altitudes of up to approximately 76 km. Specific technologies to be built into the vehicle included composite structures, composite reusable propellant fuel tanks, an advanced thermal protection system, low-cost avionics, leading-edge tiles, and autonomous flight operation systems.[50]

Program Difficulties and Cancellation of the Program

The failure of the two missions to Mars and other deep space missions might have had an influence on the restructuring of the X-34 program (Li, 2001b), reinforcing the reliability of the vehicle. This included the redesign of avionics for redundancy, the introduction of human-supervision in lieu of the original fully automated launch, and the loss of operation concepts. These were the sources of the cost increase as well as the schedule delay (Space Access Update # 95, 2000). NASA also experienced problems in the development of engine-Fastrac[51] and in testing delay (Li, 2001a). The propellant tank design experienced problems and the airframe had a significant electrical interface problem with the carrier aircraft (Space Access Update # 95, 2000). These factors caused the schedule of the first powered flight to slip by about four years from September 1998 to October 2002 incurring an increment in cost of about 348 million US dollars - a 307% ($262 million) increase from the 1996 estimated 86 million dollars budget for the vehicle and engine development projects (Li, 2001a).

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[50] Adapted from NASA Website last modified on 6 February 2002, 9 August 2005, <http://www.dfrc.nasa.gov/Gallery/Photo/X-34/HTML/index.html>.

[51] Fastrac is named after a fast track to propelling the next generation of launch vehicle. A kerosene and liquid oxygen propellant rocket engine aiming at simplest low cost turbopump rocket engine; the engine uses much simpler pieces of machinery by using more casting parts than machined parts, skipping an expensive on board computer for engine control and instead using the vehicle's computer for simplified engine operations, and adapting ablative cooling for the nozzle to remove hundreds of feet of tediously welded tubing (NASA Facts, 1999).

On 1 March 2001, NASA announced that the increased cost induced by enhanced safety and mission success requirements for the X-34 program was not justified (NASA News Release, 2001).

Congressional Disputes

In May 1995, the Office of Technology Assessment (OTA)[52] issued a report on the national space transportation policy in which it raised the issue of the dual-track strategy for the X-33 and X-34 programs. Conceived as dual track strategy, NASA launched both RLV programs simultaneously and the Agency believed that early X-34 test flights could have a positive effect on X-33 development by steering it toward, or away from, certain technology. In addition, if the target of the three-fold cost reduction for launching the payload was achieved, then it could generate significant benefit for the government, as well as the launch industry. There is some criticism to be made of this approach. A dual-track strategy is most effective when both tracks aim to solve the same problem. However, the X-33 and X-34 programs do not address the same problem; the X-33 program is focused on developing a fully reusable SSTO to replace Space Shuttle, while the X-34 program addresses the problem of developing a partially reusable launch system for delivering small payloads to orbit (OTA, 1995: 46). The absence of any one of the two X-vehicles would not therefore increase the likelihood of arriving at the wrong technological answer because each track is seeking a different technological answer. Based on this argument, there were analysts and policymakers who suggested cancelling the X-34 Program (OTA, 1995: 46).

On 20 June 2001, three months after NASA ceased the X-33 and X-34 programs, the Subcommittee on Space and Aeronautics of the House of Representatives Committee on Science convened a hearing to review ‘Space Launch Initiative.’ During the hearing, the GAO gave testimony on their analysis of the problem of the X-33 and X-34 programs, and suggested the direction to be followed in order to avoid the problems experienced during the programs. The GAO analysis is focused on the project management. The analysis concluded that accurate and reliable cost estimates needed to be developed, technical and program risks

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[52] Office of Technology Assessment (OTA) provides in depth and more technically oriented analysis for the US Congressional members and staffs confronting technological issues in crafting public policy, while the General Accounting Office (GAO) which is primarily concerned with evaluation of ongoing programs, and the Congressional Research Service, which provides rapid information on legislative topics. OTA served for 23 years before it cease its doors in September 1995.

needed to be anticipated and mitigated, sound configuration controls needed to be put in place, performance needed to be closely monitored, and all these undertakings needed to be carried out with a high level of communication and coordination. Lack of careful implementation of such project management skills was a recipe for the program failures. (GAO, 2001)

A Bottom up Approach Familiar Technology

The underlying strategy of the X-34 program is similar to the bottom up approach since the flight regime of the X-34 is similar to that of the reusable booster and it could become a platform technology of the booster first strategy.

On the surface, the reason for the cancellation of the X-34 program appears to be that there was an increased program cost without producing any justifiable benefits. However, the underlying reason was the disappearance of the motivation to complete the program. The market situation had drastically changed since the inauguration of the program, especially with respect to the Low Earth Orbit (LEO) telecommunication satellite launch market which the program was intended for. The drastic down-turn in this market after the collapse of the Iridium program which filed for chapter 11 in August 1999, coupled with the difficulties in the Fastrac engine development deprives the X-34 program of its raison d'être, for both of the involved actors, the participating companies and NASA. The technology difficulties the X-34 experienced were different than those of the X-33. In the former case, the technology was within the technology frontier but it was essentially the lack of competence of the developers that contributed to the problem. The designer of the Fastrac engine, the Marshall Space Flight Center, did not have previous experience in designing rocket engines and most of the participating companies were new to rocket technology. As such, it is less of a contingent in the problem solving for X-34 since the problem can be solved either by borrowing existing knowledge or by an independent creation process, while the problem for X-33 can only be solved by creation of the technology since no knowledge exists to solve the problem.

5.4.2.3 X-43A Program

The X-43A is the first series of vehicles for the experimental hypersonic flight-research program, hyper-X program. The experiment is carried out with a three stage vehicle consisting of a HTHL first stage B-52 aircraft, a HTVD second stage: modified Pegasus rocket booster, and a HTVD third stage: X-43A.

Chronology

The X-43/Hyper-X was contracted in January 1997. The X-43/Hyper-X vehicle arrived at NASA Dryden in October 1999. The first captive flight took place on 28 April 2001. Two controlled accelerating flights at Mach 6.8 were concluded on 27 March 2004 and a 10 seconds scramjet burn at Mach 9.6 on 16 November 2004.

Objective and Background

Hyper-X research began with conceptual design and wind tunnel work in 1996. The Hyper-X program sought to demonstrate airframe-integrated, airbreathing engine technology to propel hypersonic aircraft (faster than Mach 5) and the first stage of a RLV. Since the airbreathing engine allows for more airplane-like operations with increased affordability, flexibility and safety, the first stage launch vehicle adapting the technology will also offer more airplane-like operations capability. The X–43A was a critical step in the development of scramjet technology which was included in the National Aerospace Initiative (NAI) Hypersonic roadmap.

In addition to the X-43A vehicle which incorporates a hydrogen fuel burning scramjet engine, the X-43 program included two additional X-vehicles, the X-43B and X-43C. The X-43B vehicle would incorporate a turbine based combined cycle engine or a rocket based combined cycle engine that functions as a normal turbojet or rocket engine at low altitude and velocity, and switches to ramjet and scramjet mode at high altitude and Mach number. The X-43C would incorporate a hydrocarbon fuel burning scramjet engine. Both the X-43B and X-43C programs were cancelled in March 2004 because NASA needed to mobilize its resources to support the President’s Vision for Space Exploration of January 2004 and the X-43 did not fit into the exploration systems development program.[53] However, Congress directed NASA to continue design work on the Hypersonic X-43C vehicle by adding an appropriations amount of 25 million US dollars (CRS, 2004).

A Bottom up Approach Familiar Technology

The underlying strategy of the X-43A program is similar to the bottom up approach as the technology to be demonstrated could be used for a reusable HTHL airbreathing engine powered first stage booster.

From the beginning, the X-43 vehicle wore two hats: one for the NASA NGTL program and another for the DoD's National Space Initiative (NAI). The NGTL program was launched to seek the development of RLV technologies needed for safe, routine, space access for scientific exploration, commerce and national defense. Since the inauguration of the President's Vision for Space Exploration in January 2004, the NGTL program has been closed in order to channel support to the CEV and heavy lift off launcher. The X-43 vehicle now only supports the DoD's NAI.

The X-43 program is a stepping stone for one of the three pillars of the NAI program, the first pillar of which is High-speed/Hypersonics (HS/H). The remaining two pillars are Space Access (SA) and Space Technology (ST) (DoD, 2003).

5.5 Analysis for the Efficiency of the U.S. Reusable Launch Vehicle Technology Evolutionary Paths

In the previous paragraph, we studied the U.S. RLV programs from their birth to the death of each program and analyzed the underlying strategy of the RLV program at the individual level. In this section, we will figure out the US RLV technology evolutionary path using the

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[53] The Exploration Office Head Craig Steidle stated that "The X–43C, did not fit our particular needs at this particular point for an exploration systems development program, so it was, indeed, terminated," during a hearing on "NASA–Department of Defense Cooperation in Space Transportation," House of Representatives, Space and Aeronautics Subcommittee. Washington, D.C. 18 March 2004.

evolutionary hierarchical tree to analyze the efficiency of the path. The strategic issues in relation to the RLV technology evolutionary paths will also be discussed.

5.5.1 Reusable Launch Vehicle Technology Evolutionary Paths

In addition to the contemplated technology evolutionary path based on mission oriented programs, we will review potential technology evolutionary paths based on the RLV technology demonstration programs.

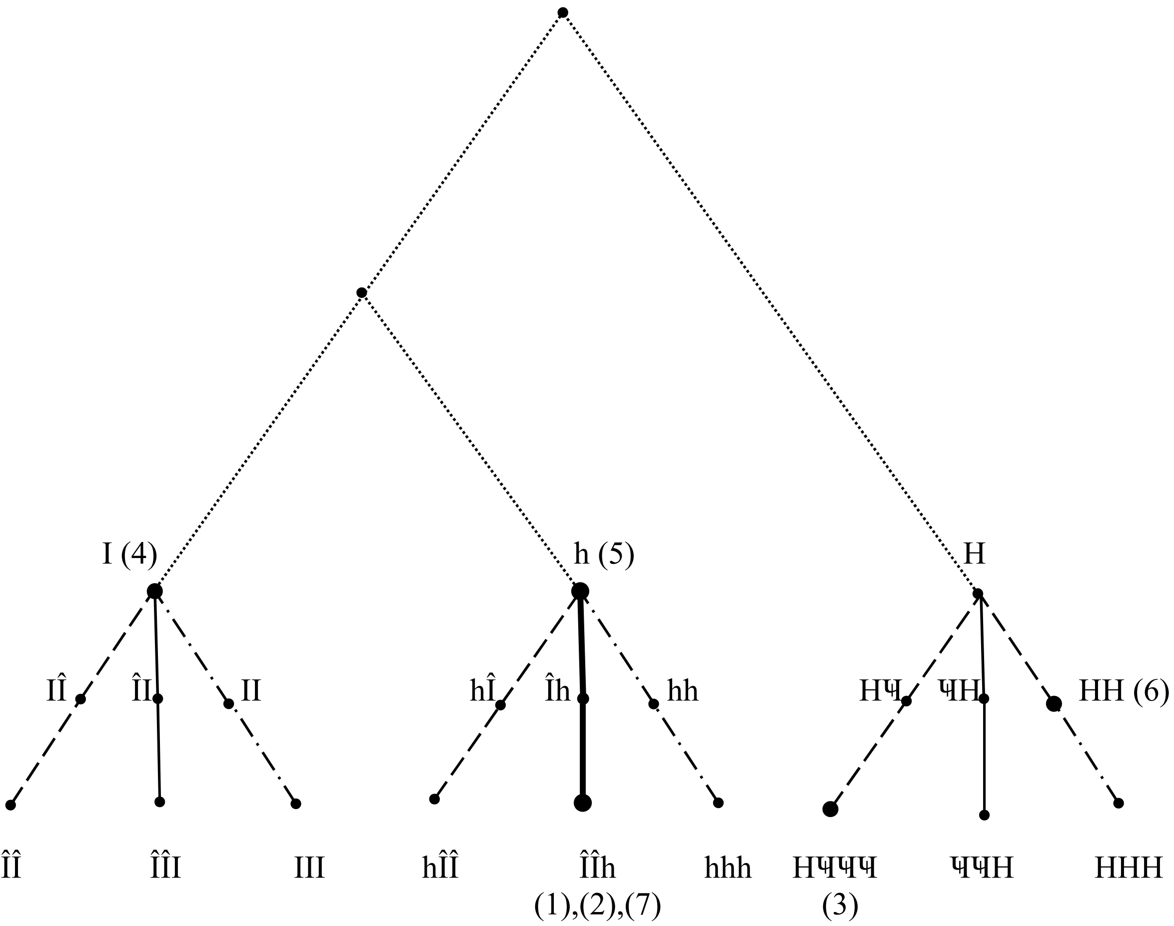
Contemplated Evolutionary Path

When we look into the U.S. RLV programs on an individual level, it looks like chaotic and as if there is no coherence among the technology options of the programs. However, if we review the RLV programs from the technology evolutionary point of view, then we can see that there is coherence in pursuing the top down approach. Fig. 5-2 shows contemplated technology evolutionary hierarchical tree of the U.S. RLV programs to date.

The programs represented by a number in a circle are the RLV programs of which the technology option is fixed, i.e. the architecture of the vehicle is fixed. The order in the figure is based on the time of vehicle rollout, except for the X-33, for which the program termination date is referenced.

The branch on the left of Fig. 5-2 is the sub-family of launch vehicles which are supposed to evolve to VTVL SSTO launch vehicles. The branch in the middle of the figure is the sub-family of launch vehicles which are supposed to evolve to VTHL SSTO launch vehicles. The branch on the right of the figure is the sub-family of launch vehicles which are supposed to evolve to HTHL SSTO launch vehicles.

Each node of the tree denotes the technology option of a launch vehicle. The symbols Î, I, h, Ҹ, Ч, H denote VTVD, VTVL, VTHL, HTVD, HTVL, HTHL operational options respectively. The order of the symbols denotes the order of the stage. The launch vehicle option, ҸЧH, means an HTVD first stage, HTVL second stage and HTHL third stage vehicle. The small dotted node means there is no contemplated RLV program for this technology option and the bold dotted node means there are contemplated RLV programs for this technology option. The line represents the technology evolutionary path which is based on the top down approach, i.e. introducing reusability to the orbiter first strategy.



Legends: 1: X-20 (1964), 2: Space Shuttle (1974), 3: Pegasus/L1011 (1990), 4: DC-X (1993), 5: X-33 (2001), 6: SpaceShipOne (2003), 7: X-37 (2005)

Fig. 5-2 U.S. Reusable Launch Vehicle Contemplated Technology Evolutionary Hierarchical Tree

A dashed line represents a technology evolutionary path which is based on a bottom up approach, i.e. introducing reusability to the booster first strategy. A dash-dot line represents a technology evolutionary path which introduces reusability to all stages and is therefore the most sophisticated evolutionary path.

As can be seen in the figure, there is one contemplated technology evolution path with a top down approach, ÎÎh ((1), (2), (7)) → h ((5)), shown in bold line. It is interesting to note that all the RLV programs in the top down path are government initiated programs.

Two privately initiated programs, (3) and (6), are shown in the path of the pattern of the bottom up approach but we could not constitute the corresponding evolutionary path because of a lack of sufficient programs to constitute paths. The path HH→ H is usually a sophisticated evolutionary path for an orbital vehicle. However, the suborbital launch vehicle concept, as appeared in SpaceShipOne ((6)), should be regarded as a bottom up approach because the flight regime and the level of the technology of the suborbital vehicle technology is similar to the reusable booster technology which is the typical first stage for bottom up approaches (see Table 5-2 for the technological comparison). Also, and more importantly, the evolutionary pattern of the suborbital vehicle follows the typical pattern of the bottom up approach, i.e. a step by step increase in the flight regime of the vehicle to reach that of the orbital vehicle.

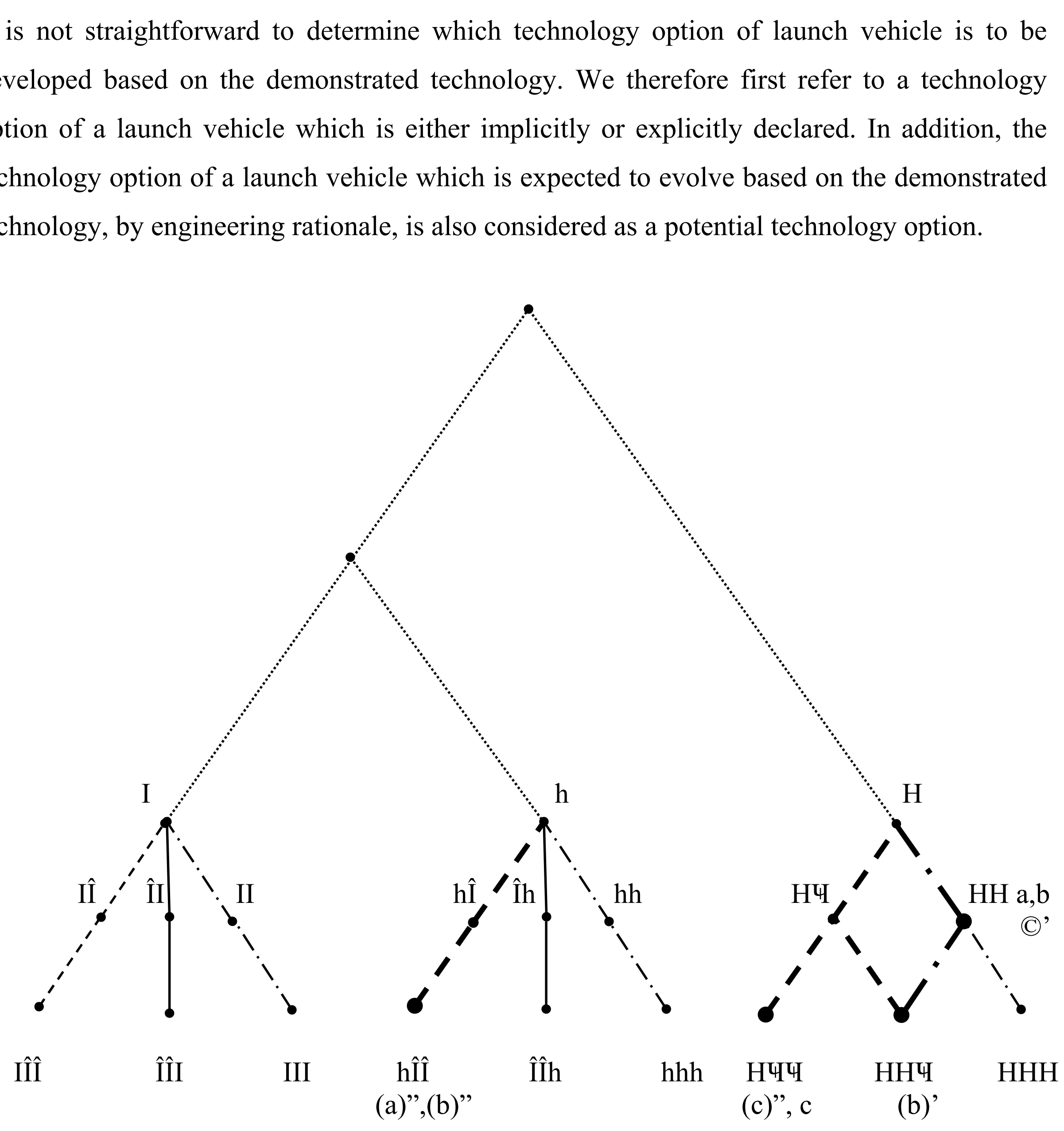
It also shows a small cluster for the technology option of ÎÎh ((1); X-20, (2); Space Shuttle, (7); X-37). There is only one program which belongs to the VTVL SSTO sub-family – the DC-X ((4)). It could not constitute the path but the technology gap between the technology frontier and the requirement to build VTVL SSTO is still high and therefore it could be regarded as top down approach as well.

As we reviewed in the previous section, the consequence of the top down approach is less than sub-optimal. The cluster of government initiative RLV programs in this sub-optimal evolutionary path indicates that there is no wisdom of foresight in the selection of the technology option and resultant technology path for the complex system-RLV. Rather, it confirmed that the path dependency (Arthur: 1983, David: 1985) or momentum of the technology (Sahal, 1985b) acts as the dominant factor for selection of the technology option and the technology path thereof. It is not surprising that the two privately initiated programs show a different evolutionary pattern, bottom up approach, since the decision mechanism and motivation for the programs differs from that of the government initiated programs.

Potential Evolutionary Paths

The technology demonstration vehicles themselves have technology options, as represented in the node marked with a letter in Fig. 5-3. However, these options are for the convenience of the technology demonstrations and hence there is no meaning in terms of technology evolutionary path. Rather, the technological options of a vehicle to be developed based on the demonstrated technology, as shown by the circled letters, are more important because they have the potential to construe the technology evolutionary path.

It is not straightforward to determine which technology option of launch vehicle is to be developed based on the demonstrated technology. We therefore first refer to a technology option of a launch vehicle which is either implicitly or explicitly declared. In addition, the technology option of a launch vehicle which is expected to evolve based on the demonstrated technology, by engineering rationale, is also considered as a potential technology option.



Legends: a: X-15 (1958), b: X-34 (1999), c: X-43A (1999)

Fig. 5-3 U. S. Reusable Launch Vehicle Potential Technology Evolutionary Hierarchical Tree

As shown in Fig. 5-3, there are two potential technology options for launch vehicles which are explicitly or implicitly declared, as marked with a circled letter with a single quotation mark, both (b)’ and (c)’. The former is a technology option declared in the X-34 program - a three stage RLV including a HTHL (H) first stage airplane such as a large B-747 aircraft (or

L1011 aircraft), a HTHL (H) reusable rocket-powered second stage booster, a X-34 derivative, and a HTVD (Ч) small expendable third stage vehicle (X-33 Fact Sheet # 7, 2000). For the latter case, which is implicitly announced in a technology road map, the NAI technology road map shows that the airframe-integrated airbreathing engine technology to be developed by the X-43A program could be used for a HTHL (H) first stage reusable airbreathing engine powered booster to be mated with a HTHL (H) rocket engine powered second stage launch vehicle (DoD, 2003).

There are two technology options which could feasibly emerge from the demonstrated technology, as marked with a circled letter with double quotation marks, (a)", (b)" and (c)". The reusable booster technology to be developed by the X-34 program or X-15 could be useful for the three stage RLV such as a VTHL reusable rocket powered first stage booster (X-34 or X-15 derived vehicle), and two VTVD expendable upper stage vehicles. Similarly the airframe-integrated airbreathing engine technology to be developed by the X-43A program could be used for a HTHL (H) first stage reusable airbreathing engine powered booster to be mated with two HTVD (Ч) upper stages.

Contrary to the contemplated evolutionary path of government initiated mission oriented RLV programs which are clustering in the top down approach, no potential technology paths are shown in this pattern. This is because all the technology demonstration programs are focused on the technology required for the reusable booster rather than the orbiter.

The bottom up approach could be the most common possible technology option based on the demonstrated or to be demonstrated technologies, as marked (a)", (b)" and (c)".

The technology option HHЧ, based on the X-34 technology as marked (b)', could evolve either to HЧ to construe a bottom up evolutionary pattern, or to HH to construe a sophisticated evolutionary path.

The potential path foreseeable by the technology option HH based on the X-43 technology, as marked ©', showed the least optimal approach in terms of a sophisticated evolutionary path. These are the results of the strategy of the three-pillar approach in the NAI program. We will discuss the three-pillar approach in paragraph 5.5.3.

5.5.2 Efficiency of the Reusable Launch Vehicle Technology Evolutionary Paths: Top down vs Bottom up Approach

There are two contradicting U.S. RLV evolution paths, the top down approach path, which has been ruling all government initiative, mission oriented RLV programs, and the bottom up approach which is emerging with private initiatives, both for air launched partially reusable small payload launchers and for suborbital RLV programs, and which is also foreseeable from the technology demonstration programs.

In terms of learning and knowledge creation, the bottom up approach is more plausible for developing product technology, especially for a knowledge intensive industry since it offers an efficient way for knowledge accumulation as well as the preservation of knowledge during the evolutionary process. The bottom up approach could increase the flight regime of the reusable first stage booster step by step follwing or leading progressive technology advancement. Hence, it offers minimum risk in the development as well as promotes learning by using for this knowledge intensive complex systems.

There might be feasible evolution from the bottom up approach when considering private initiatives such as the Pegasus/L1011 launch system and SpaceShipOne. The former has remained in service for the small payload market since 1990; the latter is a technology demonstrator where the operable launch vehicle has not yet been introduced to the market. More time and more cases may be needed to confirm the formation of the bottom up approach and the plausibility of this path.

For the top down approach, the number of programs provides evidence that the approach is not plausible since it is not only too risky in terms of technology, as the X-33 demonstrated, but is also too much of a cost burden to operate, as the Space Shuttle case demonstrated.

In addition to the direct unsatisfactory consequences, the top down approach has indirect but significant drawbacks. The launch fleet adapts premature technology with, like the white elephant, huge operation costs which drain the allocation of resources and prevent timely launching of the next generation of vehicles, as shown in the case of the Space Shuttle and the US second generation RLV program. The engineers and managers who participated in the development of the Space Shuttle, supposing they were 27 year-old new comers in 1975 when the first orbiter was rolled out, now would be around 57 years old. The codified knowledge may be well kept, but the tacit knowledge is hard to maintain over such a long period. The evaporation of the knowledge learned in development and production is therefore inevitable and has a serious impact on the preservation of knowledge, especially non-codified knowledge, during the technology evolution in this knowledge intensive industry.

Accordingly, our argument for preferring the bottom up approach over the top down approach is half proven. It is expected that the remaining half might be proven when considering the accumulation of successful RLV programs which have adapted the bottom up strategy, such as the DoD's Affordable Responsive Spacelift (ARES) program[54] and current suborbital private initiatives for the space tourism market.

5.5.3 Strategic Issues for Reusable Launch Vehicle Technology Evolution

In reaction to the costly experience of RLV programs based on the top down approach, U.S. industry became aware of the strategic deficiency of the RLV programs and NASA introduced the bottoms-up approach or component priority strategy in NGLT. The DoD also introduced a three pillar strategy for their NAI program. Current suborbital activities open up a new pattern for the technology evolutionary path and also trigger fruitful arguments on the technology evolution for the RLV.

Bottoms-up and Bottom up Approach

The US RLV industry awoke to the importance of strategy for RLV development and came to focus on increasing the maturity of the component technology in NASA's Next Generation Launch Technology (NGLT) program and on avoiding the selection of launch vehicle technology option architecture which has too much of a technology gap between the component technology requirements for building a specific architecture and the available component technology, the so-called bottoms-up approach or component technology priority approach.

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[54] Affordable Responsive Spacelift (ARES) is a contemplated two stage launch vehicle under NAI, consisting of a reusable first stage Liquid Fly Back Booster (LFBB) equipped hydrocarbon propulsion rocket engine as well as a jet engine and expendable upper stages (Knauf, 2005).

The component technology priority approach is a practical strategy since it could reduce the technology risk in developing launch vehicles. However, the component technology priority itself is not sufficient. There is a certain limit in this approach if it is matched with the technology option of a vehicle in the sub-optimal path because:

First, there would be problems in learning. The launch system is a highly complex system where the opportunity for learning and positive feedback contributes significantly to the path dependence (Arthur, 1994) and reinforces the competence of incumbents. Learning comes from a series of procedures encompassing the research and development (Atkinson, 1969, Rosenberg 1982), production-learning by doing (Arrow, 1962), and operation-learning by using (Rosenberg, 1982). For the reusable space transportation system, the process of learning by using is significant since it not only accumulates the knowledge for operation & maintenance, such as the Time Between Overhaul (TBO) which is essential for economical operation of the reusable system, but it also feeds back to the development process resulting in continuous upgrades of the product to enhance maintainability and operability. As evidenced in the aviation industry, the synergetic effect of the technology advancement, through the close interaction between the manufacturer and the user, cannot be disregarded. The component technology priority approach provides less opportunity for these positive synergetic interactions when it is matched with too demanding a technology option since it takes a longer time to extend the technology frontier to accommodate the demanding technology option. This prevents the frequent introduction of a new generation of launch vehicle, or its derivative, allowing synergetic interaction between manufacturer and user.

Second, there would be problems in localized advancement of the component technology. Component technology typically advances in localized patterns. A breakthrough in a key component technology should be followed by advancement in the peripheral component technology in order to acquire the performance advancement at the system level and this can be feasible through continuous modification of the components. The component priority approach may handle the problem by using design iteration and prototypes. However, it is very difficult, though not impossible, to solve the entire problem using only design iteration and prototyping.

Where the component technology priority approach is deficient, it is complemented by the bottom up approach. The bottom up approach, with minimum investment, through development, manufacture and operation of a reusable booster or a suborbital vehicle, provides positive feedback for operation and maintenance of the vehicle for product improvement, i.e. learning by using. This, through continuous upgrading of the vehicle and introduction of a new generation or derivative of the new generation vehicle, results in balanced improvements in the component technology as well.

These two approaches are not mutually conflicting but actually complement each other. Paralleling these two strategies, bottoms-up (components technology first) and bottom up approach, therefore offers a good strategic option for RLV development. In this regard, the NAI's High-speed/Hypersonics (HS/H) program deserves high strategic interest, and the current Congressional decision to resurrect the X-43 program is a good example of how one of the actors of the iron triangle can create a positive balanced strategic decision in the area of space policy. The airframe-integrated airbreathing engine technology to be demonstrated by the X-43 is the result of the bottoms-up approach but the technology to be demonstrated is a key technology for the development of a HTHL airbreathing engine powered first stage booster which can be mated with expendable upper stages to construe the bottom up approach.

Dual Pillar Strategy

The National Aerospace Initiative (NAI) technology roadmap consists of three pillars: High-speed/Hypersonics (HS/H), Space Access (SA) and Space Technology (ST) (DoD, 2003). Since the third pillar relates to payload technology, we will focus only on the dual pillar strategy which is directing the launch vehicle technology evolutionary paths.

Since the existing NASA RLV initiatives have ceased by the initiation of President Bush's Vision for Space Exploration, the DoD's NAI has become the center of U.S. RLV activities.

Of the three pillars, the first HS/H pillar, which X-43 vehicles are to serve, is focused on providing revolutionary technology advancements in both propulsion elements (such as turbojet, ramjet, dual-mode scramjet and combined cycle engines) and airframe elements (such as configuration aerodynamics, stability and control, and high temperature structural concepts) for military systems, including HS/H strike weapons, high-speed cruise vehicles and airbreathing first-stage systems for space access. The second pillar of the NAI, the SA pillar, is focused on developing and demonstrating advanced technologies (such as hydrogen and hydrocarbon fuelled main rocket engines, large integrated structures and cryogenic tanks, thermal protection systems, and efficiency improvements derived from integrated health management and advances in range and ground operations) that can enable future space lift systems to be more affordable, responsive, safe and flexible to serve the Air Force Space Command pursuit of a military space plane and NASA needs both a reusable launch vehicle for Shuttle replacement and a new capability for space exploration beyond low earth orbit. The third pillar, the ST pillar, is focused on developing and demonstrating various military payloads (DoD, 2003).

According to the roadmap, it seems the envisaged space transportation system would be TSTO RLV, consisting of a HTHL airbreathing engine powered first stage booster, operating at Mach 0 to 12, a derivative of the long range strike vehicle, and a HTHL rocket engine powered second stage orbiter, a derivative of the space maneuvering vehicle (DoD, 2003).

The envisaged TSTO launch vehicle consists of two reusable stages: the reusable first stage booster and the second stage orbiter which is locked in the least optimal evolutionary path, the sophisticated evolutionary path. Both stages require huge resources in development but any one of them could evolve to the reusable SSTO launch vehicle. Once the evolution is achieved then a large part of the other conception would be redundant investment in the long run.

However, the two technologies have their own peculiar, primarily military, application and therefore the technology evolution to SSTO based on any one of these two conceptions can be considered as a spillover of military technology to civilian/commercial technology (as experienced historically in the aircraft industry). The least optimal evolutionary path argument might therefore be avoidable in some way.

Suborbital Launch Vehicle vs Reusable Booster

As we studied in section 5.5.1, both the suborbital launch vehicle and the reusable booster could be the platform vehicle for bottom up technology evolution. In terms of the level of technology requirements, there is not much difference between the two product technologies. However, there are noticeable differences in the market environment in which the launch vehicle could survive.

The technical risk of these two conceptions also differs because the sub orbital launch vehicle is usually a manned vehicle consisting of two reusable stages or a single stage vehicle, while the reusable booster is most likely to be an unmanned vehicle mated with expendable upper stages.

It is also widely recognized that piloted aircraft cost much less to develop than unmanned launch vehicles since:

1) The unmanned launch vehicle demands extensive and costly ground tests to insure that they fly properly. In the case of system failure, in some instances, it is difficult to find the cause of the failure since the vehicle usually crashes on the surface of the sea preventing recovery of the vehicle for inspection to determine the cause of the malfunction.

2) Piloted aircraft could start testing using simple exercises in taxiing and takeoff and then progress step-by-step to higher speeds and greater levels of performance (Heppenheimer, 1999). At each step, the engineers could study the vehicle performance and correct deficiencies and such flight testing is far less costly than ground testing, as evidenced by the X-15 program. The X-15 was more complex than the Atlas but incurred less than half the development cost (Heppenheimer, 1999). SpaceShipOne performed its powered flight after 3 mated flights and 7 gliding flights to check the vehicle functions step by step (Logs: White Knight and SS1, 2004).

3) The test pilot can save the vehicle in case of minor malfunctions which might otherwise cause disastrous failure of the vehicle were there no adequate human intervention. The X-15 would most likely have been destroyed on as much as a third of its flights had no pilot been aboard (Heppenheimer, 1999). SpaceShipOne experienced anomalies three times during its first five powered flights, including two vehicle control anomalies which might have caused disastrous failure if no corrective action had been taken by the test pilot (Logs: White Knight and SS1, 2004).

The traditional launch market is already overcrowded (FAA, 2004) and even one of the most competitive launch vehicle programs, Ariane, survives only with significant direct or indirect governmental subsidies. It is also hard to expect new orbital launch vehicles using reusable boosters to have comparable price competitiveness over existing expendable launch vehicles because the new launch vehicle would need to recover the nonrecurring development cost for the booster and the whole system, as well as the recurring cost of the expendable upper stages. The suborbital launch vehicle is primarily aiming at a new market, space travel, where no incumbent competitors exist and therefore the competition is not so high.

Criticism for Current Private Suborbital Approaches

SpaceShipOne concluded the X-prize competition. However, there are two distinct appraisals for the achievement and the future of the suborbital launch vehicle industry – the first is a popular view of the achievement as a stepping stone for the evolution of the reusable launch vehicle and the other is lukewarm technological view of the future of the technology evolution.

The proponents of suborbital activities believe that the suborbital launch vehicle could evolve step by step into an orbital launch vehicle, i.e. the bottom up approach, just as aircraft evolved incrementally from the development of the Wright brothers' flier in 1903.

Criticisms of suborbital vehicle technology are widespread in the incumbent launch industry and include: (1) the performance achieved and the state of the technology adapted by SpaceShipOne is no better than, or inferior to, those of the X-15 spaceplane which was developed 40 years ago; (2) there is a large gap between the performance requirement for the suborbital vehicle and the orbital vehicle (for example, StarShipOne only has about Mach 4 velocity capability and encounters no significant thermal load, while the orbital launch vehicle should have a capability of Mach 25 equivalent delta velocity and endures a hostile thermal load during reentry); and (3) the key technology, more importantly, such as the engine and material for the suborbital vehicle, is dead end technology, i.e., it is hard to expect that a launch vehicle using hybrid engine and a graphite-epoxy composite could be evolved for use as an orbital vehicle. Accordingly, the role of the suborbital vehicle in the evolution of the orbital vehicle is questionable.

No fully reusable orbital launch vehicles have been developed yet. Space Shuttle is only partially reusable, with tremendous refurbishment efforts required to restore it to flight condition. Even with current technology, there are still large gaps between the technology requirements to develop an operable reusable orbital launch vehicle and the technology frontier as shown in Table 5-3.

	Major Technology Area	Current Maturity Level (Scale 1 to 5)
Airframe System	Thermal Protection	2 to 4
	Propellant Tanks and Feeding System	1 to 4
	Integrated Structure	3
Propulsion System (Rocket Based)	Propellant Management Devices	3 to 4
	Combustion and Energy Conversion Device	3
	Controls	2 to 4
	Material	2 to 3

Table 5-3 Current Level of Technology Maturity (Adapted from NRC, 2004)

It is therefore not surprising that there are large gaps between the technology applied to the suborbital launch vehicle and the level of required technology to build an operable reusable orbital launch vehicle. Conversely, these technology gaps justify the suborbital approach, since the suborbital vehicle could be developed in compliance with appropriately matured technology.

The component technology of SpaceShipOne seems to be a dead end technology since it is hard to expect that the hybrid engine and the graphite-epoxy composite material could prove useful for a reusable orbital vehicle. However, this does not mean denying the technology advancement of the component technology in general. Rather, there are continuous incessant efforts to increase the frontier of component technology, such as the first pillar of the NAI, High-speed/Hypersonics (HS/H), which seeks to extend the scope of the component technology. There are good opportunities for spillover of the component technology from governmental military RLV initiatives as was demonstrated in the aviation industry.

The privately initiated suborbital bottom up approach and the government initiated dual pillar approach benefit each other. The former could benefit from spillover from the latter, while the latter could also benefit from the former by convincing the tax payers that their money is spent for the technology not only for military use but also for commercial use as well, i.e. dual use technology.

5.6 Conclusions

Theoretically, for the space transportation system, a very complex system having high path dependence, it is feasible to direct the technology evolution toward a plausible path through governmental involvement in R&D and product design leading to ‘user push’ or ‘demand driven’ innovation.

However, the case study of the U.S. Reusable Launch Vehicle (RLV) programs confirmed our presupposition that all the mission oriented government initiated RLV programs, including X-20 (1964), Space Shuttle (1974), DC-X (1993), X-33 (2001), and X-37 (2005), are based on the top down approach resulting in a sub-optimal path, indicating that there was no positive intervention from the decision making mechanism for the selection of this technology option.

It is very intriguing that two privately initiated programs, Pegasus/L1011 and SpaceShipOne, showed a different pattern of technology evolution, bottom up. However, this is not particularly surprising since private initiatives have different decision mechanisms and different motivations for the decisions.

Contrary to the mission oriented RLV programs, technology demonstration RLV programs including X-15 (1958), X-34 (1999), and X-43A (1999) do not follow the top down approach but rather have potential to support the bottom up approach since the technology to be developed is useful for reusable boosters.

The top down approach is not an optimal path for RLV evolution, not only because of the inefficiency in the creation and preservation of the knowledge, but also because of the white elephant syndrome. As in the case of the Space Shuttle, the adaptation of the premature technology places a heavy burden on operations and hence prevents sufficient support for the next generation of launch vehicles. This lowers the opportunity of having a healthy next generation of launch vehicles and causes evaporation of the accumulated knowledge and experience in the industry by delaying the launch of that next generation. Therefore, white elephant syndrome is not as drastic as program failure as experienced in the case of the X-33 but has a more detrimental impact on sustainable development.

In recent years, in reaction to the painful consequences of the top down approach programs, especially the costly operation of Shuttle and the technological failure of the X-33, industry has become aware of the underlying deficiency in their strategies. They have therefore introduced new strategies, such as the component technology priority or bottoms-up strategy in the Next Generation Launch Technology (NGLT) and the dual or three pillar strategies of the National Aerospace Initiative (NAI). Suborbital activities stimulated by the X-prize initiated a new technology evolutionary path and triggered fruitful strategic debate on Suborbital launch vehicle technology evolution.

The component priority strategy is a required strategy since it could reduce the system development risk by extending the frontier of the component technology. However, the component priority strategy alone is not enough since it could not show which technology option should be sought. There might be the localization problem in component technology development and a lack of positive feedback from learning by using, as would be the case if the technology option to be sought were locked in a non-optimal path. Where the component priority strategy is weak, the bottom up approach is strong. These two approaches are not mutually opposed but rather supplement each other, as if the former is showing how to plant a tree, while the latter is showing how to select a healthy tree. The concurrent adaptation of these two strategies would therefore be beneficial for obtaining a healthy forest and so for sustainable development of launch technology as well.

The current Congressional decision on resurrecting the X-43, which not only supports the bottoms-up strategy but also supports the bottom up strategy, would therefore be regarded as a successful result of the iron triangle regime in space policy.

There are two feasible bottom up approaches, the booster first approach and the suborbital conception approach. For the efficiency of technology evolution, the suborbital approach is less risky, as well as less costly, than the booster first technology because of the benefits of the manned vehicle. The market situation is also preferable for the suborbital vehicle rather than for the booster first orbital vehicle since the former aims at a new market where no incumbent exists.

In this regard, the most appropriate evolutionary path for RLV would be the bottom up approach through a suborbital conception coupled with bottoms-up approach such as the airbreathing engine technology priority strategy.

The dual pillar approach of National Aerospace Initiative (NAI) envisaged Two Stage To Orbit (TSTO) RLV, consisting a Horizontal Take off Horizontal Landing (HTHL) airbreathing engine powered first stage booster and HTHL rocket engine powered second stage orbiter. Redundancy therefore exists since once one vehicle evolves to a Single Stage To Orbit (SSTO) than the other vehicle should be discarded. However, each vehicle has its own mission and therefore the redundancy can be justified. This military technology, especially for the first pillar, would be a good source for technology spill-over in the commercial bottom up approach for both the booster first conception and suborbital activity.

Criticism of suborbital activity as a dead end technology could not be justified because there is no evidence of an absence of spillover from military technology evolution, such as from the first pillar of the NAI program as experienced in aviation industry.

Even with the adverse impact of the current policy change on Space Transportation Systems (STS), which focuses on expendable heavy launcher development for Crew Exploration Vehicles (CEV), and the sinking budget for military space programs, good signs of technology evolution come from increased suborbital activity in the private sector and government technology demonstration programs with their relatively sound technology evolution path supporting the bottom up approach.

However, we need to wait a few more years, or even decades, before we can be convinced of whether these good signs turn out to be a sustainable path since the plausibility of the bottom up approach is not firmly evidenced yet by real programs and even the bottom up approach offers a short cut for technology evolution. Uncertain factors also still remain, such as the market which influences the fate of the seed activity of the bottom up approach, as with suborbital activities, which are strictly governed by the rules of profit and loss. It is very difficult to predict a totally new market such as space tourism which is being pursued by suborbital activity.

Chapter 6

Conclusions: *Combined Approach – Bottoms-up and Bottom up with Suborbital Vehicle Conception*

> *Finally, the foresight of the earthworm evolved to enable it to discern a short cut to cross the road. Will it succeed in crossing the road? There are no guarantees of success since wheels or birds can terminate its journey at any time. However, the earthworm with foresight has a better chance of crossing the road than those without.*

We started our journey to find the foresight to discern the short cut to cross the road and investigated the US RLV programs in terms of the efficiency of the technology evolutionary paths based on this foresight.

We found that the attributable root cause of the long list of casualties in RLV programs is the sub-optimal lock-in in the paths of the top down approach, and the continuation of this approach. This phenomenon, induced from path dependency or technology momentum, has continued for over 40 years, as if it were an earthworm continuing in its fixed direction.

6.1 Answers and Findings

This thesis set out to address four key questions and succeeded in finding some interesting answers in the process of its investigation. The summary of these answers and findings are presented below.

Military space activity is a two-edged sword

The increment in military space activity will expand the space transportation market in general since there is no budget crowding out between military and civilian space budgets. There is the possibility of a continuation of the third cyclic boom in space activity led by military space activity since there are high possibilities that space weaponization by a super power will occur. This would inevitably trigger counter measure activities from other space-faring nations who would not want to lose their strategic capability for national security. There would also be technology spillover from military Space Transportation System (STS) technology to the commercial STS sector. This is the positive side of military space activity for the space transportation market and technology.

However, such military space activity cannot be so highly evaluated in terms of its potential to lead to a sustainable development of the launch industry because if we look into military space activity further then we can find that it has firm limits. There are various ways to maintain the strategic capability of a nation without placing space systems in Earth orbit. In addition, there is rigidity in government budgets in terms of their potential to expand. Inversely, there is a risk of physical conflict in space which would produce a huge amount of space debris. Once space is crowded by the debris, then there is a high possibility of crowding out of space systems, either through the increased development cost of the systems due to heavy shielding requirements or through physical damage to the systems due to penetration by space debris. This is the negative side of military space activity which could become the precursor for doomsday in space.

The Public space travel market segment has a potential for sustainable development but needs time to prove itself

The public space travel market has its peculiarities compared to the non-human payload market. Typically, once a satellite is launched into earth orbit, it can stay there for years to provide its designated service, while humans only stay for days or weeks in orbit. This is a limitation for growth of the market with current STS, for which inserting a payload into orbit is a demanding task in technological as well cost terms. However, once STS technology has matured enough to develop a STS whereby inserting a payload into orbit is considered a trivial task in terms of cost and technology, then this change in the limit will act as a driving force for sustainable development of the launch industry. Public space travel, with its peculiarities, could be one of the most plausible destined markets to lead to sustainable development in the launch industry.

However, in order to materialize the potential market, there needs to be a high performance STS in terms of cost and safety factors, while the current technology is not mature enough to build such a STS. There is no firm proven market to induce the huge development cost of such a STS, and without such a high performance STS there can be no chance to prove the market. In other words, there is a Catch-22 trap and, to make things worse, there are also high technical risks.

Suborbital activity offers a good opportunity to escape from this Catch-22 and to avoid high technical risk since this could ramp up the launch vehicle capability progressively with the evolution of the technology and market. However, we will need to wait for years or even decades before we can be convinced of whether this potential market is prosperous or not since suborbital activity is a private initiative which is strictly governed by the profitability of the business, and also influenced by uncertain institutional factors.

A Trilateral approach to perceive the multifaceted nature of the product technology

In order to develop a framework to perceive technology change, we first investigated the root of the technology change to find concrete ground on which the conceptual framework stands. Through investigating the root of the technology change, the formation and manifestation of the product technology, we induced theoretically possible methodologies to gauge the product technology change using three different stages in the product technology:

(i) The formation stage - a production function study by means of measuring the input efficiency,

(ii) The embodied stage - a static study by means of perceiving the form (morphology for the shape of the product and components, and its structural aspects including complexity, decomposability and architecture) and a statistic study by gauging the property (such as reusability and reliability) of the product, and

(iii) The manifestation stage - a characteristics study by means of measuring functional aspects of the product both in physiocentric and anthropocentric views.

The literature study showed that the existing methodologies to gauge technology change well matched the theoretically possible methodologies. However there are some methodologies which appear in the theoretically possible methodologies but are missing in the existing methodologies, those are the methodologies in relation to the physiocentric view in the characteristics study and in relation to properties such as reusability which are supposed to be essential for future technology evolution in a ‘spaceship economy’ but which are not important in the ‘cowboy economy’ where the reservoir to pollute and to extract is unlimited.

By analyzing the existing methodologies and our view of the theoretically possible methodologies to gauge the technology change we concluded that any new or existing methodology gauging a single aspect of a product technology could not appropriately capture the multifaceted product technology. Accordingly, we introduced a new way of perceiving product technology, a ‘trilateral approach,’ which is effective in gauging the multifaceted nature of product technology not only for the historical technology change but also for future technology changes, by means of studying the structural aspect of the product (complexity, decomposability and architecture), the property (reliability and reusability), and the functional aspect of the product (performance). We further developed a framework of evolution space to describe the change in STS technology consisting of a Cartesian coordination, each axis of which represented key factors, including performance in engine efficiency and structural efficiency, reusability and reliability, based on the trilateral view of the product technology.

Bottom up approach, the most plausible technology evolutionary path

For the tradeoff of the technology evolutionary paths we introduced two new conceptions. One is the methodology to construe an evolutionary path which is immune from the exogenous factors of the technology change, the so-called Exogenous Factor Impact Free Evolutionary Hierarchical Tree (EFIFEHT) methodology. The other is the evaluation criteria for the path, 'facility of learning and efficiency of the knowledge creation and preservation', which are derived from our perception of the launch industry as a 'learning industry' where knowledge creation is essential for the sustainable development of the industry and the product technology.

Using the EFIFEHT methodology, we obtained physically possible technology evolutionary paths for STS which are only endogenous factor directed. We then screened out the sustainable technology evolutionary paths by applying the exogenous factors (politics, market and environmental constraints) and found that the Horizontal Take off and Horizontal Landing (HTHL) conception shows the highest sustainability. The Vertical Take off Horizontal Landing (VTHL) conception comes second and the Vertical Take off Vertical Landing conception shows the least sustainability in terms of political factors and market compliance. For the environmental constraint, a preliminary review showed that the VTHL and Vertical Take off Vertical Landing (VTVL) conceptions are similar in terms of their effect on ozone depletion and are more environmentally efficient than the HTHL conception.

Finally, we evaluated the plausibility of the paths by applying the evaluation factors to the sustainable paths. From our evaluation, we concluded that the bottom up evolutionary pattern, introducing reusability of the vehicle from the lower stage, offers efficient learning, i.e. offers the least amount of knowledge obsolescence during the technology evolution process, and facile learning, which enables the accumulation of knowledge from a lower to a higher level. The top down approach, introducing reusability of the vehicle from the upper stage, offers efficient learning but not facile learning since the development of the reusable upper stage is still a demanding task. The sophisticated evolution pattern, introducing reusability of the vehicle in all the stages, offers neither economic learning nor facile learning.

US government initiative RLV program technology was locked in a sub-optimal path but there are signs of change.

For the analysis of the technology evolutionary paths, we introduced two different types of technology evolutionary paths - contemplated technology evolutionary paths induced from the cases of the mission oriented RLV programs, and potential technology evolutionary paths induced by studying technology demonstration programs. Seven mission oriented RLV programs (X-20, Space Shuttle, Pegasus/L1011 Launch System, DC-X, X-33, SpaceShipOne and the X-37 program) and three technology demonstration programs (X-15, X-34 and X-43A) were studied.

The case study for the contemplated technology evolutionary path confirmed that our proposition stands, that ‘all the government initiated programs are locked in a sub-optimal technology evolution path based on the top down approach philosophy.’ It is very interesting that both privately initiated programs – the Pegasus/L1011 Launch System and SpaceShipOne - are locked in an optimal path, both of which are based on the bottom up approach philosophy.

The potential technology evolution path inducible from the technology demonstration program does not follow the top down approach but rather has potential to support the bottom up approach as the technology to be demonstrated is akin to that of the reusable booster which constitutes the core technology for the bottom up approach. However as the National Aerospace Initiative (NAI) road map showed, some technology, such as the airframe-integrated airbreathing engine technologies of the X-43, also supports the sophisticated approach if a HTHL (H) first stage reusable airbreathing engine powered booster is mated with a HTHL (H) rocket engine powered second stage launch vehicle.

The case study revealed what the consequence would be when the technology is locked in a sub-optimal technology path. It causes program failure, as in the case of the X-33, or bears white elephants, as in the case of the Space Shuttle. The latter case is not as striking as program failure but its influence is much more serious since it has a long lasting negative effect on sustainable development of the technology by draining the resources due to costly operation of the vehicle and thus preventing the launch of any sound new generation of launch vehicle programs, as NASA's experience with the second generation RLV programs has demonstrated.

Considering the lock-in of US RLV technology in the sub-optimal evolution path for the past forty years and the current 'Vision for Space Exploration' which is calling for expendable heavy launchers, it looks like there may be no future for US RLV technology. However, positive signs have arisen from both the increasing suborbital activity with its relatively sound technology evolution path using the bottom up approach, and from some of the technology demonstration programs, such as the X-43 program, which could give rise to the development of an airframe-integrated airbreathing engine which could become a key technology for the bottom up approach conception.

Recommendation: A Combined approach for both bottoms-up and bottom up approach through the Suborbital Conception

Confronted with the repeated undesirable consequences of the RLV programs, such as the heavy operational cost burden of Space Shuttle and the failure of the X-33, the US launch industry are beginning to discuss the strategic deficiency of their RLV programs.

The bottoms-up conception of the US launch industry is a required strategy in RLV development but is not sufficient. The bottoms-up approach can be applied to technology options for a vehicle in any technology evolutionary path. Therefore once it is coupled with the technology option of a launch vehicle in a non-optimal evolutionary path then problems might arise such as localized component innovation and lack of opportunity for positive feedback from the learning process with increased development time due to the large technology gap between the in situ component technology and the requirements technology to build up the launch vehicle.

Where the bottoms-up approach is deficient the bottom up approach is able to supplement, since the bottom up approach shows which technology evolutionary path to seek for the sustainable development of the launch industry and the product technology. The best strategy for RLV development programs would therefore be a combined approach: the bottom up approach for the technology evolutionary path and the bottoms-up strategy for the component technology development.

There might be two different avenues for the bottom up approach - the booster first approach and the suborbital vehicle approach. In terms of market competition, the suborbital vehicle approach is preferable since there are no incumbent competitors in the suborbital launch vehicle market, such as in the space tourism market segment, while the booster first concept orbital launch vehicle must compete with existing expendable launch vehicles for the traditional launch market which is already over crowded. In addition to the market advantages, the suborbital vehicle approach can easily break out of the Catch-22 trap with a relatively small amount of system development costs.

However it should be noted that the bottom up approach is not proven yet because of the lack of empirical data. Positive evidence might be obtainable once performance data have been accumulated from suborbital activities or from booster first strategy orbital RLV programs such as the DoD’s Affordable Responsive Spacelift (ARES) program. Even with the positive evidence for the technology evolution, we might wait for years, or even for decades, to see suborbital activity flourish. This is because the suborbital activity is based on private initiative, targeting the new market of public space travel, which is strictly governed by profit and loss. However it is very difficult to figure out the result in this early stage of the market evolution.

6.2 Contributions

This thesis has made several important contributions to state of the art studies in evolutionary economics in technology change by introducing a novel methodology to trade off the technology evolutionary paths applicable, not only for *ex post* but also *ex ante*. The methodology has been developed for the study of STS technology but would also be useful for the study of the knowledge intensive area of any other complex system and technology. The launch industry could gain insight from the thesis for their decision making process on future RLV development programs.

What are the novelties of the thesis?

This thesis introduced three novel conceptions: the EFIFEHT methodology, evaluation criteria for technology evolution paths for a knowledge intensive area, and the trilateral approach for the perception of the product technology.

1. EFIFEHT Methodology:

‘Exogenous Impact Factor Free Evolutionary Hierarchical Tree (EFIFEHT)’ is a methodology to develop evolutionary paths of a product technology which are immune from exogenous factors.

2. Evaluation criteria for the technology evolutionary path:

‘Facility of learning and efficiency of knowledge creation and preservation’ are the evaluation criteria for the selection of the plausible technology evolutionary paths for knowledge intensive areas based on Knowledge Oriented Policy (KOP).

3. Trilateral Approach:

The trilateral approach is not a new methodology but a new way to perceive product technology in order to capture the multifaceted nature of the product technology by studying three aspects of the product technology: structural aspect, property and functional aspect.

What are the expected contributions to industry?

This thesis investigated the root cause of the problems that the RLV launch industry has suffered during the past 40 years. Our argument for the sub-optimal lock-in in the technology evolutionary path as the root cause, as well as strategic issues as summarized below, will extend the dialogue of the industry in its decision making process for the selection of future launch vehicle technology options which is essential for the sustainable development of the launch industry.

1. What is the root cause of the problems of the US RLV programs?

All the government initiated mission oriented RLV programs are locked in the top down approach which is sub-optimal because of the difficulties of learning due to the large gap between the knowledge available and the knowledge required to build the highly technologically demanding reusable upper stages.

2. What is the best strategy for RLV development?

A combined approach using both the bottoms-up and bottom up approaches coupled with the suborbital vehicle conception would be the most robust strategy in terms of technology development as well as market creation. Both approaches, booster first and suborbital vehicle development, allow a plausible path for efficiency of learning and knowledge creation and preservation; however, the suborbital vehicle approach can create market as well as offer an easy way out of the Catch-22 trap.

3. What is to be learnt from the top down approach?

A technology lock-in in a sub-optimal path induces an imminent consequence of program failure, as with the X-33. However, the serious damage comes from the white elephant syndrome which drains the resources to prevent bearing a healthy next generation of launch vehicles which are essential for sustainable development of the launch industry.

6.3 Boundary, Limitation and Recommendations for Future Study

Answering the original question is a wonderful part of writing a thesis - full of graceful suffering to create new knowledge, like delivering a baby. Although the author will have limits which will in turn limit the arguments, the thesis nonetheless generates interesting new lines of inquiry which could lead to a wonderful journey for further study.

First, we discussed the qualitative factors of learning process and knowledge creation and preservation as the evaluation criteria to select the technology evolutionary path. However, less focus was placed on these criteria in the case study. The lack of plausibility was confirmed by the heavy operational cost burden due to adapting premature technology, as in the case of Space Shuttle, or by the program failure due to the large gap between the technology requirements for the technology options of the vehicle and the technology frontier, as in the case of the X-33.

1. There is therefore a need for a further case study focussing on the analysis of the learning and knowledge creation efficiency itself, preferably in a quantitative manner.

Second, we investigated the most plausible evolutionary path for the technology in a monopolistic environment. In the real world there are usually multiple players and therefore the second runner's interest may be influenced by the first runner's evolutionary path and vice versa.

2. It might be an interesting study topic to investigate the change in the plausibility of the technology evolutionary path in a situation where multiple players select their own technology paths and compete in an open market.

Third, for the selection of the sustainable technology evolutionary path, environmental constraints were reviewed. Through the literature study, we made a very preliminary review of two technology options, one using kerosene and the other using hydrogen propellant, and their effect on ozone depletion. However, the current state of knowledge in this area is not enough to induce any credible discussion of the issue, so we will leave this issue open.

3. Once the knowledge has advanced in terms of the environmental impact of RLV activity, then this issue should be readdressed since it is too important a factor in determining the plausibility of the technology evolutionary path. The impact of the emission of hydrogen propellant on ozone depletion is particularly important since, in the long run, after depletion of the carbon based chemical energy, hydrogen propellant is the most probable source for the chemical energy which powers the STS.

Appendix

A-1 Description of Space Transportation Market Segments (Adapted from ASCENT Study)

Existing Government Mission: missions that are predominantly funded by the federal government budgets.

Hazardous Waste Disposal: means the disposal of any substance that poses a substantial threat, present or potential, to human health or the environment when improperly treated, stored or disposed of, or otherwise mismanaged. As an example, placement of nuclear waste on the Moon or sending it on a collision trajectory with the Sun.

Human Space Exploration (Non-ISS): Government-sponsored human mission into orbit, the interplanetary medium, and celestrial objects. Excludes human missions to ISS.

Military and Civil Communication: includes orbital communications and telemetry platforms dedicated to military and/or civil application.

Positioning: includes orbital platforms dedicated to providing timing and positioning data for purpose of navigation. Excludes value added products which are included in the commercial data market.

Public Space Travel: is the transportation service to Earth orbit or suborbit that supports leisure travel, business travel, and the human crewed components of other evolving commercial markets.

Remote Sensing: Military- includes orbital military platforms dedicated to intelligence gathering and treaty verification missions using passive or active sensors focused on the surface and atmosphere of the Earth.

Space Testbed: tests new equipment, components and modules in space for use in future flight hardware or space missions.

Space LEO business park: includes the facilities and utilities service for research, production and space tourism.

Weapon Systems: means space-based platforms used to negate hostile activities on the surface and in the atmosphere of Earth, as well as in space.

B-1 Anatomy of Space Transportation System

The function of the launch vehicle is delivery of a payload to an altitude high enough to free it from atmospheric drag with a velocity fast enough to maintain the orbital flight. The launch vehicle consists of three principal elements: propulsion to generate thrust to propel the vehicle, structures to contain the propellants and to carry the structural loads, and GN&C (Guidance, Navigation and Control) to maintain the attitude of the vehicle and to lead the vehicle to the desired destination.

Propulsion

There exist various types of propulsion systems, among them the chemical propellant rocket is the most widely used engine for current launch vehicles. The most commonly used chemical propulsion types are solid fuel engines and liquid rocket engines.

Solid fuel engines are simpler and cheaper to design and produce and can be stored for a longer period. However, the fuel efficiency is lower than for liquid fuel rockets and there is also a drawback in operability - once a solid fuel engine is fired, it is almost impossible to change the thrust or to extinguish the fire. Its use as the primary propulsion system for launch vehicles is therefore limited. However, a solid fuel engine does generate high thrust to weight ratios and therefore can be used as a strap-on booster for the first stage of the launch when higher thrust is needed to lift the heavy initial mass of the launch vehicle.

Liquid propellant engines can offer better controllability and usually higher fuel efficiency but the high performance engine requires a high performance turbo-pump which is demanding in design and manufacturing, and hence also comes at a higher cost. Liquid propellant engines are used as the primary propulsion system for most launch vehicles.

Fig. B-1 shows a diagram of a liquid propellant engine. The major components of the propulsion system consist of a turbo-pump for pressure feeding the engine, a combustion chamber and a nozzle.

The turbo-pump consists of a turbine that produces rotational force using hot gas momentum and a pump where propellants are compressed to flow into a high-pressure chamber.

The highly pressurized propellant is injected into the combustion chamber where the propellant burns to produce high velocity gaseous material under high pressure. The hot gas expands and exits through the nozzle to produce thrust.

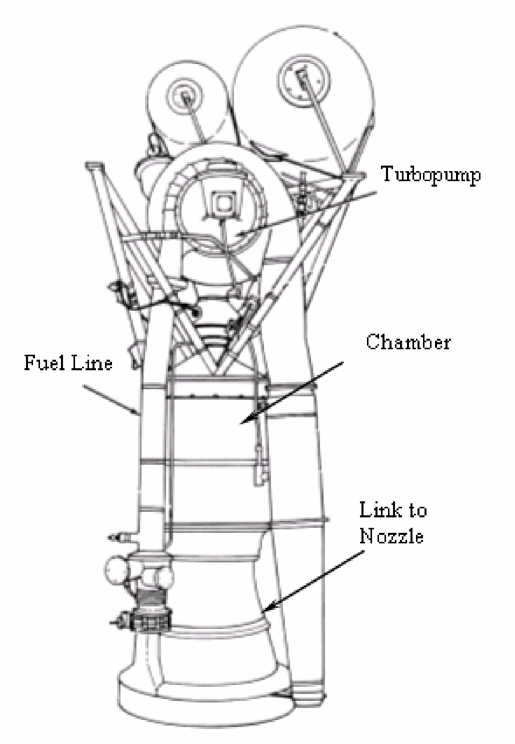

Fig. B-1 Mercury-Redstone Rocket Engine[55]

Manufacturing the turbine is technologically demanding because of the critical operational requirement of the turbine section. The typical range of the turbine speed exceeds 30,000 Revolution Per Minite (RPM) at the intersection of the hot working gases.

The performance of the chemical propellant engine is highly dependent on the property of the fuels it uses. Cryogenic propellant provides the highest engine efficiency - about 450 vacuum Isp in the case of the Shuttle main engine. However the lower density of the propellant means a bigger size of tank is required and a careful trade off needs to be made in selecting the type of propellant, especially for the reusable winged body launch vehicle concept. The bigger tank size not only increases the weight of the tank but also significantly increases the vehicle mass. The increment in vehicle size to accommodate the large tank increases the surface area of the vehicle which in turn requires additional heavy thermal protection as well as heavier larger wings and landing gear structure to support the increased vehicle mass.

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[55] Adapted from http:/www.hq.nasa. gov/office/pao/History/diagrams/mercury10.gif.

Structure

The structure carries the load of the vehicle and supports all the vehicle's subsystems. The major structure comprises the interstage, the engine thrust mount and propellant tanks for the integrated tank structure, the external aeroshell, and the payload bay and wing/control surface-box structure for winged reusable launch vehicles.

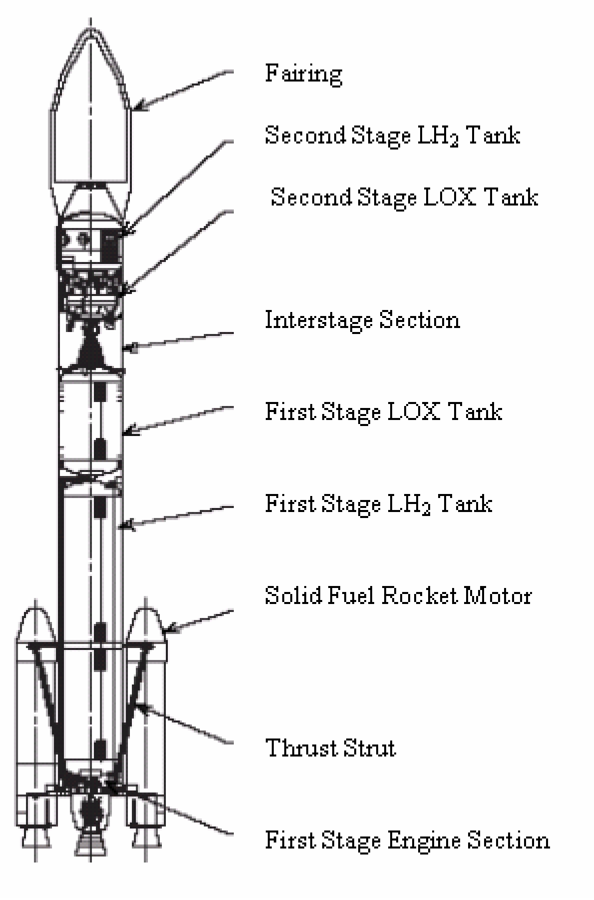

Fig. B-2 Outline of H-IIA Structure (Source: Maemura, 2002: 44)

The interstage is the structure between the stages and is designed to carry loads to adjacent propellant tanks. The propellant tanks, with their large volume and heavy mass, are designed not only for storing the propellant but also for carrying the structural load of the vehicle. This is the case with the integrated tank design where the 'skin' of the vehicle is the outside of the propellant tanks. The integrated tank conception for reusable vehicles requires complicated thermal design insulation, cryogenic liquid oxygen and/or liquid hydrogen tanks and thermal protection from aerodynamic heating during ascent and reentry flights. The thrust structure transfers and distributes engine thrust loads throughout the launch vehicle.

Fig. B-2 shows an outline of the H-IIA structure. The thrust generated by the solid rocket booster is carried to the tail end of engine section via the thrust strut and then passes through the vehicle's main structure consisting of the tanks and the interstage, as with the thrust produced by the LE-7A main engines. The typical cylindrical shape is one of the most mass saving structures to carry the thrust load while maximizing the volume of the vehicle to accommodate the volumetric propellant tank. This is because it can reduce vending load and minimize twisting movements during the vertical take off.

The shape of the vehicle determines its aerodynamic characteristics. Cylindrical tandem mating with a pointed nose can reduce the cross section area and hence the vehicle is subject to less supersonic drag (the drag which causes over three quarters of total drag losses). The typical flight path of a vertical take off launch vehicle is an almost vertical trajectory and hence the launch vehicle remains in the dense atmosphere for a very short time effectively reducing atmospheric drag. The Saturn V moon rocket had drag losses of only 40m/second (The Sarigul-Klijn's, 2003).

However, any reusable launch vehicle using an airbreathing engine, or horizontal take off or landing concepts has a longer flight time in the dense atmospheric air. The design of the vehicle becomes much more complicated because of the hostile aerothermal load and the wide range of the flight envelope experienced. The surface of the SR-71 black bird, the highest velocity aircraft designed to fly at a maximum velocity of Mach 3.2, is composed almost entirely of titanium and titanium alloy to withstand high thermal loads of up to 430° C (NASA Fact, 2002). However, the thermal load a reusable launch vehicle would experience during the ascending or descending flight is much more severe than that which the high velocity aircraft encounters. According to the Shuttle experience data, the flight velocity range of the launch vehicle would exceed 7 km/sec and the maximum temperature is close to 1650° C. Thermal stress during ascent for horizontal take-off, airbreathing propulsion launch vehicle concepts and their reentry flights therefore becomes one of the most challenging tasks for vehicle designers.

GN&C: Guidance Navigation and Control

The GN&C (Guidance Navigation and Control) system stabilizes and controls the vehicle to maintain the correct attitude and flight path during the flight. The vehicle should control its attitude as well as its main engine thrust vector in order to maintain its flight path.

The schematic of the GN&C block diagram is shown in Fig. B-3. The navigation system determines the vehicle's position and velocity, and provides accurate vehicle attitude references by using an Inertial Measurement Unit (IMU) typically consisting of accelerometers and gyros.

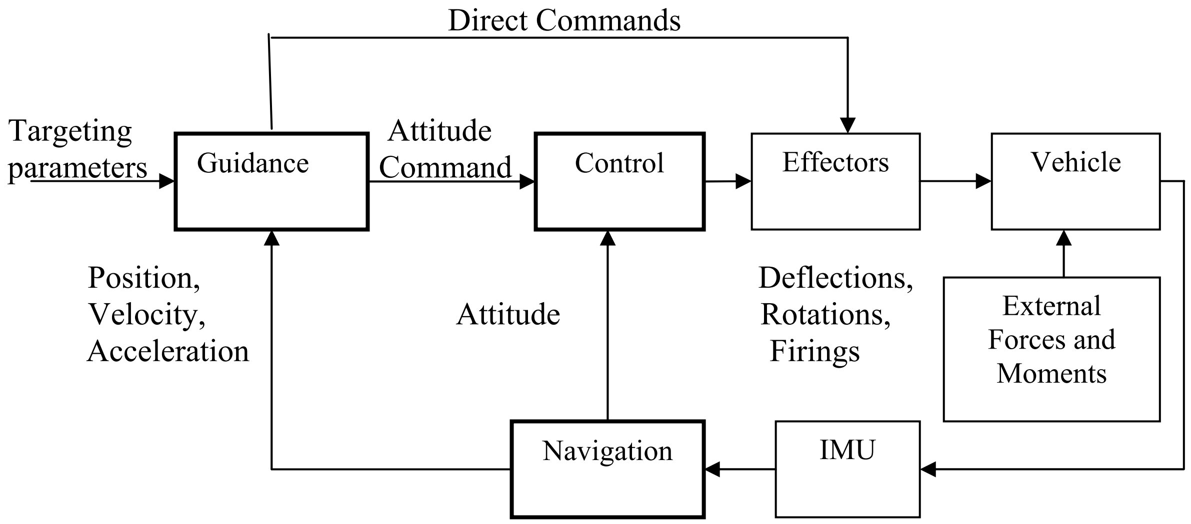

Fig. B-3 Schematic Block Diagram for GN&C (Source: Blestos, 2004)

The guidance system uses the navigation data, including position, velocity and acceleration of the vehicle, and targeting parameters, to produce vehicle attitude commands and to guide the vehicle to the desired position during the flight through activating effectors including fins, gimbals, reaction control systems, etc. During atmospheric flight, the primary goal of the guidance system is to minimize aerodynamic loading and heating. Hence, the trajectory is designed to minimize the angle of attack as the vehicle passes through atmospherically dense areas.

The primary role of the flight control system is to maintain the vehicle attitude, as designated by the guidance system, by rotating the angle of the main engine gimbals to control the thrust vector, deflecting control surfaces during atmospheric flight and igniting the reaction control system beyond atmospheric flight. The vehicle is not a rigid body - the deflection of the body changes as the external force changes. The center of gravity and the mass of the body also change as the propellant is consumed and as the propellant slosh varies during the flight. These variances make the control of the vehicle more complex. The control system should calculate the desired vehicle attitude during each control time sequence taking into consideration these variances.

C-1 Technology Options for a Vehicle: an Operational Configuration

Î: Vertical Take off and Vertical Drop (VTVD)

Launch vehicle operational type which lift off and land in a vertical direction. Since the vehicle levitates only by the thrust of the engine, a high thrust to weight ratio for the engine is desired. The rocket engine is a typical power source for this flight pattern. Usually no guidance or powered flight is contemplated during the drop and hence the vehicle free-falls to impact on the Earth's surface. The parachute dropping Solid Rocket Booster (SRB) falls into this category. There might be some controversy as to whether it is landing or dropping, but since the path is not controlled and a search recovery action is usually needed, it is put in this category. Typically, the booster, external tank, and expendable stages of a launch vehicle fall into this category.

I: Vertical Take off and Vertical Landing (VTVL)

VTVL is the same as VTVD except that it has soft landing capability using a retrofit rocket (DC-X) or rotary wing (Roton). Both the Delta Clipper Experimental Vehicle (DC-X) and the Delta Clipper Experimental Advanced Vehicle (DC-XA) failed on the eighth and fourth test flight respectively.[56] The Roton Atmospheric Test Vehicle only reached a height of 75 feet on its third test flight[57] and the program was then cancelled due to technological as well as financial problems. However, since this configuration does not need heavy wings and landing gears, has simple geometry with axisymmetric design, and is less susceptible to atmospheric drag, the vehicle could be designed to have a higher fuel fraction[58]. However, it should carry fuels at approximately 305 m/sec for vertical powered landing and hence the total vehicle Growth Lift Off Weight (GLOW) of the conception might be comparable with the VTHL conception (RAND, 1997). The typical ballistic figure offers less drag during the ascent but the vehicle experiences high reentry velocity caused by small planform area resulting in high thermal load and heavy thermal protection requirements for the vehicle. It is known that there are no overwhelming advantages in performance of vehicle compared to the VTHL conception (RAND, 1997).

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[56] Source from http://www.hq.nasa.gov/office/pao/History/x-33/dc-xa.htm, viewed on 23 May 2005.

[57] Source from http://www.space.com/missionlaunches/launches/roton_thirdflight.htlm, viewed on 23 May 2005.

[58] Sphere is the most material efficient way to gain larger volume with a given material so a higher fuel fraction is obtainable. Ceteris paribus, the more the vehicle shape deviates from the sphere, the lower the resulting fuel fraction. The cylindrical shape configuration of an expendable launch vehicle therefore offers a higher mass fraction than a lifting body reusable configuration.

h: Vertical Take off and Horizontal Landing (VTHL)

This is the same as the VTVL except for controlled horizontal landing flight. Two proven technologies exist - the Space Shuttle and Buran. Because of the heavy weight of the wings, landing gear and thermal protection system, the fuel fraction is lower than for the VTVL launch vehicle. Vehicle configuration could be either winged, as with the Shuttle Orbiter, or lift body as with the X-33. Since the vehicle would not pass through dense atmosphere at high speed, the blunt nose design is feasible and the ratio of the volume to planform area, the Küchemann's τ, could be higher than that of the HTHL configuration which flies through dense atmosphere at very high speed to catch air during the airbreathing flight mode. The landing gears of the vehicle only have to endure the landing load and not the full vehicle Gross Lift Off Weight (GLOW). Hence the landing gear could have a more light weight design than that of HTHL. The structural efficiency of this configuration could be more efficient than the HTHL configuration. However, in emergencies, an emergency landing is feasible only after dumping the propellant and hence the level of vehicle safety is less attractive than for HTHL vehicle.

Ч: Horizontal Take off and Vertical Drop (HTVD)

Similar to the drop tank of a fighter aircraft, vehicles of this type of option take off horizontally mated with a winged vehicle. Then, after its mission, it separates from the vehicle either as an expendable booster or an external tank cross feeding the main engine and free falls or parachute drops to the surface of the Earth. The rocket system of the Pegasus air launcher falls into this category.

Ч: Horizontal Take off and Vertical Landing (HTVL)

This is similar to HTVD but equipped with devices for soft landing. Typically, the booster or external tank takes off with the winged stage and, after its mission, it separates and the velocity of the vehicle is reduced using decelerating devices such as retrofit rockets or rotary wings for a soft landing.

H: Horizontal Take off and Horizontal Landing (HTHL)

This is an airplane like vehicle, since the vehicle uses aerodynamic force to take off and has a longer atmospheric flight time. It is advantageous to use highly efficient airbreathing engines. Since the typical turbine based aircraft engine is not sufficient to accelerate the vehicle (it can only accelerate the vehicle to a velocity of about Mach 3 - 0.9 km/sec at 13.7 km altitude), innovative engines are contemplated to achieve a high Mach number flight, such as ramjet engines up to Mach 6 (1.8 km/sec at 18.9 km altitude) range and scramjet engines up to Mach

10 to15 (3.0 km/sec at 27.4 km to 4.6 km/sec at 32 km altitude)[59], depending on the mission requirements (National Academy Council, 1998). However, it still needs rocket engines to accelerate the vehicle to an orbital velocity of around 7.8 km/sec, which is far beyond the capability of airbreathing engines.

The engines can be integrated by simply integrating stages which mount different types of engines, such as a turbo jet powered first stage, a ramjet/scramjet powered 2nd stage and a rocket powered third stage, or just by putting together the engines in a vehicle as a combination engine, or mounting the different types of engines in a more integrated way by sharing the air flow-path of each engine. All the engine concepts are proven technology except for scramjet but the combination engine is at a theoretical study level and provides tremendous engineering challenges such as the variable geometry of the engine inlet and complex shock wave control, etc.

The vehicle configuration is peculiar with an engine and airframe integrated configuration. The entire lower surface of the vehicle becomes part of the engine flow path since it uses the traditional engine mounting method. An engine inside the axisymmetric cowl, connected to the vehicle by a pylon or struts, produces huge drag on the pylon and cowl to cancel out the internal thrust at a high Mach number.

This configuration requires a complicated geographic configuration to handle complex aerodynamics as well as the propulsion system. Typical configuration is an engine and vehicle integrated asymmetric design requiring high structural mass. Heavy landing gear is needed in order to support the fully fuelled heavy Gross Lift Off Weight (GLOW). Since the vehicle should fly in dense atmospheric areas at very high speed, the nose of the vehicle should have a sharp leading edge and the vehicle should have a low Küchemann's τ value leading to lower structural efficiency compared to the VTHL configuration. However, the configuration could offer the most robust vehicle performance in terms of vehicle reliability with its airplane-like take off and landing, payload capability and its highly efficient engine performance.

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[59] The conversion is based on; the altitude of the flight regime is referenced from Hunt (1995) and the speed of the sound is based on the standard day mathematical model of the atmosphere and equation, a (speed of sound) = $[g \cdot R \cdot T]^{1/2}$ where, g = ratio of specific heats (1.4 for air at standard temperature and pressure), R = gas constant (286 $m^2/ sec^2/K°$ for air), T = absolute temperature (273.15 + °C) adapted from <http://www.grc.nasa.gov/WWW/K-12/airplane/sound.html>

C-2 Catalogue for the Technology Options for Space Transportation System

Single Stage To Orbit	Two Stage To Orbit	Three Stage To Orbit
Î	ÎÎ ÎI Îh	ÎÎÎ, ÎÎI,ÎÎh ÎIÎ, ÎII, ÎIh ÎhÎ, ÎhI,Îhh
I	IÎ II Ih	IÎÎ, IÎI, IÎh IIÎ, III, IIh IhÎ, IhI, Ihh
h	hÎ hI hh	hÎÎ, hÎI, hÎh hIÎ, hII, hIh hhÎ, hhI, hhh
Ҹ	ҸҸ ҸЧ ҸH	ҸҸҸ, ҸҸЧ, ҸҸH ҸЧҸ, ҸЧЧ, ҸЧH ҸHҸ, ҸHЧ, ҸHH
Ч	ЧҸ ЧЧ ЧH	ЧҸҸ, ЧҸЧ, ЧҸH ЧЧҸ, ЧЧЧ, ЧЧH ЧHҸ, ЧHЧ, ЧHH
H	HҸ HЧ HH	HҸҸ, HҸЧ, HҸH HЧҸ, HЧЧ, HЧH HHҸ, HHЧ, HHH

C-3 Maximum Possible Evolutionary Paths

For the tradeoff of the evolutionary paths in consideration of the endogenous factor of product technology, first we look into the feasible number of evolutionary paths using the morphology method. Suppose that the launch vehicle consists of *m* units of stages and each stage can be designed as *n* different types. This means there might then be n^m ! different launch vehicle types. The theoretical number of feasible evolutionary paths can be calculated by the Eq. 4-1, with the proposition that the possible evolutionary path of a launch vehicle occurs in the direction of maintaining the number of stages or reducing the number of stages. This means any evolution path is possible unless the path is directed toward an increase in the number of stages, i.e., once the evolution path reaches any one configuration of a three stage concept then the next step will be any one of the configurations in the three stage, two stage or one stage conception.

The theoretical number of evolutionary paths among the *m* stage vehicle ($PATH_m$) can be expressed by Eq. 4-1:

$$PATH_m = {}_{n^m}C_0(n^m - 0)! + {}_{n^m}C_1(n^m - 1)! + {}_{n^m}C_2(n^m - 2)! + {}_{n^m}C_3 n^m - 3)! + \ldots + {}_{n^m}C_{n^m}(n^m - n^m)$$

Eq. 4-1

The first part represents the number of paths which pass whole configurations. The second part represents the number of paths which pass whole configurations except any one configuration. Similarly, the third part shows the case of the paths which pass whole configurations except any combination of two configurations. The remaining part represents the number of paths accordingly, and the last part represents no path pass in this 4 stage vehicle.

The theoretical number of evolutionary paths in the (*m*-1) stage vehicle ($PATH_{m-1}$) can be expressed by Eq. 4-2:

$$PATH_{m-1} = {}_{n^{m-1}}C_0(n^{m-1} - 0)! + {}_{n^{m-1}}C_1(n^{m-1} - 1)! + {}_{n^{m-1}}C_2(n^{m-1} - 2)! + {}_{n^{m-1}}C_3 n^{m-1} - 3)! \cdots$$
$$+ {}_{n^{m-1}}C_{n^m}(n^{m-1} - n^{m-1})$$

Eq. 4-2

The theoretical number of evolutionary paths from *m* stage vehicle to single stage vehicle (*PATH*) can be expressed by Eq. 4-3.

$$PATH = PATH_m \times PATH_{m-1} \times PATH_{m-2} \cdots \times PATH_1$$

Eq. 4-3

According to Eq. 4-1, 4-2, and 4-3, we can develop Eq. 4-4.

$$
\begin{aligned}
PATH = & \left({}_{n^m}C_0(n^m-0)!+{}_{n^m}C_1(n^m-1)!+{}_{n^m}C_2(n^m-2)!+{}_{n^m}C_3n^m-3)!+.......+{}_{n^m}C_{n^m}(n^m-n^m)\right) \\
& \times\left({}_{n^{m-1}}C_0(n^{m-1}-0)!+{}_{n^{m-1}}C_1(n^{m-1}-1)!+{}_{n^{m-1}}C_2(n^{m-1}-2)!+{}_{n^{m-1}}C_3n^{m-1}-3)!+.......+{}_{n^{m-1}}C_{n^{m-1}}(n^{m-1}-n^{m-1})!\right) \\
& \times\left({}_{n^{m-2}}C_0(n^{m-2}-0)!+{}_{n^{m-2}}C_1(n^{m-2}-1)!+{}_{n^{m-2}}C_2(n^{m-2}-2)!+{}_{n^{m-2}}C_3n^{m-2}-3)!+.......+{}_{n^{m-2}}C_{n^{m-2}}(n^{m-2}-n^{m-2})!\right) \\
& . \\
& . \\
& . \\
& \times\left({}_{n^1}C_0(n^1-0)!+{}_{n^1}C_1(n^1-1)!+{}_{n^1}C_2(n^1-2)!+{}_{n^1}C_3n^1-3)!+.......+{}_{n^1}C_{n^1}(n^1-n^1)!\right)
\end{aligned}
$$

Eq. 4-4

Eq. 4-4 can be rewritten as Eq. 4-5 and Eq. 4-6.

$$PATH = \prod_{k=1}^{m}\sum_{p=0}^{n^k} {}_{n^k}C_p(n^k-p)!$$

Eq. 4-5

$$PATH = \prod_{k=1}^{m}\sum_{p=0}^{n^k} \frac{n^k!}{p!}$$

Eq. 4-6

If the evolution starts from three stage vehicles with each stage having six different types, then the number of possible different vehicle configurations is 216 and the resulting number of possible paths is approximately 2.723836 x 10^{412} which is far beyond of our capability to handle.

We need to look at the internal consistency of the technology option to reduce the number of possible combinations of the technology option, and investigate an applicable rule for the construction of the evolutionary path.

C-4 Assessment of the State of the Technology of Operational Options and Stage Options

(Performance)

The upper stage (i.e. third stage is higher than the first or second stage) should have a higher vehicle performance both structurally as well as in engine performance. Any one kg of mass reduction in the final stage mass means gaining the same mass in the payload, while the effect of the mass reduction on the payload gain is reduced in the lower stage. The payload sensitivity against engine efficiency is also increased in the higher stages as the typical burn time of the engine of the upper stage is longer than that of the lower stage. Therefore, it is more likely that the upper stage will adapt technology which is closer to the frontier technology than the lower stage.

(Property)

Reusability

(VTVD/HTVD) VTVD and HTVD are supposed to be expendable vehicles. It might be conceptually reusable but actually near to expendable. For example, for the Shuttle's Solid Rocket Booster (SRB), the conception is reusable but the high recovery cost which is comparable to the procurement cost of a new booster makes it no different from an expendable vehicle from an economic point of view[60]. There is not much difference between the two configurations, VTVD and HTHD. The former is a typical rocket powered expendable stage or external tanks to be mated with vertical takeoff vehicle configurations. The latter typically involves second or third stage mating with the HTVL or HTHL first stage. Thus, they are considered as homogeneous technology options.

(VTVL/HTVL vs VTHL) There is not much difference between VTVL and HTVL configuration except in the takeoff mode. VTVL configuration is supposed to be a rocket engine powered vehicle. HTVL is also supposed to be a rocket engine powered second or third stage vehicle to be mated with an airbreathing engine powered first stage vehicle. Thus, they are considered as homogeneous technology options. Both use rocket engines; hence, the reusability of the engine could be considered to be similar. However, for the vehicle structure,

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[60] According to Chiles (1996), Thiokol, SRB manufacturer, estimated that reusing the metal booster parts instead of buying all new pieces each time cuts each mission's cost by $42 million. However, the NASA budget in 2001 showed that SRB cost per mission flight was about $74 million, equivalent to $515 million per 7 missions (Noneman, 2002). Setting aside whether NASA pays for the Navy's SRB recovery operation or not, the cost of the refurbished SRB is comparable to that of the new procurement cost.

especially the Thermal Protection System, the VTVL/HTVL experiences a more severe thermal load because of the small plan area and hence the reusability capacity of the vehicle is worse than that of VTHL conceptions.

(VTHL vs HTHL) There are no directly comparable data. The VTHL configuration, as evidenced by the space shuttle main engine, needs to be refurbished after every flight incurring high direct labor as well as material cost. However, the combustion chamber temperature of an airbreathing engine also increases with the increment of the vehicle - by more than 2,760° C at Mach 8 flight[61] (National Academy Council, 1998). It also uses a rocket engine to obtain orbital velocity which is far beyond mach 8-15 and hence there is a high possibility that there is no significant difference in reusability between the airbreathing engine based combined cycle engine and the rocket engine. For the structural section, HTHL might have a larger plan area for horizontal take off and hence experience a less hostile thermal load during reentry. However, during the ascent flight, the HTHL vehicle is exposed to more thermal load than the VTHL vehicle since it needs to fly through an atmospherically dense area at very high velocity in order to accelerate the vehicle using the airbreathing engine. Comparing these two factors, the reusability of the engine and the thermal protection system, HTHL might have a slightly higher reusability factor than the VTHL vehicle.

Reliability

(VTVD/HTVD vs others) VTVD/HTVD are expendable types while the other configurations are reusable types. *Ceteris paribus*, the reliability of the reusable concept must be higher than that of the expendable concept. There are two different types of deficiencies that might cause a vehicle failure; one is deficiency of the design and the other is production deficiency such as poor workmanship or defective material.

The reusable vehicle is exposed to the risk of production deficiency only during the first flight of the vehicle, i.e. the first flight acts as the acceptance test for the vehicle. Once it succeeds in its first flight, i.e. it has no problem in its first flight, then it is more likely that the vehicle is free from the detrimental production deficit.[62] Hence, once it succeeds, then the reliability probably increases with the accumulation of the number of flights.

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[61] It would be even higher if the airbreathing acceleration becomes higher Mach number, considering the increment of the stagnation temperature of the oncoming airflow, it increases from 600° C at Mach 4 to about 1,400° C at Mach 6 and to about 2,300° C at Mach 8. (National Academy Council, 1998)

[62] The Proton fleet suffered two launch failures in 1999 was due to poor workmanship that left debris inadvertently left within the engines caught up in the power plants, triggering catastrophic in-flight explosions. (Karash, 2000) On 22 February 1990, Ariane 44L exploded 100 seconds after liftoff due to water line blockage caused by a piece of cleaning mob left in the first stage Viking engine water cooling system. Adapted from: The Wrong Stuff- A Catalogue of Launch Vehicle failures. 25 September 2005. <http://www.astronautix.com/articles/thelures.htm>

The new product experiences a higher failure ratio from the beginning but with time the failure ratio reduces to a certain level and continues as a low failure ratio. It then rises again as the parts wear out showing a bath tub pattern. However, with expendable launch vehicles, all flights are maiden flights, therefore all flights are exposed to the same risk of poor workmanship and defective material. The current asymptotic nature of the reliability of the expendable vehicle might suggest that its reliability is near its matured state. For example, assume that both the reusable and expendable vehicle has a design reliability of 99.99 % and the risk of the vehicle loss due to the production problem is 1 % for both reusable and expendable vehicle. Assuming a reusability capacity of 1,000 times, then the reusable vehicle reliability can converge into design reliability while the expendable vehicle converges into the 1% because it is exposed to the same risk of production problems on every flight.

During the lifetime of the vehicle, the reusable vehicle is exposed to the risk of loss due to production deficiency only on its first flight. Surely the case is too simple to explain what goes on in the complex real world. There might also be poor workmanship or defective material during the refurbishment of the reusable vehicle. However, as we have learnt from the Shuttle case, the possibility of vehicle loss due to refurbishment might be negligible. The two accidents of the Space Shuttle were mainly caused by design problems. The O ring of the solid rocket booster was redesigned after the loss of Challenger and the Columbia accident also related to design problems. For Columbia, there was production of foam debris from the external tank during the launch but no solution was actually found to resolve this problem.

(VTVL/HTVL vs VTHL) There is no empirical data available to compare the reliability of these types of launch vehicles. The VTVL/HTVL configuration needs main engine restart as well as precise thrust vector control during the retrofit burn. This suggests higher failure rates than the VTHL conceptions (RAND 1997). Also, using the analogy of the vertical landing aircraft, Harrier, vertical landing is more dangerous than horizontal landing and hence, *ceteris paribus*, the vertical landing launch vehicle would experience more fatal failures than horizontal landing concepts.

(VTHL vs HTHL) The HTHL vehicle uses an airbreathing engine for its main engine and a rocket engine as a supplement. The VTVL vehicle uses rocket engines only. The reliability of airbreathing systems is expected to be high due to lower thermal loads and lower pressure requirements for the fuel turbo-pump. Rocket based vehicles require a maximum flow rate which is considerably higher than for an air breathing engine vehicle: 3,400 kg/sec vs l68 kg/sec in a vehicle with 11 ton payload to ISS orbit. Because of the large flow rate, rocket engines fail catastrophically. A failure rate study shows a significant benefit for the airbreathing, Rocket Based Combined Cycle (RBCC) engine vehicle when compared with the rocket based vehicle. Since the turbojet reliability is excellent, the Turbine Based Combined

Cycle (TBCC) engine would be even more reliable (Kumar et al, 2001). However, the TBCC engine is also operated in rocket mode a significant amount of the time, and the engine temperature increases as the Mach number increases. There is no evidence of significant reliability merit for TBCC engine. The rocket based VTHL has limited abort capability in the early stage of the flight where most failures occur. It needs to dump or burn fuel for the return flight but a malfunctioning vehicle might not afford enough flight time to do that. The historical failure record of liquid fuel propulsion launch vehicles confirms the vulnerability of the rocket engine. The top two high ratios of failure relate to the propulsion system, both the propellant feeding system and the engine (Lee, 2001). The sharp leading edge configuration of the HTHL vehicle may require an active cooling system and complex airflow in the combined engine concepts and non-continuity of the air combustion flow during the engine phase change would increase the risk to the vehicle. Hence, it is supposed that in the initial stage of the technology development, HTHL suffers from a higher failure ratio than the VTHL concept. However, in the long run, when the technology matures, the HTHL conception would have a higher reliability than the VTHL conception.

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Abstract:

This study aimed to seek out the root cause of the problems in US Reusable Launch Vehicle (RLV) development programs by investigating plausibility of the technology evolutionary paths. In order to trade off the paths, we first constructed all the physically possible technology evolutionary paths which are purely endogenous factor directed. Secondly, we analyzed the plausibility of the evolutionary paths. For the first step, the study introduced a novel methodology, “Exogenous Factor Impact Free Evolutionary Hierarchical Tree (EFIFEHT).” Using this methodology, we first developed a catalogue of the technology options for launch vehicles and built up the evolutionary hierarchical tree from the catalogued launch vehicles by applying the governing rule of the evolution, both heredity ranking of the technology elements and patterns of the complexity growth. For the second step, first, the sustainable evolutionary paths were screened by applying exogenous factors to the EFIFEHT. We then analyzed the plausibility of the path by applying the evaluation criteria of “facility of learning and efficiency of knowledge creation and preservation” induced from the perception that Space Transportation System (STS) technology is a knowledge intensive area where knowledge creation is crucial for the sustainable development of the industry as well as the product technology. Based on this analysis, we induced our argument that the bottom up approach is a more plausible path than the top down approach. A case study of the US Reusable Launch Vehicle (RLV) development programs revealed that all government initiated mission oriented programs are based on the top down approach philosophy, while two private initiatives, the Pegasus launch system and the SpaceShipOne suborbital vehicle, are based on the bottom up philosophy. The case study partially confirmed the argument that the top down approach is less plausible through consideration of the development failure of the X-33 and the high operation cost for Space Shuttle. With regard to the bottom up approach, more cases are needed to verify the plausibility of this approach because there are currently a very limited number of RLV programs in service through which the approach can be studied.

(Key words: Space Transportation System (STS), technology change, evolutionary hierarchical tree, path efficiency)

Résumé:

Cette étude vise à analyser les facteurs à l'origine des problèmes rencontrés par les programmes américains de développement de lanceurs réutilisables (Reusable Launch Vehicles – RLV), en évaluant la plausibilité des sentiers d'évolution technologique. Afin d'arbitrer entre les sentiers, nous construisons dans un premier temps l'ensemble des sentiers évolutionnaires physiquement possibles, tels que déterminés par les facteurs purement endogènes. Nous avons dans un deuxième temps analysé leur plausibilité. Pour mener à bien la première étape nous avons élaboré une nouvelle méthodologie, ' l'Arbre Hiérarchique d'Evolution Hors Facteurs Exogènes ' (AHEHFE). A l'aide de cette méthodologie, nous avons tout d'abord développé un répertoire des options technologiques des lanceurs puis construit l'arbre hiérarchique évolutionnaire à partir des lanceurs répertoriés, en appliquant les règles d'évolution suivantes: le classement d'hérédité des éléments technologiques et le degré de complexification. Pour la deuxième étape, nous avons trié les sentiers évolutionnaires soutenables en appliquant les facteurs exogènes à l'AHEHFE, puis analysé leur plausibilité en fonction de deux critères d'évaluation: le degré de difficulté de l'apprentissage et l'efficience de la création de connaissances et de leur consolidation. Ces deux critères découlent de la nature du domaine des Systèmes de Transport Spatial (STS), domaine intensif en connaissances où la création de connaissances joue un rôle crucial dans le développement de l'industrie tout comme dans la technologie du produit. Notre analyse démontre que l'approche 'bottom up' offre un sentier plus plausible que l'approche 'top down'. Le cas des programmes de développement américains de RLV montre par ailleurs que les programmes orientés mission initiés par le gouvernement sont basés sur l'approche 'top down' alors que deux initiatives privées, le lanceur Pégase et le véhicule suborbital SpaceShipOne relèvent de l'approche ' bottom up'. Cette étude de cas a partiellement confirmé que l'approche 'top down' est moins plausible, au vu de l'échec du développement du X-33 et des coûts d'opération extrêmement élevés de la navette spatiale. En ce qui concerne l'approche 'bottom up', le nombre de programmes de RLV en cours est insuffisant pour fournir les données nécessaires à une analyse satisfaisante permettant de conclure sur la plausibilité de cette approche.

(Mots-clés: Système de Transport Spatial (STS), innovation technologique, arbre hiérarchique évolutionnaire, efficience de sentier)