

Towards the Sustainable Industrial Development of Mars: Comparing Novel ISRU / ISM Architectures Using Lifetime Embodied Energy

by

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Abstract

Aerospace engineers use mass (e.g. IMLEO) as a reliable proxy for space mission costs in space system architecture and trade studies. However, in recent years, the true cost of human space exploration architectures is progressively being decoupled from IMLEO, mainly as a result of reusable rockets, adoption of ISRU and ISM, and a new emphasis on developing permanent infrastructure on other worlds. This thesis investigates the case for adopting embodied energy as a novel and more capable metric for the value and cost of in-space activities. Energy is the natural metric for work, and all in-space activities require costly direct and indirect energy sources. *Embodied energy* is an objective metric of cumulative past work, first developed by ecologists and economists in the 1970's and mainly used today to evaluate the lifecycle energy performance of buildings. The embodied energy expended in space logistics is proposed as the primary source of embodied energy for all in-space activities, coupling the proposed new method with currently accepted practice of mass minimization. Howard Odum's energy language, which charts flows of embodied energy from sources to producers, consumers and sinks, is adapted for use in the design of an early industrial outpost on Mars. A case study of seven scenarios for this simple Mars outpost over 20 and 40 years, all with identical IMLEO but widely varying embodied energies, is used to demonstrate how embodied energy leads to superior system-wide architectural insights in the design of sustainable, permanent human outposts on other worlds. An early finding is that lifetime embodied energy cost reductions increase with the time horizon and the up-front investment in ISRU and ISM capabilities. Future work based on lifetime embodied energy may result in new approaches for the simultaneous optimization of lifetime emplaced and logistical masses, lifetime energy efficiency and other figures of merit for long term system performance. The proposed Lifetime Embodied Energy metric supports the development of improved methods and tools for the system design of human outposts on other worlds. Improved system design may in turn contribute to the outposts' sustainable growth in an organic manner, and shorten the time between their establishment and Earth independence.

Thesis Supervisor: Jeffrey A. Hoffman

Title: Professor of the Practice of Aeronautics and Astronautics

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Dedication

*To my late mother Marianna, who taught me how to read,
to my father Constantinos, who taught me how to sail,
and to heroes who inspire us to reach for the stars.*

“Those who came before us made certain that this country rode the first waves of the industrial revolutions, the first waves of modern invention, and the first wave of nuclear power, and this generation does not intend to founder in the backwash of the coming age of space. We mean to be a part of it – we mean to lead it.”

President John F. Kennedy
Speech to Rice University, September 12, 1962



Image credit: Robert Knudsen. White House Photographs.
John F. Kennedy Presidential Library and Museum, Boston.

“Our leverage on the future is high, just now. We seem, these days, much more willing to recognize the perils before us than we were even a decade ago. The newly recognized dangers threaten all of us equally. No one can say how it will turn out down here.

But this is also, we may note, the first time that a species has become able to journey to the planets and the stars. **Sailors on a becalmed sea, we sense the stirring of a breeze.**”

Carl Sagan
Closing lines of *The Pale Blue Dot*, 1994

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Cambridge, MA
May 16th, 2018

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List of Acronyms

ALS	Advanced Life Support
AMCM	Advanced Mission Costs Model
CER	Cost Estimating Relationships
COTS	Commercial Orbital Transportation Services
DDT&E	Design, Development, Test & Evaluation
EROI	Energy Returned On (Energy) Invested
ESM	Equivalent System Mass
GMCNF	Generalized Multi-Commodity Network Flow
IMLEO	Initial Mass in Low Earth Orbit
IO	Input-output model
IOH	Input-output hybrid model
ISM	In-Space Manufacturing
ISRU	In Situ Resource Utilization
ISS	International Space Station
LCC	Life Cycle Cost
LCM	Life Cycle Mass
LEE	Lifetime Embodied Energy
LEO	Low Earth Orbit
MOXIE	Mars Oxygen ISRU Experiment
MPP	Maximum Power Principle
NAFCOM	NASA-Air Force Cost Model
PCEC	Project Cost Estimating Capability
SLS	Space Launch System
STS	Space Transportation System (Space Shuttle)
TRL	Technology Readiness Level

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1 Introduction

1.1 Motivation and Background

As we approach the 50th anniversary of the historic first journey to the Moon, there is a sense of renewed optimism among those of us who believe that humanity ought to have spread out into the Solar system by now. On May 11th, 2018, Space Exploration Technologies, Inc. (SpaceX) successfully launched and recovered their first ‘Block 5’ Falcon 9 first stage booster, tail number B-1046, marking yet another potentially historic spaceflight milestone in just a few short years. After almost a decade of iteration between commercial operations and development, the ‘Block 5’ Falcon 9 first stage is expected to be good for dozens of reuses, with fast turnarounds and minimal maintenance, bringing SpaceX one giant step closer to its stated goals of making space travel faster, safer, and above all, cheaper and much more frequent.

The extremely high cost of spaceflight has been the main obstacle preventing the settlement of the frontier lands and worlds of our Solar system. The laws of chemistry and physics make it hard, but not impossible, for our species to escape the bonds of gravity that tie us to the world of our birth. Faced with this challenge, we appear to have mastered the efficient combustion of energy-carrying propellants and the efficient exchange of momentum to propel our ships through the ocean of space towards other worlds. But our grades so far in the subject of space economics leave much to be desired. This thesis will explore some of the ways we fall short in the economic analysis and planning of in-space activities, and attempt to contribute a metric and methodologies that aim to improve our performance in this regard.

In the early 1970s, even as the Moon landings were still ongoing, for its next act NASA had already set its sights on the development of a reusable spacecraft which, it was hoped, would enable inexpensive and easy access to space. The Space Shuttle, formally known as the Space Transportation System (STS), was publicly announced in January 1972, eleven months before the last men walked on the Moon. The Space Shuttle program has given us valuable experience with the construction and maintenance of space structures, such as the ISS and the Hubble Space Telescope, and it has also contributed to the large body of knowledge about the effects of the space environment on human health – all necessary and useful for an aspiring spacefaring civilization. However, in nearly thirty years of operations, the Space Shuttle did not meet its launch cadence,

reusability, safety or cost targets. Thus, by mid-2011, the three remaining space shuttles were retired, to be replaced with a government-funded super heavy lift vehicle -- the Space Launch System (SLS) and, crucially, with a stable of new, privately developed launch vehicles and spacecraft supported by NASA under the Commercial Orbital Transportation Services (COTS) program, including the Falcon 9 / Dragon by SpaceX, the Antares / Cygnus by Orbital ATK, the Sierra Nevada DreamChaser, and the CST-100 Starliner by Boeing, Inc.

The COTS program has been a welcome breakthrough success, delivering real and significant reductions in the cost of space systems development and the cost of access to space. Figure 1 below compares the recurring and non-recurring costs of the COTS programs with what-if analyses of a hypothetical continuation of the STS program using publicly available data (Zapata, 2017a). Zapata found that the Falcon 9 launch vehicle was developed for a non-recurring cost of just ~\$360m, an order of magnitude less than the estimated ~\$3,977m it would have cost, had it been developed using space shuttle-era contracting and supply chain models. Zapata also modeled a scenario for ISS cargo delivery operational costs, had the shuttle not been cancelled. By making a like-for-like economic comparison, he calculated that COTS had resulted in a threefold reduction in operating costs, from ~\$272,000 per kg¹ delivered to Low Earth Orbit (LEO) that the Space Shuttle would have cost in 2017, down to ~\$89,000 per actual kg of cargo delivered to the International Space Station (ISS) by the Falcon 9 / Dragon. Zapata also pointed out that the Falcon 9 and Dragon were *developed* for a sum total cost not exceeding what it would have cost for ~two deliveries to the ISS under the old operating costs regime.

¹ Zapata's calculated hypothetical cost of ~\$272k/kg for shuttle-delivered cargo to the ISS in 2017 is an order of magnitude higher than typically quoted shuttle payload cost figures. Zapata made the following key assumptions/observations in this calculation: (i) post-2006, some of the operational costs of the shuttle were booked under 'cross-agency support' (Zapata, 2017a, fig. 7); (ii) the mass of the multi-purpose logistics module (MPLM) is *payload* from the perspective of the STS system, but it is not ISS *cargo*; (iii) the denominator represents cargo delivered to the ISS, which was an average of 13,841kg for shuttle and 1,889kg for Dragon, per flight; (iv) the flight rate of the shuttle was set to two per year, to match the contractual obligation of 20,000 kg/yr per COTS partner; this low flight rate resulted in high cost loading from overheads; (v) the aging shuttle fleet's upgrades should be expensed as a yearly recurring cost, not capitalized as investments. As a rough order-of-magnitude validation, a ~\$5b/yr of annual recurring cost divided by 13,841kg/flight for two flights/year yields a cost of ~\$180k / kg for cargo delivered to the ISS by "shuttle" in 2017. Zapata's work is based exclusively on publicly available data.

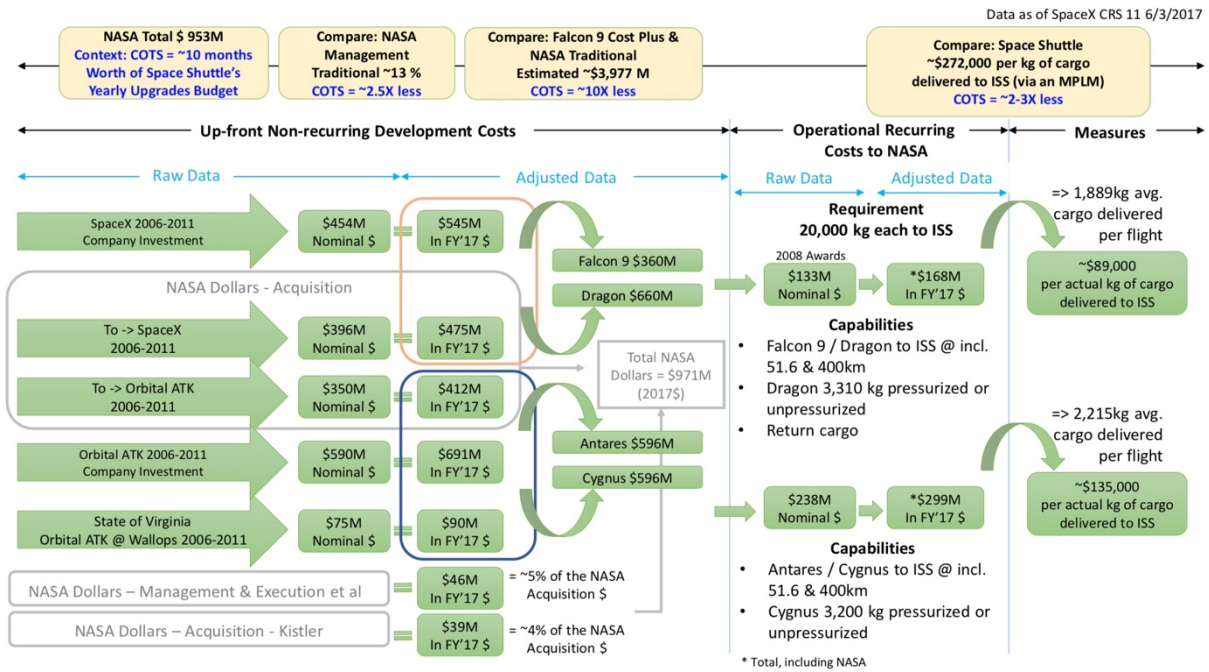


Figure 1 : Analysis of COTS Development and Operating Costs, compared to a “what-if” scenario of projected 2017 Space Shuttle costs. (Image credit: Edgar Zapata)

Given transportation costs to LEO at \$89,000 per kg and with the price of gold at \$42,795² per kg, mass sent to LEO -- even today, even after a threefold reduction in costs – can be literally said to be worth twice its weight in gold. The reasons for these high costs are primarily rooted in the physics of the Tsiolkovsky Rocket Equation. A rocket is any device that can accelerate itself by expelling mass at high velocity; from the Tsiolkovsky equation, it follows that for any given desired change in velocity Δv , the more the mass m_{rocket} ³ that is to be ultimately accelerated, the more mass m_{fuel} must be expelled:

$$\Delta v = v_{exhaust} \ln \frac{(m_{rocket} + m_{fuel})}{m_{rocket}}$$

Physics aside, launch costs to date have been high in practice because launch vehicles and upper stages are typically discarded after their first and only voyage, and because the reusable space shuttles ended up requiring extensive inspection, refurbishment and re-qualification by an army of engineers between their infrequent flights. The entrenched reality of high launch costs led to space mission architects investing substantial fractions of total mission budgets into Design,

² <https://www.moneymetals.com/precious-metals-charts/gold-price> (Retrieved: April 20th, 2018)

³ Here, m_{rocket} includes the payload mass.

Development, Test & Evaluation (DDT&E), so as to obtain maximum performance and reliability for the minimum amount of mass (Jones, 2003). In effect, high launch costs drive an intense mass focus which dictates very high DDT&E, leading to a “mass trap” which locks in a high floor for space mission costs across the industry.

This focus on mass has been universal and uncontroversial: space mission architects, from John Houbolt⁴ to the present day, have been using Initial Mass in Low Earth Orbit (IMLEO) as a key figure of merit and as a proxy for dollar cost (Ho, De Weck, Hoffman, & Shishko, 2016). Space mission architectures generally have been and are still being optimized accordingly to minimize IMLEO. The usefulness and relative accuracy of IMLEO as a proxy for space mission cost held up well for the last several decades, for a number of reasons:

1. Launch cost was often the largest single line item
2. Every mission was a *sui generis* engineering project (lack of true comparables)
3. No pre-emplaced useful infrastructure at the destination (exception: ISS)
4. All consumables and equipment originated from Earth, not from the destination
5. Dollar costs had a way of becoming politicized and/or leading to “sticker shock”
6. IMLEO does not have to be adjusted for inflation, as dollar costs do.

All the above factors which had led to IMLEO being the universally accepted and used proxy for the cost of a space mission are currently undergoing change, especially with respect to long term human exploration campaigns on the surfaces of other worlds (Moon, Mars):

1. As launch costs fall, other cost items which are not necessarily proportional to payload mass increasingly drive the total mission and campaign cost
2. Campaigns of many sequential, similar missions are being planned (Musk, 2017)
3. Future destinations will accumulate infrastructure (Mars base / city, Moon village)
4. In Situ Resource Utilization (ISRU) is entering the critical path of human exploration campaign architectures (Linne et al., 2017)

⁴ Between 1961-62, NASA engineer John Houbolt was prioritizing minimum IMLEO when he famously persuaded his colleagues at NASA to adopt his Lunar Orbit Rendezvous (LOR) architecture for the Moon landings, leading to the behemoth 15m diameter Nova rocket being abandoned in favor of the more realistic 10m diameter Saturn V design. The wisdom of this decision was later proven by the four pad explosions of the ill-fated, 17m diameter Soviet N-1 Moon rocket: the N-1 never made it to space.

5. The private sector (investors, capital markets) views dollar costs quite differently from the US Congress and Administration

As shown in Table 1 below, IMLEO was a useful proxy for total mission cost for several decades. However, going forward, total space mission cost is progressively being decoupled from IMLEO and will increasingly be driven by mission architecture and context instead.

Table 1 : Linkage Between IMLEO and Space Mission Cost

LINKAGE BETWEEN SPACE MISSION ARCHITECTURAL DECISIONS, IMLEO AND SPACE MISSION COST

Historical Experience: the past 60 years

Space Mission Architectural Decision	1957 - 2017	Link between Space Mission Architectural Decision and Initial Mass in Low Earth Orbit (IMLEO)	Link between IMLEO and Cost of Space Mission Architecture Elements
Source of Mass & Energy for Mission	Earth	Mission mass required at destination directly determines IMLEO requirement	Mission payload mass cost element proportional to IMLEO
Repeat visits to same planetary surface site?	No*	No pre-emplaced infrastructure, so mission mass required at destination directly determines IMLEO requirement	
Number of Uses per Launch Vehicle	One**	IMLEO requirement directly determines the amount of launch mass consumed	Launch cost element proportional to IMLEO
On-orbit refueling	No	ΔV requirement to reach destination from LEO directly determines IMLEO requirement	Transit cost element proportional to IMLEO
			Total space mission cost used to be proportional to IMLEO

Emerging and Likely Future Trends: the next 30 years

Space Mission Architectural Decision	2018 - 2048	Link between Space Mission Architectural Decision and Initial Mass in Low Earth Orbit (IMLEO)	Link between IMLEO and Cost of Space Mission Architecture Elements
Source of Mass & Energy for Mission	Earth + ISRU	Mission mass employed at destination will increasingly be decoupled from IMLEO requirement	Mission payload mass cost element will in future vary independently of IMLEO
Repeat visits to same planetary surface site?	Yes	Pre-emplaced infrastructure may reduce IMLEO requirement for follow-on missions or increase it for early missions	
Number of Uses per Launch Vehicle	Many	IMLEO requirement will no longer 'consume' the entire mass and economic value of the launch vehicle (LV)	Launch cost element will be proportional to IMLEO <i>divided by</i> number of reuses of the LV
On-orbit refueling	Yes	ΔV requirement to reach destination will be met using the IMLEO of the primary <i>as well as</i> of the refueling missions	Transit cost element will in future vary independently of IMLEO of primary mission
			Total space mission cost is progressively being decoupled from IMLEO and will increasingly be driven by the mission architecture and its context.

ISRU = In Situ Resource Utilization

* Apollo 12 did not make use of the mass of the Surveyor III spacecraft

** Cost & time of refurbishing the Space Shuttle was orders of magnitude higher than the cost & cadence of SpaceX building brand new Falcon 9 launch vehicle systems. Hence, the Space Shuttle system architecture was arguably not 'reusable' in the economic sense of the word.

In recognition of such decoupling, and to address the limitations of mission analysis and design where the cost metric is solely based on mass / IMLEO, alternative space mission cost analysis methodologies and approaches have been developed and employed over the years:

Equivalent System Mass (ESM), previously Equivalent Mass (EM) (Levri, Vaccari, & Drysdale, 2000) is a metric used only for Advanced Life Support systems (ALS). ESM⁵ is the

⁵ During the Apollo era, equivalent mass (EM) included mass, volume, power, cooling and materials and spares logistics. In 1992, crew time spent maintaining the systems was incorporated in EM, and in 1998 EM was renamed to Equivalent System Mass (ESM).

direct mass cost of the life support system under study, plus the allocated indirect mass requirements for all or some of: power, cooling, consumables, spares, crew time and structural volume, enabling the proper trade-off of life support systems against a mass-based cost metric.

Life Cycle Cost (LCC) (Jones, 2003) (Jones, 2015) includes all costs incurred in the life cycle of a project, from analysis and definition, to DDT&E, launch and emplacement and operations costs for the lifetime of the project, typically tabulating and reporting the cost as \$/kg of payload. Line item costs in LCC calculations are estimated using parametric cost models, including the Advanced Missions Costs Model (AMCM), the NASA-Air Force Cost Model (NAFCOM⁶) and the commercial PRICE-H space hardware cost model. All are based on analogs drawing from historic data of past projects.

Life Cycle Mass (LCM) (Jones, 2004) was an effort to merge and improve on both ESM/EM, which was only used in ALS, and LCC, which was used throughout NASA. Dollar life cycle costs, including development, launch and emplacement and operating costs, are converted from millions of dollars to mass using a derived parametric equation.

All the above NASA-developed metrics implicitly assume a carry-along strategy, where all the mass required for the mission is launched from Earth. As we have described above, this implicit assumption will not apply for future human missions to the Moon and Mars which will rely extensively on ISRU for life support and fuel. The promise and potential of ISRU, however, has led academic researchers to develop more sophisticated analytical methods:

Generalized Multi-Commodity Network Flow (GMCNF) (Ishimatsu, de Weck, Hoffman, Ohkami, & Shishko, 2015) is a method for designing and optimizing space missions in Earth – Moon – Mars space where lunar ISRU water production is assumed to be available, enabling e.g. refueling of a mission to Mars from lunar resources. The optimization goal is minimum total IMLEO across all missions in the campaign.

Time-expanded Networks (TEN) (Ho et al., 2016) is an improvement on GMCNF which introduces a temporal dimension in the analysis to solve chicken-and-egg problems (e.g. ISRU relying on itself), thereby improving realism and fidelity. Again, the optimization goal is minimum total IMLEO.

⁶ As of 2015, NAFCOM was being replaced by the Project Cost Estimating Capability (PCEC) (*ibid.*)

Integrated Space Logistics Mission Planning and Spacecraft Design (Chen & Ho, 2018) is an optimization framework which builds on GMCNF and TEN to allow for the simultaneous consideration of mission planning and spacecraft design, using mixed-integer nonlinear programming. Results show significant improvements in IMLEO relative to traditional mission-level design.

However, none of the above efforts to address the limitations of naïve single-mission, 100% carry-along IMLEO analyses addresses the inherent weakness of any IMLEO-based analysis in a future characterized by an extensive and expansive human presence in space. Qualitatively speaking, in a future where launch costs may fall by orders of magnitude, and where habitat and life support systems may be manufactured either on Earth, or in ISRU-supplied facilities on the Moon or Mars, the total “life cycle” cost of various human activities in space may well display a very low statistical correlation vis-à-vis the logistical IMLEO mass of required, associated payloads launched from Earth.

Hence, any analysis which explicitly or implicitly presumes that minimizing logistical mass transported through space is or should be a key objective of mission or campaign design may miss something which a broader analysis might uncover. This realization is echoed by NASA life support system experts, who have recently started questioning mass minimization and are calling for a return to classic NASA “first principles” of system architecture and systems engineering for mission design: (Jones, 2017) literally states in the title of his paper that we should “reconsider life support goals such as high closure and low mass using systems analysis”. Such calls will only grow louder as launch costs continue to fall, as the Technology Readiness Level (TRL) of ISRU technologies continues to improve (Linne et al., 2017), and as human missions to the Moon and Mars based on village, city, outpost, asteroid mining, a cislunar space economy or Exploration Zone concepts continue to be studied in more and more detail.

What all these visionary concepts have in common is that they harken back to earlier ages of our global civilization, when humans migrated from one continent to another in search of underutilized resources and new lives in new lands. We are everywhere on the planet by now, from the indigenous peoples living north of the Arctic Circle, to cities built in deserts, to fifty different outposts all around Antarctica. We have nowhere else to expand to, other than into the oceans and to nearby worlds across the ocean of space. When this transition does take place, it is all but certain

that we will employ the tried and tested strategy of “living off the land”; ISRU will be the indispensable linchpin for human exploration across our solar system.

Already, the first ISRU experiment on another world, the Mars Oxygen ISRU Experiment (MOXIE) (Hecht & Hoffman, 2016) is scheduled to fly to Mars with the 2020 rover. SpaceX has started the construction of the Big Falcon Spaceship, which will rely on in-space refueling in Earth orbit and ISRU refueling of CH_4 and O_2 on Mars, using electrolysis and the Sabatier process (Musk, 2017, fig. 16). The United Launch Alliance (ULA) is studying a family of interdependent, ISRU-enhanced systems as part of its push for a cislunar space economy including the Advanced Cryogenic Evolved Stage (ACES) with a months-long loitering capability, enabling in-space refueling, and its variant XEUS, which can refuel on the Moon. Planetary Resources CEO Chris Lewicki, in his presentation at MIT’s Beyond the Cradle conference in March 2018, stated to the author that ISRU can yield savings of 20% to 40% in payload cost together with increases of 150% to 240% in maximum payload. Blue Origin and Orbital ATK are both developing new reusable launch systems, which will also rely on ISRU-enabled refueling strategies.

Things, however, will not stop with the ISRU of fuel for rockets, or of water and gases for life support. Already, companies such as Made in Space, Inc. have demonstrated the manufacture of simple tools from plastic feedstock aboard the International Space Station (ISS). Given the pace of development and private sector interest, the ISRU of plastic, silicate and metal feedstocks is not far behind. In this dynamic situation, with several privately funded companies competing to open up and benefit from the space frontier, a land rush mentality is likely to emerge at some point, as it often has at similar junctures in human history. In such an environment, settlers of other worlds who industrialize early and extensively are likely to develop a sustainable competitive advantage in acquiring and maintaining a share of the space economy, with attendant benefits in standards of living and technology development for their nations. Given these needs and objectives, new architecting tools for designing extended human space exploration campaigns will be required if we are to optimize the choice of future industrialization pathways, a choice which begins with strategic decisions regarding the initial form and function of the first human outposts on other worlds.

1.2 Research Objectives

It follows from the above that, in designing the future of human space exploration and settlement, we will benefit from new cost metrics for in-space activities, and new costing methodologies and approaches which go far beyond the inherent limits of IMLEO optimization. These cost metrics and costing methods must facilitate design and trade-off freedom over more than traditional space logistics variables such as spacecraft designs, propellant ISRU capabilities and mission sequencing. It will also be necessary to ask and answer the question “what is the mission for” and then to modify the form, functional intent and sequencing of *all* the mass launched into space, including payload mass, so as to best accomplish those higher level objectives within the cost, performance and risk tolerances of the space economy stakeholder. For long term exploration campaigns to the same destinations, architects should ask themselves whether it is most cost effective to be transporting factories rather than their products.

The emergence of a space economy characterized by in-space human activities is no longer in the realm of science fiction. With the cost of access to space falling rapidly as several privately funded launch vehicles and spacecraft are being competitively developed, and with the future potential size of the space economy dwarfing the size of today’s global economy, the capital markets are very unlikely to pass up the opportunity to pursue returns from the greatest risk-loving adventure of all time.

The question is what cost metric and method would best serve the designer of in-space activities at this very early, “blue sky” stage. As we saw, dollar costs are politicized and, in any case, unreliable in the midst of the ongoing industry disruption. We also saw that the mass of space systems will at some point cease being a reliable proxy of true economic cost, as we develop ISRU capabilities and reusable spacecraft and launch vehicles which are not discarded after each flight.

Looking ahead, the hypothesis in this thesis is that the ideal cost metric, unit of account, store of value and medium of exchange of the space economy will be energy. All human activities in space, and thus the space economy as well, will necessarily rely on high quality, human-made energy sources, even more so than we do here on Earth. Beyond the thin protective layer of our world’s atmosphere, we cannot even take a single breath without implicitly relying on the availability of a high quality artificial energy source. Even a bottle of compressed oxygen, passively supplying air to an astronaut, is powered by the potential energy of the compressed gas

which can be traced back to the energy used to manufacture the bottle, and the energy used to separate, purify, pressurize and store the oxygen. All such past direct and indirect energy expenditures generate and accumulate *value* which can be measured objectively and dispassionately in units of *energy*. Best of all, we should be able to easily and accurately model and trace all value-creating energy flows at the same time as we design and test the finite number of space systems that we will need on the Moon and Mars. In short, all activities we will undertake in space, biological and technological, will require the space pioneers to have a robust plan for sustainable energy flows in support of their required and desired activities. And all activities and systems, at least at first, will be designed and modeled in advance, facilitating the computation and optimization of the associated energetics. It therefore seems intuitively fitting and potentially useful, including in ways not yet foreseen, to account for in-space activities in units not of dollars, not of mass, but of *energy*.

One source of this in-space energy could be nuclear, such as NASA's Kilopower system, which recently passed an important test milestone (NASA, 2018), while a downstream carrier for this energy could be water. Commenting on the United Launch Alliance (ULA) plans to have 1,000 people working in space by 2045, Prof. Angel Abbud-Madrid of the Colorado School of Mines stated that "*ULA's detailed analysis of the **water-based propellant market** in cislunar [Earth-moon] space has established specific price points at various orbital destinations*"⁷. (emphasis added). The author has also heard similar sentiments about "water being the currency of the space economy" expressed by a presenter at the Asteroid Mining session of IAC 2016 in Guadalajara, Mexico, in a presentation which was heavily attended by immaculately dressed and coiffed representatives of investors and bank analysts, who were keeping extensive notes. These "money men" were drawn there by nothing less than the immense future growth potential of the space economy, which is at least of the same order of magnitude as the cumulative growth of our global economy from the dawn of the industrial revolution to the present day.

⁷ <https://www.space.com/33297-satellite-refueling-business-proposal-ula.html> (Retrieved: 4/20/2018). Note also comments in the same article by ULA's George Sowers: "As a customer, ULA is willing to pay about \$1,360 per lb. (\$3,000 per kilogram) for propellant in low Earth orbit. The going rate for fuel on the surface of the moon is \$225 per lb. (\$500 per kg), Sowers said. In talking with asteroid-mining experts, ULA would take delivery of propellant at L1 for \$450 per lb. (\$1,000 per kg), he said. "Having a source of propellant in space benefits anybody going anywhere in space, to be honest," Sowers said. "What excites me is that, once you have the propellant capability going, you make a lot of other business plans look a lot better, be they on the moon, at L1, or other places."

There is one more interesting parallel with the industrial revolution, and it also points towards the role of energy as a fundamental building block for human activities in space. In the history of the industrial revolution, James Watt's innovations, which increased the thermodynamic efficiency of steam engines, directly led to the substantial expansion of coal mining and steel making, as shown in Figure 2 below. The self-reinforcing expansion in coal mining, steel making, railways and lower cost steam laid the foundations for our present-day industrial civilization (Sorrell, 2010). This critical 18th century energy efficiency innovation was analogous to the innovations which are dramatically increasing the energy efficiency of space flight as this thesis is being written, i.e. the reusability of spacecraft and the planned reliance on refueling from ISRU propellant. The feedback effects of reusability and refueling will likely operate in similar ways as the feedbacks from the improved efficiency of steam engines three centuries ago, and towards a similar outcome of unprecedented exponential growth.

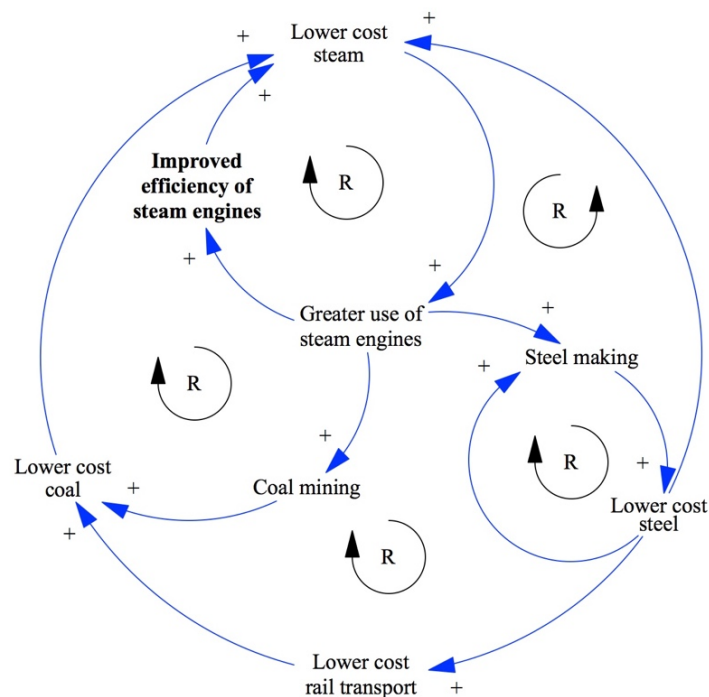


Figure 2 : The Energy Dynamics at the Dawn of the Industrial Revolution. The improved efficiency of steam engines leads to lower cost of steam, to greater use of steam engines, to steel making and coal mining, to lower cost rail and lower cost coal, and back to lower cost steam. The interacting, mutually reinforcing feedbacks (marked "R") illustrate the nonlinear, multiplicative impact to economic output which results from the availability of large energy surpluses. Image credit: George Lordos, after (Sorrell, 2010)

What will it take to grow and expand the space economy? As will be argued in this thesis, just as in the case of the industrial revolution, and indeed much more so, energy resources in space will be the *sine qua non* of every in-space supply chain. Every product and every activity in space will rely directly and/or indirectly on inputs of high quality energy, all of which must be paid for on market terms. Those strict market terms will be in contrast to the realities of Earth-bound markets for goods and services, where we do not actually pay the true economic costs of all the energy services we actually require for our survival. The air we breathe is free; most of the heating and cooling for our buildings is free; and our water, firewood and fossil fuels are *nearly* free, when we consider the immense benefits we derive from them. All these are the gifts of current and ancient sunlight. As a result of these largely invisible gifts, when economic theories were being developed in the last few centuries, energy was not even considered to be a “factor of production” – that pride of place went to labor and capital. Some ecological economists have argued convincingly that this omission was a serious mistake (Daly, 1997), and others have reproduced the empirical trajectory of GNP growth with good accuracy by modifying the neoclassical production function with factors which account for the previously unaccounted-for services provided by energy inputs. (Cleveland, Costanza, Hall, & Kaufmann, 1984) and (Ayres & Warr, 2005).

Space economists, however, are quite unlikely to repeat the mistakes of their classical counterparts. Humans living on the Moon or on Mars will have no free air, no free water and probably no (nearly) free fossil fuels⁸. On Mars, we will consume energy and employ complex systems which are themselves the product of past, ‘embodied’ energy to provide fresh air and water, 24.6/668.6⁹. It follows that merely surviving in space will, by definition, require the maintenance of a reliably persistent energy surplus. And, from the seminal study of the collapse of dozens of complex societies in (Tainter, 1988), we can intuit that the organic growth of space settlements will require *large* and *ongoing* subsidies from energy surpluses.

⁸ One should “never say never”; it’s *possible* that methane clathrates may be found underground on Mars, and we already know that Saturn’s moon Titan has liquid methane seas and lakes, earning it the well deserved moniker of “gas station of the solar system”.

⁹ One day on Mars, known as “one Sol”, is ~24.6 hours long. It takes ~668.6 sols for Mars to complete one orbit around the Sun.

Thus, if the designer is interested in plotting optimal pathways towards the maximum sustainable organic growth of a human settlement on Mars, it seems intuitively correct to hypothesize that energy efficiency and energy productivity *must* be woven deeply into the DNA of our space systems from the outset. In this new space economy, where we will depend for our very survival on machines, and where the rules of the economic game will be written to a large extent by the indispensable, trailblazing entrepreneurial engineers, we hypothesize that ***energy, embodied in energy sources and energy carriers***, has just as good an opportunity of becoming the universal currency of spacefarers, as the good old United States Dollar.



Figure 3 : “Red Mars”: Nadia building Underhill, loving her work while listening to Louis Armstrong. Notice the direct energy sources in the background (nuclear, wind and solar) and the embodied energy in all the goings-on. (Image credit: Travis Smith)

And so we ask, what if we could develop a new way of assessing the cost and value of all in-space activities *in units of energy*? How might we do that? Might an energy-based value metric be more objective and universal in its coverage, more solution-neutral and more directly to the point than any other measure, given the primacy of energy in enabling our future in space? Might an energy-based metric be easier to implement than one might at first fear, given the precision with which we should be able to calculate its employment and embodiment at all steps in the (relatively) small value chain of space systems? Might an energy-based cost metric find near-term potential in assisting with the optimal architecting of complex campaigns consisting of very long sequences of

diverse in-space activities, with a myriad alternative future paths? And last but not least, might a more objective, formulaic, energy-based metric someday become highly relevant and useful to investors as a space economy emerges and starts to grow, in the way that options pricing theory serendipitously catalyzed the birth of many financial derivatives markets, which are today measured in trillions of dollars?

And so it is that the primary research objective of this thesis is to develop and put forward a novel energy-based cost metric primarily for human space exploration missions, which has been termed **Lifetime Embodied Energy (LEE)**. The approach put forward in this thesis is applicable to estimating the costs of in-space activities for any type of space mission, but it is especially suitable and primarily intended for use in architecting a series of space missions which form part of an extended campaign to the same site on the surface of a celestial body, where the designer intends to take full advantage of the benefits of in situ resource utilization (ISRU) not just for refueling spacecraft, but also for fabricating all kinds of habitat, life support and manufacturing systems *in situ*, with a view to significantly reducing the size of the supply train and the dependence on the mother planet over the long term.

1.3 Thesis Outline

Chapter 1 introduces the topic of this thesis, and sets out why changing circumstances might warrant the development of a new objective metric of the cost of in-space activities that is not based on mass or dollars, but on energy. Chapter 2 reviews the literature to describe in more depth both some existing approaches used to estimate space mission costs, as well as the theoretical foundations of the novel methods proposed in this thesis, which derive from embodied energy and energy analysis; these were first studied extensively during the oil crises of the 1970's, and are in use today in the assessment of the life cycle energy performance of buildings¹⁰. Although the concept of embodied energy has been around for decades, its application to a space exploration use case is novel. Chapter 3 defines the Lifetime Embodied Energy (LEE) metric in some detail, and explores methodological choices with a comparative discussion vis-à-vis other metrics. Chapter 4 walks through the setup of a model for a city on Mars using Energy Language Diagrams and equations for a hybrid input-output and process based model of LEE. Chapter 5 presents the

¹⁰ The thesis author has expertise as an Energy Auditor for commercial and industrial buildings.

results of the calculations and other insights. Chapter 6 concludes with a discussion of findings, limitations and future work.

1.4 Chapter 1 Summary

The extremely high cost of spaceflight has been the main obstacle preventing the settlement of other worlds in our solar system. Almost fifty years after Apollo 11, recent reductions in the cost of access to space and in the cost of development of new space systems have led to realistic expectations of an imminent resumption of human spaceflight beyond Earth orbit. Unlike the flags-and-footprints model of Apollo, however, all stakeholders public and private declare their intent for long-term habitation and a permanent presence of humans on other worlds. The substantial energy surpluses required so that humans will not just survive but thrive on new worlds will require a pioneering mentality (“living off the land”), as well as an ongoing, strategically designed investment in the accumulation of infrastructure in outposts and “villages” on other worlds. This new context undermines the long-established coupling between IMLEO and total mission cost, leading us to wonder whether all tradespace exploration approaches for long-term human spaceflight which ultimately correlate cost with a logistical mass metric are in fact subtly missing broader architectural opportunities, specifically opportunities related to the early establishment of ISRU-supplied manufacturing capabilities on other worlds.

Recognizing this gap, the thesis attempts to develop an energy-based metric and costing system that would not miss such opportunities at the system architecture stage. Energy-based metrics such as embodied energy had been developed during the oil crises of the 1970’s and are in use today in the narrow sector of the energy performance of buildings. The application of Lifetime Embodied Energy to the study of the cost human space exploration campaign architectures is hypothesized to be more objective, more direct and relevant, easier to implement than one might think, providing near-term benefits to space architects and, potentially, far-term benefits to space investors and spacefarers.

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2 Literature Review

2.1 Traditional Methods used to Estimate Space Mission Costs

The most recent edition of the NASA Cost Estimating Handbook lists a variety of tools and methods for developing cost estimates. Parametric approaches are top-down and typically employ equations fitted on past cost data, requiring only a small number of input parameters from the user to produce a quick estimate. Analogy approaches match proposed projects to past projects with known costs, while build-up approaches are detailed, bottom-up exercises which produce accurate results but require a large number of inputs and a fairly detailed system design including a work breakdown structure (WBS). A summary is presented in Table E-1 of NASA's Cost Estimating Handbook (NASA Executive Cost Analysis Steering Group, 2015), reproduced in full as Table 2 below:

Table 2 : NASA Cost Models and Tools Utilization Guide (Table credit: CEH v4.0, Table E-1)

Tool Type	Estimating Methodology Applicability				
	Parametric				
	Analogy				
	Build Up				
NASA-Sponsored Models and Tools		ONCE Portal ¹			
Project Cost Estimating Capability (PCEC)			✓		
NASA Air Force Cost Model (NAFCOM) <i>(Transitioning users to PCEC)</i>			✓		
NASA Instrument Cost Model (NICM)		X	✓	✓	
Technology Cost and Schedule Estimation (TCASE) Tool		X		✓	
Schedule Management and Relationship Tool (SMART)		soon	✓	✓	
Phasing Model		X	✓		
Schedule Estimating Relationship Risk Analysis (SERRA)			✓	✓	✓
Quantitative Techniques Incorporating Phasing and Schedule (QTIPS)			✓	✓	✓
QuickCost			✓		
One NASA Cost Engineering (ONCE) Database		X	✓	✓	✓
REDSTAR Database			✓	✓	✓
Models and Tools with NASA-Provided Licenses					
Polaris ⁴ <i>(JCL Analysis)</i>		X	✓	✓	✓
Argo (Monte Carlo simulation)		X	✓	✓	✓
Automated Cost Estimating Integrated Tools (ACEIT)		X	✓	✓	✓
CO\$TAT (statistical analysis package)		X	✓	✓	✓
Joint Analysis of Cost and Schedule (JACS) <i>(JCL Analysis)</i>		X	✓	✓	✓
SEER for Hardware, Electronics, & Systems (SEER-H)		soon	✓		
SEER for Software (SEER-SEM)		soon	✓		
PRICE® TruePlanning™			✓		
PRICE® Estimation Suite (PES)			✓		

In addition to the above formal costing tools, which generally compute dollar costs, NASA and academia also rely on system dry mass or IMLEO as a proxy for cost. Methods to estimate appropriate mass-based proxies for mission cost are in use by NASA and under development in academia. These methods are especially useful in concept generation and tradespace exploration. We will review some of these methods below.

2.1.1 Equivalent System Mass (ESM)

Equivalent System Mass (ESM), measured in units of kg, is a widely used and accepted metric which can be employed to condense several attributes of a system, subsystem or technology into a single equivalent-mass number. The ESM of a subsystem is its actual mass, plus mass penalties for its “share” of the equivalent mass of structural volume, of the power system, and of the cooling system plus a cost penalty proportional to the share of crew time spent maintaining the life support system (Levri et al., 2000). It is therefore a valuable approach for trading subsystems and optimizing the mass of space systems at the earliest stages of design.

Typically, ESM is first calculated without taking crew time spent maintaining the life support system into account. Then, the cost of crew time is incorporated, using a crew time cost factor calculated individually for each subsystem and summed over all the life support subsystems. The justification for this approach is that the crew is presumably there for some purpose other than maintaining their own life support system, and hence all crew time required for maintenance adds up to additional fractional persons that will have to be supported with additional life support system mass. (This basis, however, does not apply when the opportunity cost is zero – i.e. when the crew has nothing better to do during long transits) (ibid.)

For the direct mass of the subsystem, in addition to the correct amount of spares, sometimes a “working mass” is also taken into account: for example, a laundry system would have the weight of the clothes added to it, because the crew have to wear another change of clothes while the laundry system is working. Further, direct mass adjustments may have to be made to equalize levels of performance, safety and reliability. For example, the mass of spare parts that would bring the target subsystem up to a certain reliability number would be added to the mass of the subsystem, so that only alternative subsystems of equivalent reliability are compared or ranked according to lowest ESM. (ibid.)

For the equivalent mass of volume, in addition to subsystem volume, all related materials are included. For example, for an inflatable module which carries a smaller volume penalty, the mass of the one-time gas as well as make-up gas are included. (ibid.)

In the case of power, typically it is the peak power requirement of a component which drives its ESM. If the designer wishes to penalize or disincentivize peak loads, the approach can be to allocate the ESM mass penalty only to those components operating during peak load time, in proportion to their share of power consumption. This means that off-peak loads are not “charged” any of the mass cost of the power system, all of which is borne by the peak loads. (ibid.)

For cooling, when two subsystems are exchanging heat in a mutually beneficial manner (regardless of whether heat exchange equipment is actually employed) that exchange is “rewarded” by ESM, and the cooling requirement for one and the power requirement for the other are both reduced. (ibid.)

ESM is effectively an implementation of an activity-based costing system with standard costs and cost drivers, where standard costs are defined for every mass, volume, power, cooling and crew time requirement at different locations. This database of standard costs is found in the Life Support Baseline Values and Assumptions Document (BVAD) (Anderson, Ewert, & Keener, 2018), which is updated regularly.

The key point about ESM which is of interest for this thesis is that in all cases, the quantity being allocated, summed and traced is *mass*, and specifically the system dry mass of a payload that had originally been launched from Earth. For example, in BVAD Table 3-6, Cost of Pressurized Volume, the nominal ESM cost of a Martian Mission surface habitat is given as 215.5 kg/m³ for a shielded habitat, but only 9.16kg/m³ for an unshielded habitat, with the accompanying explanation “*that some “to be determined” in-situ resources, such as regolith, a natural cavern or local atmosphere will provide the necessary radiation protection*”. BVAD Table 4-92 describes Regolith as having a 3,100 Cost Leverage factor, meaning that using local regolith for radiation shielding has a cost ratio of 3,100 to 1 relative to importing the shielding material from Earth. This use of ad hoc ‘Cost Leverage’ factors put forward as cost modifiers is in fact indicative of the potential research gap in space mission costs within ISRU contexts.

Beyond this, however, and beyond the ISRU of water and gases which are also covered in BVAD 4-92 with various cost leverage ratios between 1.2 and 47, all local manufacturing possibilities which could reduce logistical mass cost are shifted out into the far future and described *only qualitatively* under lines “Option 6” or “Option 7” in BVAD Tables 2-3 to 2-7. Despite their significant cost leverage potential, these local manufacturing options are not quantified in the ESM equations found in the official ESM guidelines document (Levri et al., 2003).

For these reasons, ESM can be characterized as a sophisticated and well-established method for minimizing the total direct and indirect mass involved in the design of a complex life support system for use in space and on the surfaces of other worlds. However, at the same time, ESM – at least as currently defined and practiced throughout NASA – can *not* be used to estimate a global cost-minimizing optimum in scenarios where the fabrication of life support subsystems from ISRU supplied materials is a design variable available to the mission architect. As discussed earlier in this thesis, this is a common limitation of all mass-based cost metrics.

In short, mass-based metrics such as ESM imply and are implied by a launch-mass focus. While this is entirely appropriate now, mass-based metrics may start declining in relevance if launch costs continue to fall, or if in-space manufacturing based on ISRU becomes established. If or when the current strong correlation between mass and mission cost is weakened, it is possible that other cost-attracting system design features may take over, with different cost drivers that do not necessarily link back to system mass.

2.1.2 Life Cycle Cost (LCC)

Life Cycle Cost (LCC) analysis at NASA dates back to 1969, when a life cycle cost outlook was prepared by the Space Task Group for the president, featuring the proposed share of the annual budget from 1970 – 1979 which would be allocated to the shuttle, space station, space tug, lunar orbiting station, space base and the “1986 Mars Expedition” (Zapata, 2017b).

Life cycle cost analysis is required in any exploration of alternatives which aims to properly estimate the true lifetime economic cost of a decision. This implies reliance on uncertain estimates regarding potential future costs, with uncertainty increasing still further as the analysis extends over longer time horizons. A typical method to reduce this uncertainty is to rely on extensive

statistical analysis of historical costs as a data-driven approach to support such future projections and estimates.

Life cycle cost analysis accounts for all the costs incurred in the life cycle of a system, including Design, Development, Test and Evaluation (DDT&E); launch and emplacement; operations, and disposal (Jones, 2015). The purpose of this analysis is typically to provide the decision maker with the best possible estimate of the true economic cost of various alternatives.

Over the years, NASA and the aerospace industry have accumulated a substantial body of work comprising databases, parametric models and cost-estimating relationships, aimed at assisting the analyst in the estimation of DDT&E as part of a life cycle cost estimation for a system. Per (Jones, 2015) and (Prince, Rose, & Wood, 2008), these include:

Table 3 : Cost Models For Design, Development, Test and Evaluation (DDT&E)

Originator	Model	Model Name	Inputs	Outputs	Purpose
JSC	AMCM	Advanced Missions Cost Model	dry mass, # units, mission type, difficulty, block or hardware generation, time until entry in service	Estimated DDT&E	Top-down model for long-range cost forecasting tool, used in early conceptual stages
MSFC	SVLCM	Spacecraft / Vehicle Level Cost Model	Project type, dry mass, # units, learning curve (simplified version of NAFCOM)	Estimated DDT&E	Top-down estimates for spacecraft costs only: engines, spacecraft, LV, satellites, instruments
MSFC	NAFCOM	NASA - Air Force Cost Model	WBS, mass estimates, materials, power requirements, design life, technical and programmatic complexity	Estimated DDT&E and recurring production costs	Mid-level, for Crewed, uncrewed spacecraft and LV in early phases of development.
MSFC	SOCM	Space Operations Cost Model	Integrated into NAFCOM		
NASA	PCEC	Project Cost Estimating Capability	Successor to NAFCOM; similar inputs (mass estimates, etc.); relies on WBS and CER libraries	Estimated DDT&E and recurring production costs	Mid-level, replacing NAFCOM. NAFCOM WBS differed from NASA standard and the CER's were not transparent enough.
Commercial	PRICE-H	Parametric Review of Information for Costing and Evaluation - Hardware	hundreds; most important are electronics mass and structural/mechanical mass of WBS line items, with complexity estimates	Estimated DDT&E	Bottom-up, based on hundreds of CER's and confidential data from thousands of projects. Detailed and widely used in commercial aerospace

From Table 3 above, we note that all model-based estimates for DDT&E, which is the first of the three major inputs into life cycle cost analysis, rely on system dry mass as the main input. Difficulty, complexity, novelty, learning and number of units are also important inputs, but in

many cases of novel and difficult missions, these inputs are narrowly constrained, and are therefore not the most important architectural decisions for any one family of missions. Such families of missions include all missions where ISRU is in the critical path for life support. Further, all of these models use historic cost data as inputs, whether directly or indirectly via Cost Estimating Relationships (CER's), and historic cost data based on the old aerospace industry supply chain structure is declining in relevance for cost estimating purposes.

Life cycle costing models sit one level above the non-recurring-cost DDT&E models and the recurring-cost Operations Cost models, incorporating their outputs as inputs and producing multi-year cost phasing as their outputs. Per (Prince et al., 2008), the Life Cycle Analysis Model structure, as developed for the Constellation program, was as shown in Figure 4:

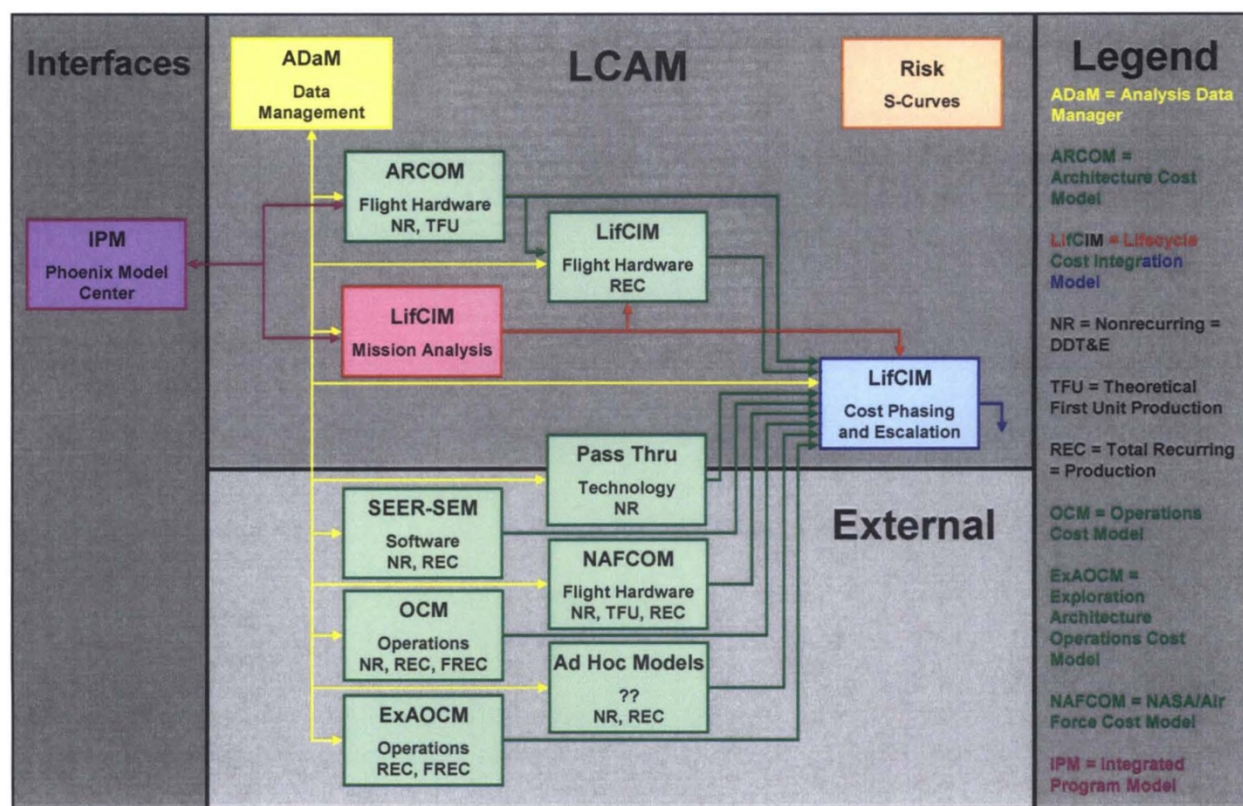


Figure 4 : Model Structure of NASA Life Cycle Cost Models

Launch and emplacement cost is driven by system (i.e. payload) mass, destination, timeframes and orbit selection, and the operations cost component of life cycle cost analysis relies partially on DDT&E as a cost driver (Jones, 2015). This means that system mass has an indirect effect on the operations cost component of LCC via DDT&E.

These dependencies of LCC on system mass and historic costs are both being challenged by the recent significant developments in the US aerospace industry, which are driving the ongoing reduction in the costs of space access and of in-space activities. As we saw in Chapter 1, (i) system mass (and/or IMLEO) are being progressively decoupled from total mission cost, for the reasons described in Table 1, and (ii) historic costs are revealed to be a less-than-reliable guide to future costs. (Zapata, 2017a) has shown convincingly that these widely used cost models would have overestimated the cost of DDT&E of the Falcon 9 and Dragon system by a factor of 10, and the operating costs by a factor of 3. This large discrepancy implies that the historic cost data in the extensive databases may not reflect true economic costs, but an unknown blend consisting of economic cost, rents plus inefficiencies. Since much of the benefit of relying on easily-obtained mass data and historic cost data for LCC computations is the reduction in subjectivity of forward-looking estimates of life cycle economic costs, it follows that the recent substantial cost reductions achieved by new commercial space companies increase the urgency for analysts to revisit these methods, tools and metrics and search for improved alternatives.

Adding to these concerns are the realities that (i) total life cycle dollar costs for a multi-year project can give rise to sticker shock which is easily politicized, and (ii) that critical new in-space activities are being contemplated, such as ISRU and long-term surface habitats, for which we have no truly comparable historic cost data at all.

These facts underlie our motivation to search for improved cost metrics and costing systems for in-space activities which bypass the need to use historic dollar costs or system mass.

2.1.3 Life Cycle Mass (LCM)

LCM was derived from the established Life Cycle Cost (LCC) and first proposed in (Jones, 2004) as a “more inclusive and potentially better metric” than EM/ESM. The life cycle costs for (i) development, (ii) launch and (iii) operations are estimated in millions of dollars and then converted into mass.

Development costs for LCM purposes can be estimated in a variety of ways, with Jones' preferred approach being the top-down Advanced Missions Cost Model (AMCM) which consists of one fitted, parametric equation with five¹¹ input variables, given by him as:

$$\text{Cost} = 5.65 * 10^{-4} \mathbf{Q}^{0.59} \mathbf{M}^{0.66} 80.6^{\mathbf{T}} \mathbf{G}^{-0.36} 1.57^{\mathbf{D}}$$

Where:

\mathbf{Q} = total number of units, including development and production units

\mathbf{M} = system dry mass, in units of kg

\mathbf{T} = type of mission parameter (2.46 for crewed planetary missions)

\mathbf{G} = hardware generation parameter (new design = 1, second generation = 2)

\mathbf{D} = difficulty scale parameter (e.g. -2 for very easy, 0 for average, +2 for very difficult)

From this equation, it is evident that once again, there is an implied and direct relationship between the development cost component of LCM and system dry mass. Within any given family of novel, difficult missions (such as, for crewed missions to the surface of the Moon or Mars), all the terms of the equation except those based on \mathbf{Q} and \mathbf{M} reduce to constants. Thus, for any given mission profile, more mass translates monotonically into more development cost. This mass-driven development cost is then an input into LCM.

The launch cost component for LCM is typically estimated using mass ratios. For example, for a one-way Mars landing, or for a Moon landing and return to LEO, Jones gives a typical initial-to-payload mass ratio of 20. This initial mass is multiplied by a typical launch cost per kg, which Jones had taken as \$25k/kg for space shuttle (Jones, 2004). So in the case of launch cost, the dependence of LCM on system dry mass is direct and strongly amplified.

Finally, the operations cost component for LCM is estimated as a percentage of the system development cost per year, in accordance with the JSC Mission Operations Cost Model (MOCM). Jones gives this percentage as 10.9% for crewed spacecraft.

¹¹ A sixth variable, time until entry into service, is also typically part of AMCM, but it was not included in the (Jones, 2004) formulation.

Therefore, in the case of LCM, the development, launch and operations costs components for a crewed mission to the Moon or Mars are all a function of system dry mass. Despite the inclusion of development costs and operations cost, we note that in the end LCM hews closely to the same launch-mass-focus paradigm, just like ESM and LCC.

2.1.4 Generalized Multi-Commodity Network Flow (GMCNF)

The Generalized Multi-Commodity Network Flow Model (Ishimatsu et al., 2015) was developed to address the need for new space logistics paradigms involving multiple destinations, and the potential for refueling spacecraft at some of those destinations via in situ resource utilization (ISRU). The problem and the solution space are represented using graph theory, with the nodes representing points of supply and/or demand for a variety of commodities, and with the arcs representing cost per unit flow for each commodity. The decision variables are the flows along the arcs, and the optimum solution minimizes the total cost of flow.

This model is “generalized” in that flows are not conserved in the traditional sense, but can grow or shrink en route between nodes as the arcs themselves generate or consume flow. It is also “multi-commodity”, in that it captures interdependencies between commodities, for example propellant consumption is driven by total mass, or crews consume food and water in transit. The model further observes constraints, such that the total flow rate of all commodities along an arc may be subject to a capacity limitation.

As developed by Ishimatsu et al, GMCNF incorporates within the model boundary flow gains and losses that arise from interactions, transformations, mass balance at nodes, and flow concurrency on arcs. The more nodes and arcs are included, the broader the possible solution space that can be searched. It is a linear programming model and therefore the minimum cost solution is guaranteed to be optimal, at least for the given assumptions made in formulating the static network graph.

Once it is set up and run, GMCNF sums up the cost flows along the arcs to calculate and minimize Initial Mass in Low Earth Orbit (IMLEO). The sources of commodities which yield reductions in total IMLEO are ISRU propellants and consumables. The end result is still an exercise in minimizing IMLEO, and as a result the implicit launch mass focus is present in this approach, as well.

2.1.5 Time-expanded networks (TEN)

Building on GMCNF, (Ho et al., 2016) introduced a time dimension to Ishimatsu et al.'s graph theoretic model, to overcome the fact that the GMCNF solution is optimized only for a hypothetical steady state. This is done by creating copies of each node for each time step, where appropriate. This would be computationally inefficient if done across the board, so Ho's implementation clusters together those nodes where the static network approach is still viable and problem-free, reducing the need for time expansion to the input and output windows between clusters. The benefit is that model fidelity is increased, incorporating both temporal precedence and time-dependent growth dynamics in the cost minimization exercise.

Other than this change, the fundamentals of Ho's Time Expanded Networks are similar to GMCNF, meaning that the same IMLEO and launch-mass focus observations made above will apply here as well: that is, TEN, like GMCNF, are still focusing on investments in ISRU-based propellant resupply capability *to minimize total IMLEO* across a campaign of several missions.

For both GMCNF and TEN, an important observation is that each destination (such as, the surface of Mars) is represented in the network by a single node, implying that the problem is being attacked from the perspective of minimizing logistical mass *given a fixed payload* for delivery from any point in the network to that node. In order to use models such as GMCNF to investigate "make or take" questions of interest to the in-space manufacturing community, it would be necessary to develop entire surface-based networks of a different nature (transport, transform, etc.) so as to include a functional representation of in-space manufacturing supply chains on the surfaces of the Moon, Mars and asteroids. The question of what is a satisfactory functional representation of such off-Earth manufacturing supply chains, which would encompass a sufficiently broad solution space, is a fruitful research area for a potential extension of GMCNF which utilizes the Lifetime Embodied Energy framework instead of IMLEO.

In short, the existing and accepted costing methods assume that the amount and nature of mass to be ultimately delivered to an in-space destination is an external requirement. Hence, all studies of the benefits of ISRU involve ad-hoc changes to these mass-focused methods.

2.2 Towards an Energy Theory of Value

Intuitively, we can appreciate the possibility that physical value creation might turn out to be inseparable from its thermodynamic foundations. But economists from Adam Smith in 1776 to Solow and Swan in 1956 had eschewed the role of energy in value creation, instead attributing economic output to capital and labor¹². Their models treated capital and labor as independent and substitutable for each other via the intermediation of markets and the price mechanism. The direct and indirect essential high quality energy flows, which enable capital and labor to create physical value, do not form part of these canonical economic models (Cleveland et al., 1984). There are indications that this choice of system boundary may be leaving something out: Solow, for instance, had attributed the substantial observed divergences in the growth rates of income and the factors of production (Figure 5 below) to an exogenous ‘technological progress’ factor, thereby inviting attempts by students of energy theories of value to endogenize Solow’s technical factor by considering all direct and indirect energy services as an input, in addition to the commercial sales of energy (Ayres & Warr, 2005, 2009; Romer, 1990).

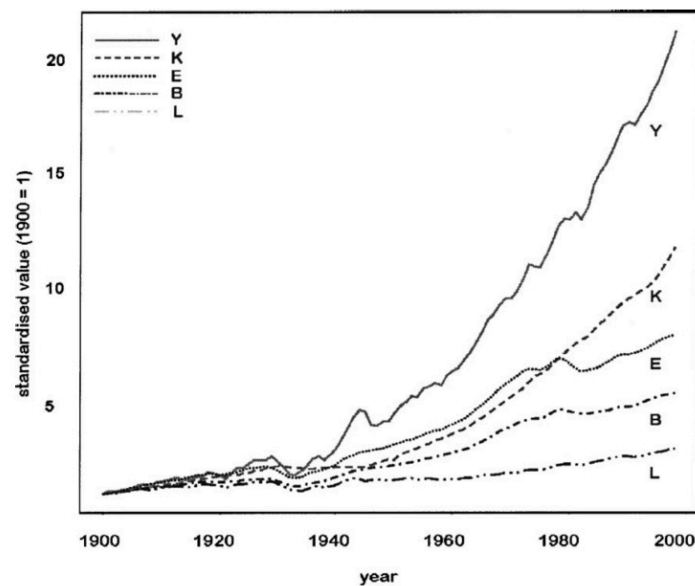


Figure 5 : GDP (Y) and Factors of Production K, L, B and E: USA, 1900-1998 (Ayres & Warr, 2005)

¹² Partly yielding to criticism from Nicolas Georgescu-Roegen, Solow modified his production function to include resources, but maintained the claim that capital can fully substitute for resources, mediated only by marginal prices. This was described as a “conjuring trick” by Georgescu-Roegen. (Daly, 1997)

Earlier in the 20th century, some physical science scholars had taken on the challenge of exploring the relationship between economic growth and energy. The Nobel prize-winning chemist Frederick Soddy, who had crossed discipline boundaries to consider issues in economics and finance, stated that “If we have available energy, we may maintain life and produce every material requisite necessary. That is why the flow of energy should be the primary concern of economists.” (Soddy, 1933). And the ecologist Howard Odum developed an energy language (Figure 7; Figure 8) which permits modeling of all types of natural and artificial systems at all scales, from a simple farm to the entire world economy (Odum, 1983).

Building on Odum’s and Soddy’s insights, (Ayres & Warr, 2005; Cleveland et al., 1984; Costanza & Herendeen, 1984; van Zon & Yetkiner, 2003) modified Solow’s classical production function to incorporate the contributions of high quality energy flows in the modeling of the GDP of the United States for the 20th century; their modeling and empirical work demonstrated¹³ the superior skill of growth and production models which explicitly incorporate economic interactions based on **energy theories of value**. However, these modifications to dominant economic models have not become mainstream.

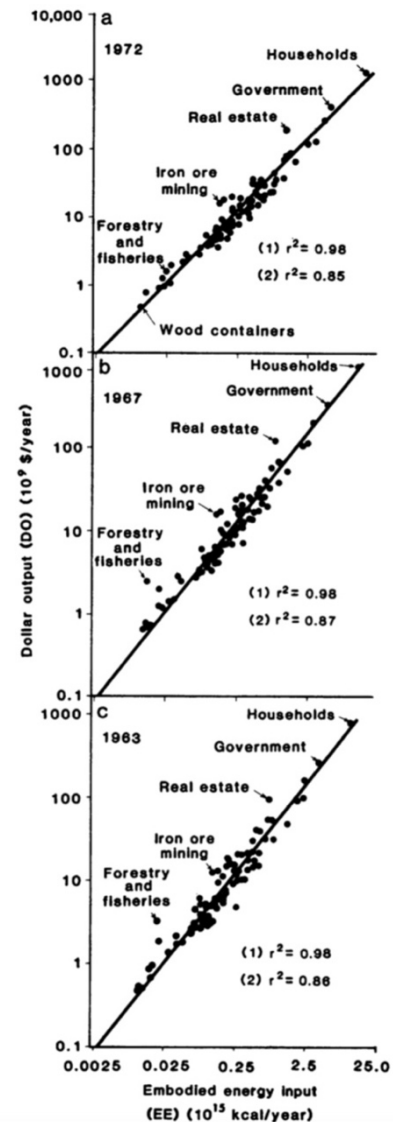


Figure 6 : Cross-sectional analysis of embodied energy inputs and dollar output for the U.S. economy in 1963, 1967, and 1972. (Credit: Cleveland et al., 1984)

¹³ See Figure 6, reproduced from (Cleveland et al., 1984). The original caption also included this note: “Energy input includes direct fuel measured at the point of combustion and embodied in intermediate goods, labor, and government services purchased by each sector.... Excluding households and government from the regression yields r^2 values of about 0.86. Excluding households and government from energy intensity calculations yields r^2 values of about 0.55.”

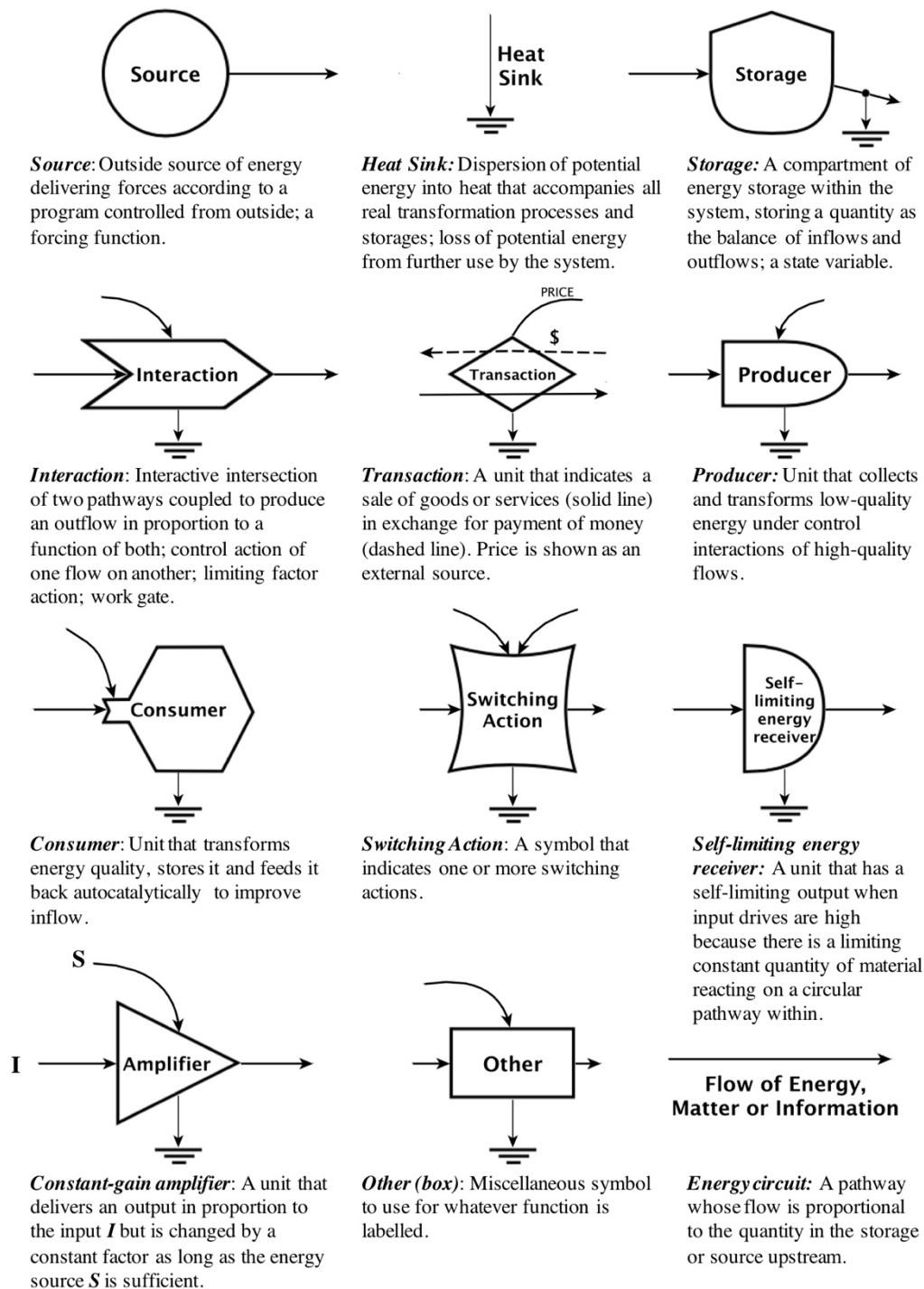


Figure 7 : Symbols used in Howard Odum's Energy Language. Any natural or artificial system, including all exchanges of energy, matter and information, can be modeled using energy language diagrams. Source: (Odum, 1983, fig. 1.4, 1996, fig. 1.2)

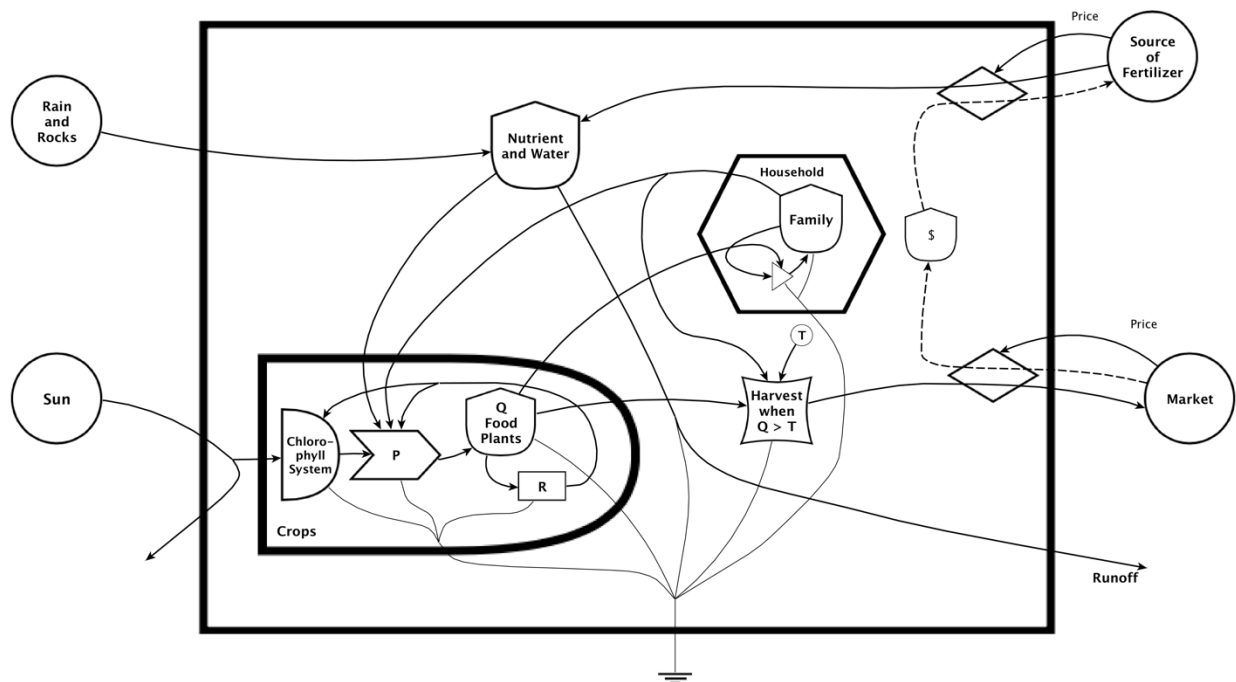


Figure 8 : A Farm Modeled Using Howard Odum's Energy Language. Source: (Odum, 1983, p. 9)

2.2.1 Thermodynamic Foundations of Value Creation

Life, as Ludwig Boltzmann pointed out in 1886, is primarily a struggle for available energy. All natural and artificial systems which survive the selection struggle perform a value-delivering function and exhibit some order. They rely on flows of available free energy¹⁴ to sustain their capability to perform their value delivering functions and to maintain their state of order. This follows directly from the Second Law of thermodynamics: in the complete absence of available free energy flows, it would be impossible to reverse the inevitable degradations imposed on highly ordered systems by the Second Law. It would also be impossible to create any highly ordered systems out of an initial state of disorder without access to a high quality source of available free energy. In this sense, *all* physical value creation takes place on foundations laid down by the laws of thermodynamics, and *only* on these foundations.

2.2.2 Available Free Energy and Energy Quality

Available free energy refers to energy that is sufficiently concentrated so as to have the potential to do work. Energy sources have different quality rankings in the “energy food chain”

¹⁴ These flows of free energy, in the formulation of this thesis, can be in the past, present and/or in the future. It is the notion of *reliance* on these flows which is of the essence here.

based on the amount of useful work they can do per unit of heat equivalent (Cleveland et al., 1984), a concept which is analogous to food chains in living ecosystems. For example, the sunlight illuminating a solar panel on a satellite in orbit is available free energy, but its energy quality is lower than that of electricity; the latter is more concentrated, more versatile and can perform more economically useful work per unit of heat equivalent.

2.2.3 Net Energy and Energy Returned on Energy Invested (EROI)

The gross energy content of an energy source is its total thermodynamic energy content, but the relevant measure of energy for biophysical economists is the net energy available to perform economically useful work. Net energy is calculated by subtracting from gross energy the amount of energy required directly and indirectly to make the energy source useful for actual work. Thus, the energy expended to extract fossil fuels, beneficiate, store, and distribute them would have to be subtracted from the gross thermodynamic energy content of the fossil fuel in order to calculate the net energy available to society from that source. Net energy can be related to gross energy through the concept of Energy Returned on Energy Invested, typically abbreviated as EROI (Cleveland et al., 1984). If the energy required to tap an energy source exceeds the gross energy of that source (i.e. $EROI < 1$), then a society cannot sustainably utilize that energy source (Hall, Balogh, & Murphy, 2009). One study of oil shale has found EROI ratios as low as 1.5 : 1 when the internal energy source of oil shale consumed during production is included in the denominator (Cleveland & O'Connor, 2011).

2.2.4 Maximum Power Principle

The maximum power principle (MPP) postulates that, in any survival of the fittest scenario, such as biological evolution, market competition, or choice under economic scarcity, the systems that tend to be selected are those which generate the maximum useful power, because these systems will be able to absorb the maximum available energy from the available sources for their maintenance, improvement, competitiveness or growth.

This principle was first enunciated by Lotka in 1922 and studied further in (Odum, 1983, p. 141). Odum vividly illustrated the MPP through his descriptions and depictions of 'autocatalytic modules', which are high order systems that tend to evolve via feedback reward mechanisms to maximize the flow of useful energy. One example of an autocatalytic system is that of the farm

depicted in Figure 8: the food output enables the family to grow, and the increasing amount and quality of labor and control from the growing family enables the farm to absorb more solar energy and increase the output of food.

Our civilization's collective failure to rein in carbon emissions from fossil fuels, despite the significant danger they pose, is likely related to the observation that our global human civilization is an autocatalytic system which obeys the maximum power principle.

The usefulness of the maximum power principle in this thesis is that it serves both as a high level guideline for system and system-of-systems design, and as a natural reference choice for subsystem point-designs at various levels, for the purpose of calculating objective values of energy inputs and outputs for any given chain of systems and subsystems.

2.2.5 Exergy, Work and Entropy

The concept of exergy is closely related to the notions of available free energy, energy quality, net energy and EROI. Exergy has been defined as the potential of energy to do work (Ayres & Warr, 2005; Bejan, 2002; Odum, 1983). In contrast to energy, which can be neither created nor destroyed, exergy of a given type is destroyed when work is performed. Physical work (termed “exergy services” by Ayres & Warr) can be in the form of exergy of a different type or quality, plus entropy.

For example, there may be a significant total quantity of heat in the small random motion of molecules over very large volumes of walls and floors in a building. However, as this heat energy is widely dispersed, with shallow heat gradients throughout and in low volumetric concentrations, it has very limited potential for economically useful work; in this case, we say that exergy is low and entropy is high. On the other hand, a barrel of crude oil or a basket of grain have a high energy density and hence a high potential for useful work; therefore, we say that oil and grain have high exergy and low entropy. Exergy is not a conserved quantity; it is destroyed when we do work, and entropy always increases when we use up one form of exergy to produce exergy in some other form.

From this lens, electricity produced from solar panels in-space is exergy of one form and quality level. If the exergy of that stored electricity is used up to produce liquid methane and liquid oxygen from a carbonaceous asteroid, then it can be said that in using up the exergy of the solar-

source electricity, we have produced a different form of higher quality exergy (plus entropy). In its new higher quality form, the exergy of CH₄/LOX is more concentrated and versatile.

2.2.6 Emergy

To put the contributions of different kinds of energy on a comparable basis, the ecologist Howard Odum formalized the concept of EMERGY (spelled with an “M”). He defined emergy as the energy of one type required in transformations to generate a flow or a storage of energy; more plainly, the EMERGY of a system is the heat equivalent of all past work that was required in order to produce that system. Odum also put forward a new unit, the **emjoule**, to clearly distinguish among these different types of energy. For example, all the flows of electrical energy that arise from the operation of a coal-fired power plant depend on a source of “coal emjoules”; that is, we can say that it takes 4 emjoules of energy from coal to make 1 joule of electrical energy. (Odum, 1988). The fact that a real, economically viable coal-fired electricity production system is dissipating $4 - 1 = 3$ joules of energy into entropy in this way means that one joule of electrical energy (exergy) must have the same or greater ultimate economic value as four joules of energy (exergy) directly obtained from coal. This shows that a hierarchy of values implicitly exists within real chains of transformations of one form of exergy into another. As we move up the exergy chain, more and more lower quality energy is dissipated, and the embodied energy increases. Odum had originally conceived of emergy as standing for ‘embodied energy’ but subsequently chose to think of it as ‘energy memory’ instead, to reflect the fact that in the process of building exergy value, most of the energy is dissipated along the way (Hornborg, 1998).

2.2.7 Transformity

Further extending the formalization, Odum defined transformity as an energy measure of hierarchical position in an “energy food chain”. It is the amount of energy of one type required to generate a unit of energy of another type under optimized conditions. It has dimensions of emjoules per joule (Odum, 1988). If we consider an energy chain, such as from solar energy, to phytoplankton, to fossil fuel, to electricity, the solar transformity of each stage in this chain can be derived from first principles of physics, chemistry, biology or thermodynamics. Odum calculated typical solar transformities, measured in units of solar emjoules per joule of energy value, as shown in Table 4 below. This indicates the usefulness of the approach in producing an objectively derived metric based on a common denominator for diverse systems and activities.

Table 4 : Typical Solar Transformities in solar emjoules per joule. (Table credit: Odum, 1988)

Item	scj/J
Sunlight	1
Wind kinetic energy	623
Unconsolidated organic matter	4,420
Geopotential energy in dispersed rain	8,888
Chemical energy in dispersed rain	15,423
Geopotential energy in rivers	23,564
Chemical energy in rivers	41,000
Mechanical energy, waves, tides	17,000–29,000
Consolidated fuels	18,000–58,000
Food, greens, grains, staples	24,000–200,000
Protein foods	1,000,000–4,000,000
Human services	80,000–5,000,000,000
Information	10,000–10,000,000,000,000

2.2.8 Embodied Energy

Having explored the above definitions and concepts, we are now prepared to consider the hypothesis that **embodied energy** might be a useful measure upon which to base an energy theory of value. The concept of embodied energy was first articulated in (Bullard & Herendeen, 1975a, 1975b), as a logical offshoot of their broader net energy analysis.

Building on the terms defined in the previous subsections, we can state that natural and artificial systems attain their low-entropy condition via the prior consumption of exergy (and the accumulation of energy) in the performance of actual physical work. By following these chains of exergy destruction all the way back to ‘primary’ sources (such as sunlight, radioactivity, or geothermal energy), and by adding together only emjoules of the same type using the transformity ratios to perform conversions at each step, it is in theory¹⁵ possible to accurately estimate the past amounts of thermodynamic work that had gone into the production of a system or of a high quality energy source. This **quantity of past work is the embodied energy** of the system of interest.

Further, by accounting for and measuring this embodied energy cost of goods and services in the emjoule units of a common-ancestor upstream source, it is possible to objectively compare the economic cost, or the minimum economic value-added, of two or more alternatives in a

¹⁵ In practice the task is complex and requires a substantial amount of diverse data. A computationally effective approach tailored to the needs of long-term space missions will be the subject of future work.

solution-neutral manner, with all degrees of freedom for embodied energy optimization open to the designer.

2.2.9 Current Applications of Embodied Energy Analysis

A generic, fundamental use of embodied energy analysis is to benchmark the total amount of energy consumed in the production of a system with its total energy output, or the energy savings it is supposed to deliver.

Embodied energy has been used to study energy efficiency in manufacturing (Kara, Manmek, & Herrmann, 2010; Rahimifard, Seow, & Childs, 2010); to calculate carbon footprints (Hammond & Jones, 2008), and to calculate the lifecycle cost, energy performance and replacement cost of buildings (Dixit, 2017). It has also been used to consider the sustainability of economic growth strategies (Lambert, Hall, Balogh, Gupta, & Arnold, 2014; Macías & Matilla-García, 2015; Sorrell, 2010; van Zon & Yetkiner, 2003).

2.3 Chapter 2 Summary

We have reviewed existing accepted costing systems in use at NASA, which are particularly suited for early-stage space mission tradespace exploration. We have also reviewed proposed improvements to costing methodologies from inside NASA (LCM) and from academia (GMCNF). In doing so, we found that almost all existing and proposed costing systems rely on space system dry mass as the key driver of, or proxy for, space mission cost.

Until now, mass has been a useful and reliable proxy for cost, but this is changing due to trends towards launch vehicle reusability, upper stage reusability and in-space refueling from ISRU sources. Furthermore, the falling cost of access to space due to new forms of contracting (COTS, CRS) is undermining the validity of parametric cost models which rely on extensive databases of historic dollar costs.

In our search of a cost metric for in-space activities that is not denominated in units of mass or dollars, and which avoids the pitfalls of subjectivity, we reviewed the literature for an energy theory of value, building up to the concept of embodied energy as a candidate measure of value and cost. Since embodied energy is calculated by summing all the past energy flows required to develop the higher-order system, and as these energy flows can be estimated analytically from first principles for any well-understood physical process, **emergy** or **embodied energy** has been put forward by its advocates as an alternative, objective theory of value which is claimed to be superior to the utility theory and factor-based methods currently in use in mainstream economics.

3 Methodological Considerations

3.1 The Lifetime Embodied Energy (LEE) Metric

As we saw in Table 1 above, the changing circumstances are weakening the traditionally strong correlation between IMLEO and true space mission cost. This decoupling is driven by several parallel trends: the private sector race to develop reusable rockets and spacecraft; the stated intention by multiple entities to accumulate infrastructure at destinations on planetary surfaces and at deep space locations; and the design of entire space exploration strategies and architectures which critically rely on situ resource utilization (ISRU).

Adding to the momentum of change is the fact that both the private and the public sector, in the United States and internationally, are actively engaging with and reacting to these disruptive trends. As actual and planned human activities in space increasingly come to resemble a broader scope of economic activities on Earth, it may be useful to draw from established practices in accounting, management, economics and ecology for inspiration on new ways to measure (and thereby, optimize) the costs and benefits of future in-space endeavors.

Thus, the concepts of investment, future income streams, depreciation and amortization from financial accounting seem a natural fit not just for the reusable rocket revolution, but also for the intention to accumulate infrastructure, capabilities and supplies at selected strategic locations in the inner solar system for use by future crewed missions. The concept of activity-based costing from managerial accounting seems a good fit for the in-space supply chain and manufacturing opportunities enabled by advances in ISRU technology. And the notion of using an energy-based metric as a universal in-space unit of account appears *prima facie* to be justifiable, given the raw, immediate priority of high quality energy as the ultimate in-space resource.

Hence, this thesis proposes lifetime embodied energy as an energy theory of value which is particularly well suited to the architecting of space missions, and which may be usefully informed by methodologies and mechanics that are already well established in the disciplines of accounting, economics and ecology.

3.1.1 Definition of Lifetime Embodied Energy

For any given natural or artificial System (hereinafter “the System”) and its external source of primary energy, the lifetime embodied energy (LEE) of the System is defined in this thesis as the sum of the fractionally allocated, direct and indirect lifetime cumulative energy flows of primary energy required to create, operate, sustain and decommission the System, measured in joules of the energy type of the primary external energy source (‘source emjoules’).

For every System, the calculation of LEE involves the generation of a network of dependencies, inputs and outputs. Each dependency or input is itself a system with a LEE which is driven by its network of lower level dependencies and inputs. At the lowest level branches of the tree, only elemental building block systems remain, and their only input is typically the selected external primary energy source.

Thus, other than the primary external energy source, all upstream systems contributing direct or indirect work to the System should be considered as lying within its system boundary. The fractional allocations of embodied energy among these systems are to be carried out in such a way as to result in the sum of the LEE of all systems within the system boundary being equal to the total LEE of the System. For each system, its fractionally allocated embodied energy flows incorporate the proportionate allocations of the LEE of upstream systems which are required inputs or catalysts for the operation of that system. The proportions for these allocations will vary according to how much of each upstream system’s lifetime work output is exclusively required by the downstream system, over the lifetime of the downstream system¹⁶.

3.1.2 Choice of Primary Energy Source, System Boundary and Units

The primary energy source is chosen with a view to making it the key figure of merit for the overall system under consideration. Once the primary energy source is chosen, the LEE of all systems and subsystems lying within the system boundary will be calculated in the same emjoule units as those of the primary external energy source. This creates a unit of account which is external

¹⁶ These proportions can also be allocated in different ways to reflect the real underlying economics of the situation. For example, a primary product may attract all the cost of an input, while its byproduct, defined as a product which would not exist if the primary product were not in demand, may be treated as “free”, with none of the embodied energy cost allocated to it.

to the system and which allows the relative comparison (value or cost) of elements within the system boundary.

Thus, for the purpose of architecting human space exploration campaigns to the surfaces of other worlds, it is recommended to initially use the **embodied energy of space logistics** in units of space logistics emjoules (slej) as the initial primary energy source, instead of embodied solar energy which was Odum's favorite¹⁷. This choice is recommended for space systems architects who wish to target the future cost of space logistics over the very long term as the variable to be optimized, in accordance with present day priorities in the field.

A corollary of the above is that a System should include energy sources, transformers and storages within its system boundary, if these elements are themselves co-dependent on a common upstream primary energy source. If a System boundary is initially drawn with more than one external energy source, the analyst must consider carefully whether the external energy sources are truly independent. If, after reflection, it turns out that these sources are co-dependent on a common upstream source, it is recommended to expand the system boundary until all co-dependent sources are brought within the system boundary (Odum, 1996, fig. 6.5). This will permit comparison of all elements against the same baseline and enable their direct objective valuation in terms of the embodied energy measured in units of emjoules of their ultimate common source. An illustration of the process of selecting the system boundary to encompass interdependent and co-dependent sources is shown in Figure 9 above.

¹⁷ Howard Odum was an ecologist, so the choice of solar energy as primary energy source was a natural choice for him. Since all natural and artificial concentrations of energy trace their origins back to the stars in one way or another, Odum was able to trace the embodied energy of all natural and artificial systems back to solar emjoules. This enabled Odum to put forward a unified valuation system for both environmental ecology and human economy on the same denominator of solar emjoules (sej). To Odum, such a unified valuation system for economic and ecological services was the key to unique insights on the relative value of services we receive from the natural environment, but which, to our great detriment, we consistently fail to correctly value in money terms. It is worth noting that Odum's last book before his death, titled *Environmental Accounting* (Odum, 1996) on the methodology of embodied energy calculations, was gifted to the MIT libraries immediately upon publication by the legendary MIT economist Paul A. Samuelson. It may also be worth noting that, apparently, this book has been checked out just twice in the 22 years since 1996: once in September 2004, and again in the spring of 2018 by the thesis author.

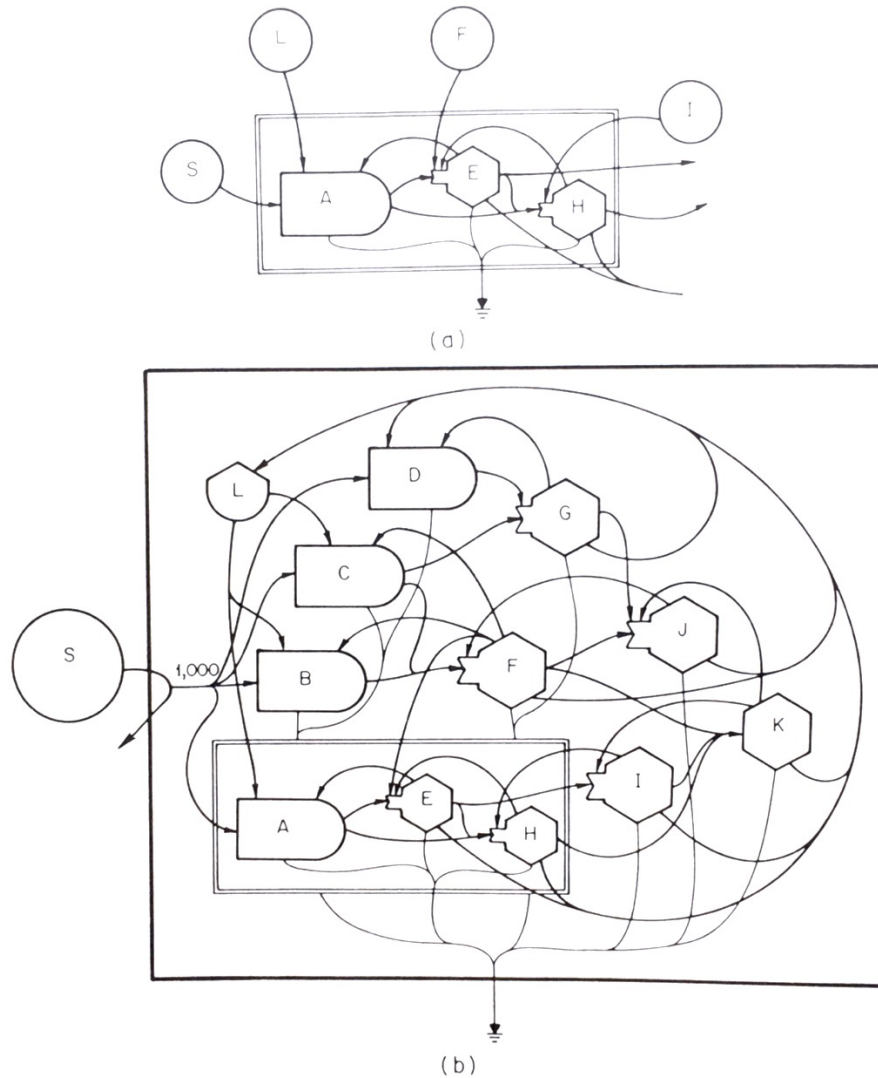


Figure 9 : Expanding the System Boundary to Incorporate Co-Dependent Energy Sources. The sources **L**, **F** and **I** in (a) above, which supply producer **A** and consumers **E** and **H**, are in fact co-dependent on a common upstream source **S**, and are depicted as such in (b). The expanded system boundary in (b) implies that the System's embodied energy will be measured in units of emjoules of the primary external energy source **S** (Image credit: Odum, 1996, fig. 6.5)

3.1.3 Gross, Net and Specific LEE; LEE Efficiency

Gross LEE is the cumulative total of all upstream energy, including losses due to inefficiency. It is therefore a measure of relative *cost*. Net LEE is defined as gross LEE minus the losses of the System to entropy, making net LEE a better relative measure of *value*.

The ratio between net LEE and gross LEE is defined as the lifetime embodied energy efficiency (LEE efficiency) of the System, and specific LEE is LEE per unit mass of the System.

3.2 Comparison of LEE to Existing Costing Systems

Depending on the choice of system boundary and energy sources, the proposed LEE metric may replicate the existing, accepted mass-based and dollar-based metrics, but also go beyond them by seamlessly handling the cost impact of not just the space *transportation* of all kinds of mass, but also of its *transformations*.

3.2.1 Relationship between LEE and IMLEO

By judicious selection of the system boundary, it is possible to derive equivalence relationships between LEE, which has units of emjoules, and either IMLEO or payload to the surface of Mars, which have units of mass. The conversion factor is a proportionality constant defined in units of emjoules per unit mass – an LEE “exchange rate”, so to speak.

This equivalence constant will be different for different routes between solar system destinations, and will also vary according to the characteristics of each transportation system. For any given transportation system this constant will vary as the required change in velocity (ΔV), and for any given route, such as Earth surface to Mars surface, this constant will vary inversely as the overall efficiency of the various transportation systems¹⁸.

This constant can be calculated to varying degrees of precision using the embodied energy principles presented in this thesis. The value of this constant is less important than the consistent use of the same constant when comparing Mars surface mission architectures. An approximation for this constant has been derived in Appendix I and will be used in the case study presented in Chapter 5.

3.2.2 Relationship between LEE and monetary costs

The same approach of system boundary selection can be used to illustrate an equivalence between LEE and empirical measures of monetary cost. Here, the system boundary incorporates the entire U.S. economy. As seen in Figure 6 above and in the associated discussion, ecological and biophysical economists, including (Cleveland et al., 1984), have already made the empirical

¹⁸ This efficiency is not just a matter of specific impulse (ISP), but also of the space logistics strategy, as we saw with the GMCNF approach to minimizing IMLEO for a given payload mass and destination

case for an improved correlation between embodied energy and economic output when energy is added to classical production functions of labor and capital, superseding them as the independent factor of production. This is not altogether surprising, since all value creation ultimately has some underlying physical basis, however remote or indirect, and all physical systems require supplies of high quality energy sources for their creation, operation and maintenance. This correlation is supportive of a causal connection between embodied energy and capital.

Regarding the correlation between embodied energy and labor, Odum observed that as human labor is at the end of the energy chain, it is almost always the most energy-intensive item in embodied energy analyses (Odum, 1983, p. 490). Odum attributed this high energy value of human labor to our ability to feed back into a system the essential controls that allow the system (and especially the *capital* in the system) to do complex things. The architects of the Apollo program, who had given human astronauts and flight controllers critical roles inside their system boundary, plainly understood this reality (Lordos, 2017 - unpublished). The high value of human labor was also noted at Tesla, Inc., whose CEO recently observed that “Humans are underrated”, after he found that some robots were in fact slowing down Model 3 production¹⁹.

Given the demonstrated links between embodied energy and the classical factors of production, it appears that Odum and Costanza were justified to separately put forward an embodied energy : dollar exchange rate by dividing the total economy-wide embodied solar energy by the GDP in dollars (Costanza, 1980; Odum, 1983, p. 481). Just like floating exchange rates among different currencies, this exchange rate was also found to be different for each economy and year (Costanza & Herendeen, 1984).

3.2.3 Forward looking LEE and Uncertainty

LEE can be said to be ‘forward-looking’ when the calculation involves future projections. It must be noted that forward-looking LEE will typically imply a projection which comes with inherent uncertainty. This is because LEE is a single consolidated metric which cumulates past, present and future direct and indirect energy flows. Space mission architects will inevitably be using forward-looking LEE values which will be informed by both past experience and alternative

¹⁹ <https://www.fastcompany.com/40559386/elon-musk-says-humans-are-underrated-after-his-robots-slow-model-3-production> (retrieved May 12, 2018)

system and subsystem designs. Uncertainty should therefore be incorporated in LEE analysis; however, a treatment of uncertainty in LEE calculations is also left as future work.

3.3 LEE System Formulation Approaches

3.3.1 Input-Output model

(Leontief, 1936)²⁰ developed the input-output (IO) model to simulate the U.S. economy as a mostly closed-loop network of input-output sectors in order to show how sectors can affect each other. In IO models, every sector has at least one other sector as an input and at least one as an output. Complications with missing data, shared sources and joint outputs can be either disregarded, or addressed by adding ad hoc adjustments and complexity to models. (Costanza & Herendeen, 1984) used the input-output method in their embodied energy calculations of economic value for the United States in 1963, 1967 and 1972.

3.3.2 Process Model

In contrast to the input-output method, which relies on aggregate sectoral data to produce matrices of energy intensities for an entire economy or ecosystem, a process-based analysis is bottom-up. This makes it possible to calculate embodied energy intensities for individual materials or specific systems. It is an empirical process which starts with the collection of manufacturing energy consumption of a given process, and works backward to collect the energy consumption data of all direct process inputs and most indirect inputs. As this task can quickly become very time consuming or frustrated by the unavailability of data, models are often incomplete or truncated (Dixit, 2017, sec. 2.1.3.1), resulting in errors which have been quantified to lie in the range of 10% to 50%.

3.3.3 IO-based Hybrid (IOH) Model

This approach is a variation on the IO method which aims to integrate process-based or other higher resolution data into an IO model to reduce the errors due to incompleteness and truncation (Dixit, 2017). In Dixit's case study of the embodied energy cost of different building materials, the incompleteness and truncation are reduced somewhat and previous results for the

²⁰ Wassily Leontief was the doctoral advisor of Paul A. Samuelson. It's a small world.

embodied energy of different building materials are revised, with differences of up to 48% from previously established estimates. Furthermore, the integration of process-level data into the sectors revealed some new insights, such as the type of fuel (coal, oil) preferred by different building materials industries.

3.4 LEE as a Cost Metric for the Human Settlement of Mars

3.4.1 Methodological Advantages of Applying Embodied Energy Analyses to Mars Industry

Despite the progress made, Dixit's hybrid model of the embodied energy cost of building materials ultimately could not cure most of the incompleteness errors inherent in process-based methods, or significantly improve the confidence in results which, in the absence of data, had to rely on cost figures as material quantity proxies (Dixit, 2017, sec. 8).

From this, it appears that there is an irreducible component of uncertainty inherent in embodied energy analyses of products made on Earth, largely because the webs of industrial supply chains on Earth are too broad, too deep, too dispersed and too interconnected. As a result, the data required to carry out an embodied energy analysis is often either nonexistent, or aggregated in different ways for different industries in different countries, requiring further pre-processing work before it can be used. On Mars, however, the establishment of industry will be a new beginning, with a streamlined supply chain which will likely be optimized for small footprint, versatility, flexibility and manufacturability, and possibly even owned by a single (or no more than a handful) economic operators, at least for the first several decades.

In addition, it is virtually certain that all systems flown to Mars will be studied in detail years in advance. Thus, the interfaces, connections and dependencies of every system to every other system on Mars are also likely to be well documented. This all bodes well for the availability of process-level data for every component, subsystem and system with which to carry out embodied energy analyses. We therefore note a methodological benefit of applying embodied energy modeling methods to the Mars ISRU – ISM use case: namely, that the analysis should be more tractable from the empirical perspective, at least for the interested organizations which possess the data.

3.4.2 Lifetime Embodied Energy of Space Logistics as Primary Energy Source for Mars

The LEE of space logistics is a useful choice for primary energy source to isolate the cost of the logistical effort for trade-offs and minimization. One can appreciate the deep, physical basis of the relevance of the LEE of space logistics to a Mars settlement campaign by considering the future of human life on Mars in terms of energy transformations, as follows:

- We begin by considering that the environment of Mars is currently in its natural state²¹, which is abundant in empty land and raw resources, but hostile to human life.
- In contrast to the Earth, where solar energy powers the natural ecosystems which in turn support human life, humans on Mars will require constant artificial life support in all respects from our technological systems.
- Therefore, all future human activity on Mars is predicated on the prior transportation of technological systems from Earth to Mars and their successful commissioning and operation. In this sense, all future energy sources available to humans on Mars, including energy sources that we will develop there²², will not be independent sources; all will be co-dependent on their common source, which is technology transported from Earth.
- As a technological system is transported to Mars, the energy expended in its transportation can be seen as having been *embodied* into it. As the cost and difficulty of transportation to Mars is currently the biggest obstacle standing between humanity and an outpost on the Red Planet, it is logical to focus our attention on the *embodied energy of transportation to Mars*.
- In view of the observations above, an Earth-Mars transportation system can also be viewed as the single, common, primary and indispensable source of embodied energy for all future Systems on Mars.

With the above considerations and with some simplifying assumptions, it is possible to calculate a satisfactory approximation of the specific lifetime embodied energy cost of

²¹ *Almost* in its natural state; technically, we have already started accumulating technology such as radios and solar panels on the surface of Mars, which in theory may be of limited use to future human inhabitants. In practice, however, these history-making robots are very unlikely to be cannibalized for spare parts.

²² Such as Areothermal or solar energy: the first expeditions to Mars will not be able to tap these energy sources on Mars without relying on technology transported from Earth.

transportation to Mars in units of slej/kg²³ with a view to using this as the primary energy source of all mass delivered to Mars, at least for the first phase of human settlement²⁴. Based on the Maximum Power Principle (2.2.4 above), for the purposes of this calculation we ought to select the most efficient Earth – Mars transportation system, which in the near future is likely to be SpaceX’s Big Falcon Rocket (BFR) and Big Falcon Spaceship (BFS). The calculation is total lifetime embodied energy expended in space transportation from the surface of the Earth to LEO and from LEO to Mars, divided by the total lifetime mass of payload emplaced on Mars by the same transportation system. A precise calculation would entail data and projections for the embodied energy of development, manufacturing, maintenance, and operations of the BFR/BFS system. However, as described above, precision is not essential; consistency is what matters here. A top-down calculation of the LEE cost of transportation to Mars using the BFR/BFS is shown in Appendix I, where we found the cost to be approximately equal to 206 MJ/kg.

3.4.3 Methodological Benefits of LEE for Space Exploration Campaign Architects

By setting the system boundary of a Mars settlement such that its primary external energy source is the lifetime embodied energy of space logistics, we can configure a LEE model to replicate traditional methods of optimizing for the least-cost strategy to *transport* mass across the inner solar system. But in addition, the same LEE-based model adds the option of *transforming* both imported and in situ mass within the model’s system boundary, and can calculate the cost of each architecture in units of the lifetime embodied energy of space logistics. In this way, LEE-based space logistics models open up a broader solution space for system architecture optimization relative to IMLEO-based models. Using LEE, it is possible to evaluate novel ISRU and ISM enabled campaign architectures alongside more traditional concepts on a common denominator for all concepts, without penalizing novel, disruptive mission architectures which seek to invest heavily and up front on ISRU and ISM capabilities and which target the early emergence of organic industrial development and growth at the destination world.

²³ The unit **slej/kg**, which stands for *Space Logistics Emjoules per Kilogram*, has the units of J kg⁻¹

²⁴ In later phases, as the industrial development of Mars matures and off-Earth human settlements become more self-sufficient, the supply chain architect may wish to broaden the Mars-centric system boundary to include the Earth, Moon, Mars and the asteroids, making the Sun once again the common primary energy source; if so, she will be grateful for an embodied energy framework which can easily enable comparison of supply chain architectures using a mix of interplanetary industrial centers, simply by transforming slej to solar emjoules (sej).

3.5 Chapter 3 Summary

This chapter reviewed a number of important methodological considerations and definitions. The increasing decoupling of IMLEO from the true economic cost of space activities opens a research gap for consideration of other non-dollar, non-mass metrics. Lifetime Embodied Energy was put forward on account of its links to energy, value and accounting, and was defined as the thermodynamic sum of past, present and future work required to create, operate, maintain and decommission a system, including appropriate shares of indirect contributions from upstream systems.

The important methodological choice of primary energy source and system boundary in embodied energy modeling was discussed and linked to the nature of the figure of merit targeted for analysis, tradeoffs and optimization. For example, by specifying the embodied energy of space logistics as the primary energy source and common cost denominator of all technological²⁵ systems and processed resources on Mars, it is possible to closely replicate the conclusions of standard IMLEO-based or ESM-based analyses, but also to go beyond them.

We also noted that an exchange rate may be calculated to relate the embodied energy of space logistics to mass-based cost metrics or to dollar costs. Some of the data required to do this may be proprietary, but even a low fidelity approximation of this specific embodied energy of space logistics, measured in units of space logistics emjoules per kilogram (slej/kg), will be useful for analysis, as all systems on Mars will be evaluated against that same common baseline.

We then reviewed the methodological approaches for embodied energy analyses, which are the input-output, process-based and hybrid models, noting the methodological difficulties faced in the Earth context. These difficulties are likely to be significantly mitigated in a Mars industrial development context, thereby making the lifetime embodied energy methodology more attractive for broad application in the space mission architecting and space economy use cases.

Finally, we concluded with the finding that using the LEE of space logistics as the cost metric is robust to the ongoing disruptive changes in the industry, and allows the architect to go beyond IMLEO-based optimization by simultaneously optimizing the logistical, ISRU and in-space manufacturing architectures of a contemplated long-term campaign.

²⁵ And biological

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4 Embodied Energy Models of an Early Human Outpost on Mars

4.1 Hybrid Input – Output Model Using Energy Diagrams

As we have seen, Lifetime Embodied Energy can be calculated for a variety of system boundaries and associated primary energy sources. For this case study, we have set the system boundary such that the primary source of energy will be the energy of space logistics, and we disregarded the energy cost of manufacturing a system on Earth. These choices enable direct comparisons with IMLEO-based costing systems as well as tradeoffs across the entire range of Mars surface system architecture elements, with immediate feedback to the embodied energy cost metric.

We also set a fixed campaign length (a time horizon) of 20 years, and keep the mass transported to Mars constant for all scenarios. This allows calculation of LEE for alternative campaign architectures, with or without ISRU or ISM, while holding other factors constant, making the LEE of alternatives more easily comparable.

A hybrid input-output and process model was created using both Energy Language Diagrams and Excel²⁶, taking advantage of the fact that the scope for a Mars outpost is orders of magnitude simpler than the U.S. economy.

A city on Mars²⁷ which aspires towards self-sustaining status would likely need to be developing at least four economic sectors: energy, natural resource processing, manufacturing/fabrication and habitation (the latter including food). The energy language diagram²⁸ in Figure 10 below shows the fundamental relationships among these four sectors, together with a level 2 view of the inner workings within each sector. It is interesting to note the rich, emergent feedback relationships between the sectors and systems:

²⁶ There are differences in naming of sectors, level of detail, and the fact that the Excel model uses a single period (no time dimension); however, the similarities exceed the differences.

²⁷ Or anywhere, for that matter

²⁸ Please see Figure 7 above for an explanation of the meanings of the symbols, arrows and boundaries used in the Energy Language Diagrams in this thesis. For more details on Howard Odum's Energy Language, see (Odum, 1983, 1996)

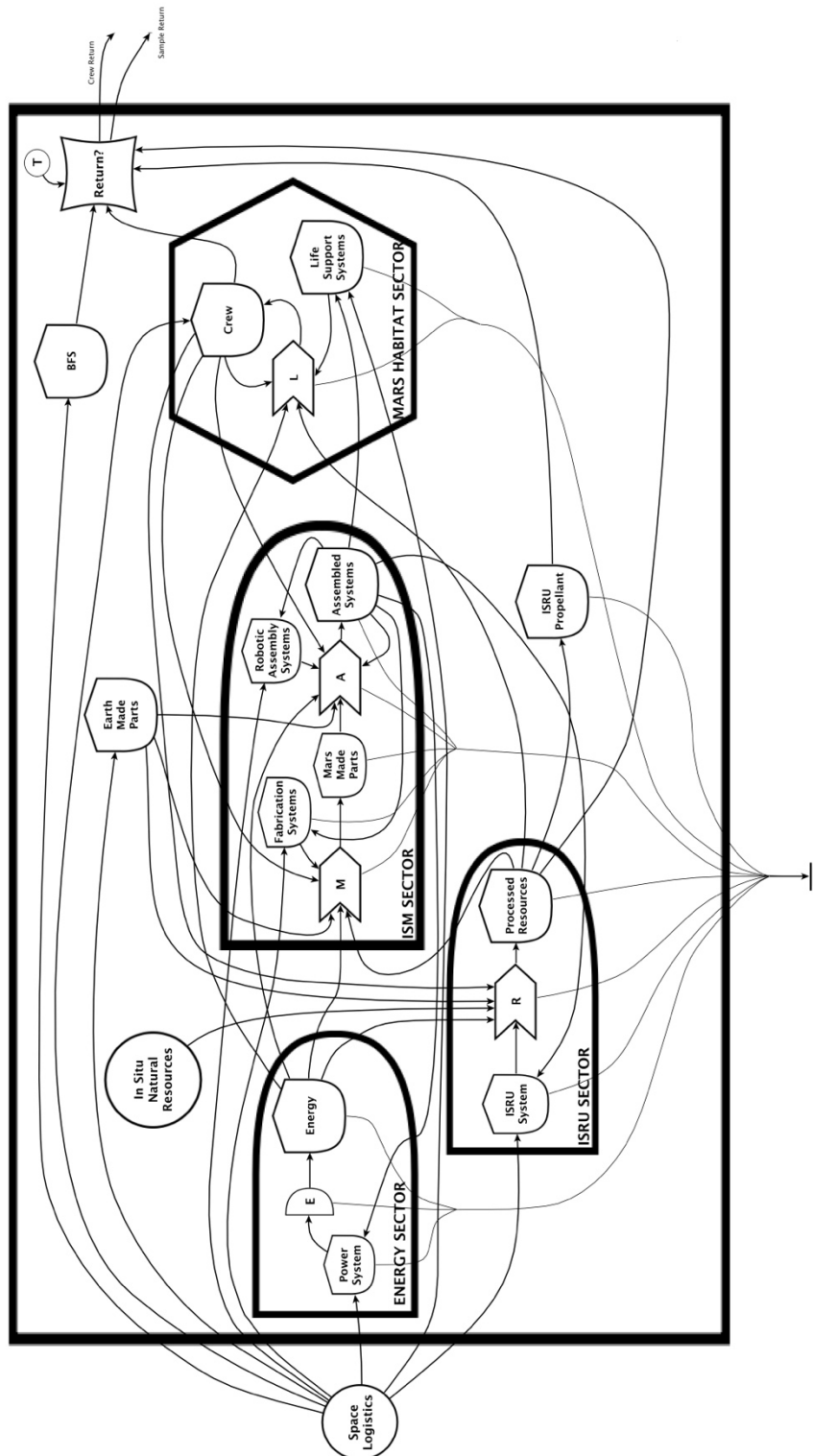


Figure 10 : Energy Language Diagram of a generic initial architecture for an (aspiring) self-sustaining city on Mars.

At the same time, a *realistic* city on Mars will, initially at least, require a large number of reliable Earth-made parts and systems, delivered to Mars via a space logistics system. These four sectors - energy, ISRU, ISM and Habitation - which will be essential for the future industrial development of Mars, can only come into existence once bootstrapped via Space Logistics; we may therefore accurately state that the substantial energy which will be expended by a space logistics effort to create a permanent settlement on Mars will be *embodied* into the Power, ISRU, ISM and Habitat systems. This will allow us to trace the downstream flows of that energy into systems made on Mars.

Several modeling approaches are well suited to the analysis of energy diagrams. For example, as an energy diagram is already in the form of nodes and edges, graph theoretic and matrix algebra methods may be used; and as the symbols represent stocks, flows and information, system dynamics approaches may also be used. However, the objective of this thesis is to assess the potential suitability and usefulness of Lifetime Embodied Energy as a cost metric for architecting space missions; therefore, a simplified approach was selected which is more transparent and easier to communicate to the reader. The development of a multi-objective optimization framework which fully utilizes LEE remains as future work.

4.1.1 Energy Sector

In energy language diagrams such as Figure 10, embodied energy flows from left to right, accumulating value in the process. In our case study, the primary producer sector is energy. The Power System produces energy and stores this energy output in the Energy storage tank.

Since energy is the only output of the Power System, the entire embodied energy of the Power System is allocated to its lifetime energy output. We can therefore calculate the specific embodied energy of energy, which in our case study will be measured in space logistics emjoules (slej) per Joule of energy produced on Mars. Upstream of the Power System, we find its two direct sources of embodied energy: Space Logistics and Assembled Systems. The latter refers to systems assembled at industrial facilities on Mars. Generally, each source has its own upstream source(s) and its downstream sink(s). We can graphically show these relationships by producing a map of the predecessor processes and sources of the lifetime quantity of energy output, as shown in Figure 11 below:

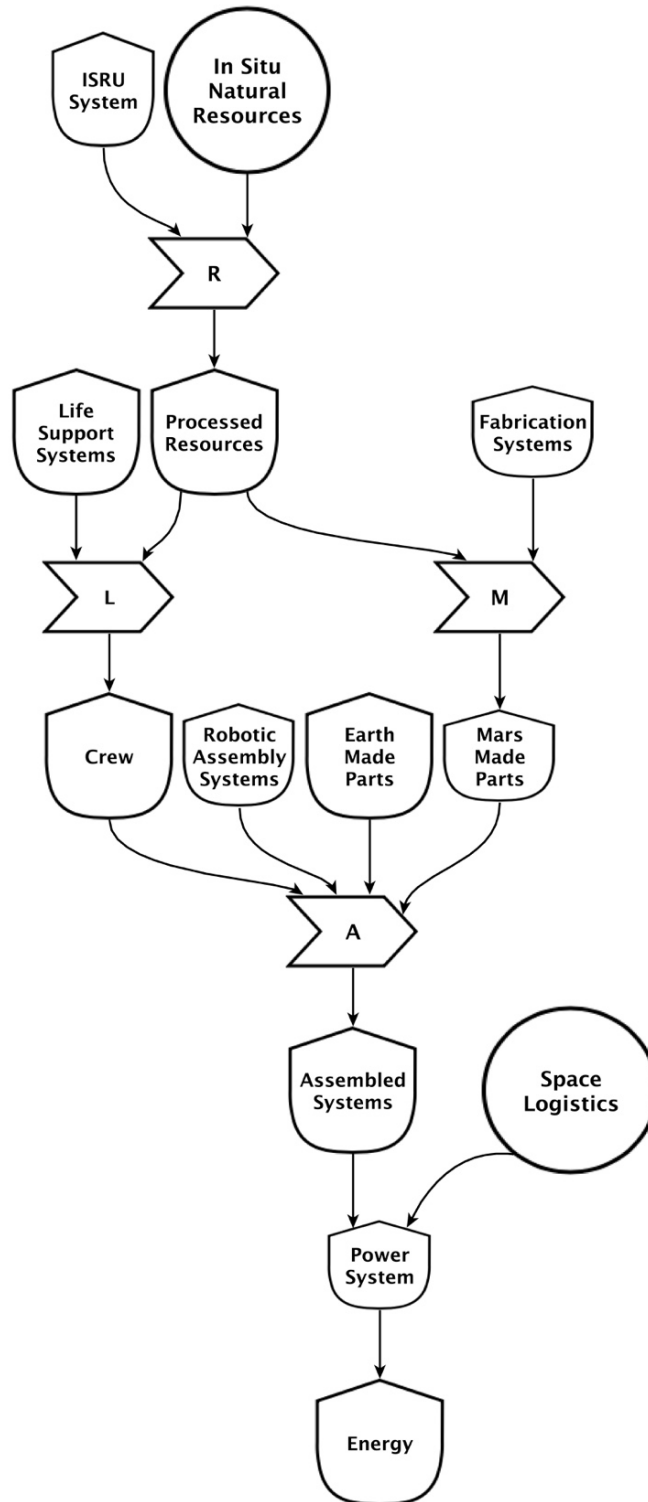


Figure 11 : Direct and Indirect Sources of Embodied Energy for Energy Supplies on Mars. The embodied energy of the power sector is equal to its “fair” share of the embodied energy of space logistics and the embodied energy of assembled systems.

In the base case where there is no in-space manufacturing, the embodied energy of the Power System equipment is equal to its fair share of the embodied energy expended by its sole remaining upstream input, which is the Space Logistics effort. This is equivalent to an IMLEO optimization scenario. In the absence of in-space manufacturing, LEE can easily be converted to IMLEO. The lifetime payload-to-Mars mass of the power system is known to the designer, and the exchange rate between mass and LEE, such as the 206 MJ/kg from Appendix I as well as the gear ratio (~10) to convert Mars surface payloads to IMLEO would also be known.

In the case where the architect selects to include in-space manufacturing in the design, then again, based on Figure 11 above, the embodied energy of the Power System will be equal to the sum of its fair shares of Space Logistics embodied energy, and Assembled Systems embodied energy. In turn, the embodied energy of the fraction of Assembled Systems which are power systems will be the sum of the fair shares of the embodied energies of the inputs which went into Assembled Systems. These are: the labor of the Crew, the work of the Robotic Assembly Systems, the work done to deliver Earth Made Parts and the work done to produce the Mars Made Parts.

4.1.2 ISRU Sector

The storage representing the projected lifetime quantity of Processed Resources refined from local raw natural resources is shown at the bottom of Figure 12, together with its upstream direct and indirect embodied energy inputs. Processed Resources are the output of the resource processing interaction labeled **R**. This interaction requires as inputs the labor of the Crew, the work of the ISRU system, the work of Energy and also consumes the mass of extracted raw, in situ natural resources, as well as an appropriate fraction of the lifetime mass of Earth Made Parts.

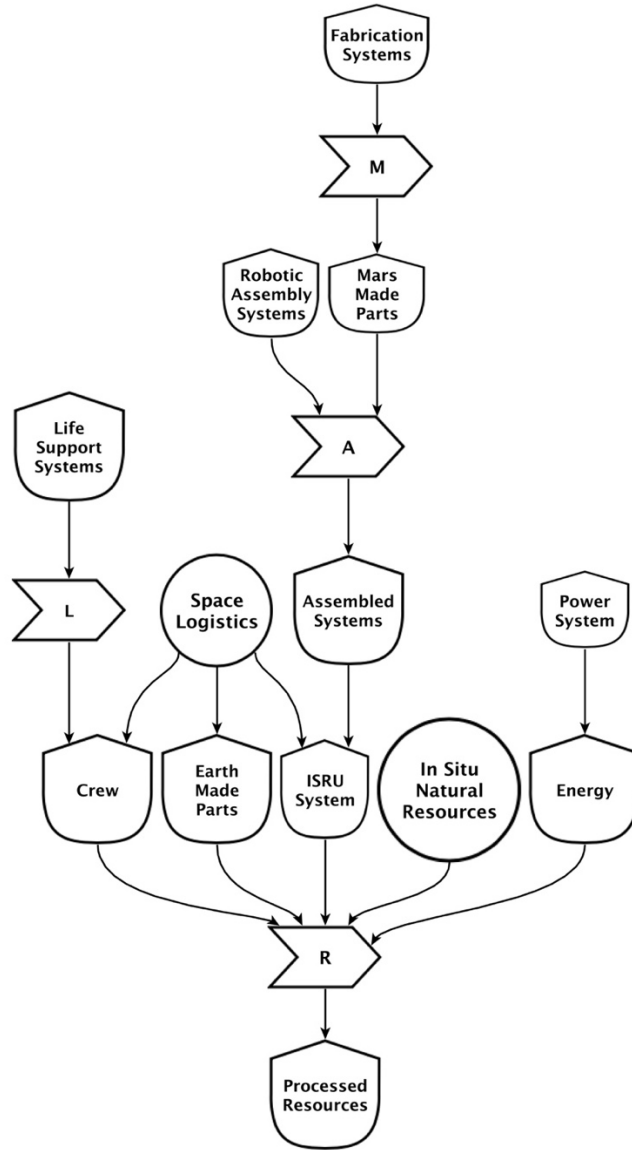


Figure 12 : Direct and Indirect Sources of Embodied Energy for Processed Resources on Mars

We calculate the total lifetime embodied energy for each of these upstream inputs, except the raw natural resources²⁹, and in each case we allocate a fraction of this lifetime embodied energy to the ISRU sector, according to the relative intensity of each upstream input into a downstream process. In all cases, for each input-output edge, this fraction is calculated by dividing lifetime input at the downstream node (sector) by the lifetime output at the upstream node (sector). This

²⁹ We do not count the embodied (solar) energy of natural resources on Mars because the purpose is to evaluate technological tradeoffs for space mission architecture, not to put a price on the natural environment of Mars.

realization provides a way forward to scale up the computation and prevents the double-counting of embodied energy.

4.1.3 ISM Sector

As we can see from the system overview energy diagram, Figure 10 above, the ISM Producer sector consists of two types of activities: (1) fabrication using processed³⁰ resources, represented by an interaction labeled with the letter *M*, and (2) assembly, represented by an interaction labeled with the letter *A*. The output of fabrication is labeled Mars Made Parts.

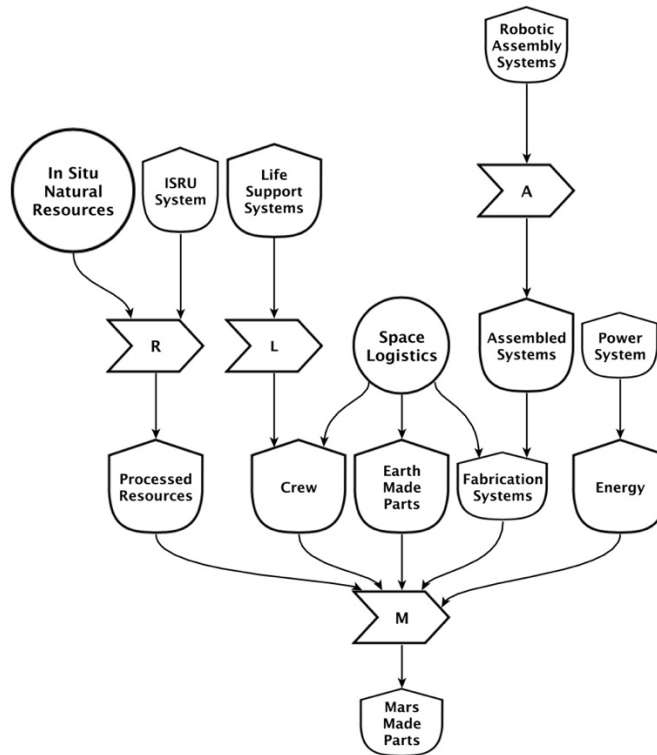


Figure 13 : Direct and Indirect Sources of Embodied Energy for Parts fabricated on Mars

In turn, the Mars Made Parts are inputs for the Assembly interaction *A*, along with Earth Made Parts. As shown below in Figure 14, Assembly requires the direct work of Robotic Assembly Systems, Crew and Energy, and consumes both Mars Made and Earth Made Parts. These in turn depend on other inputs. At all stages embodied energy flows from upstream and accumulates downstream. The output of the Assembly interaction is labeled Assembled Systems.

³⁰ And recycled, but these are not shown in the model.

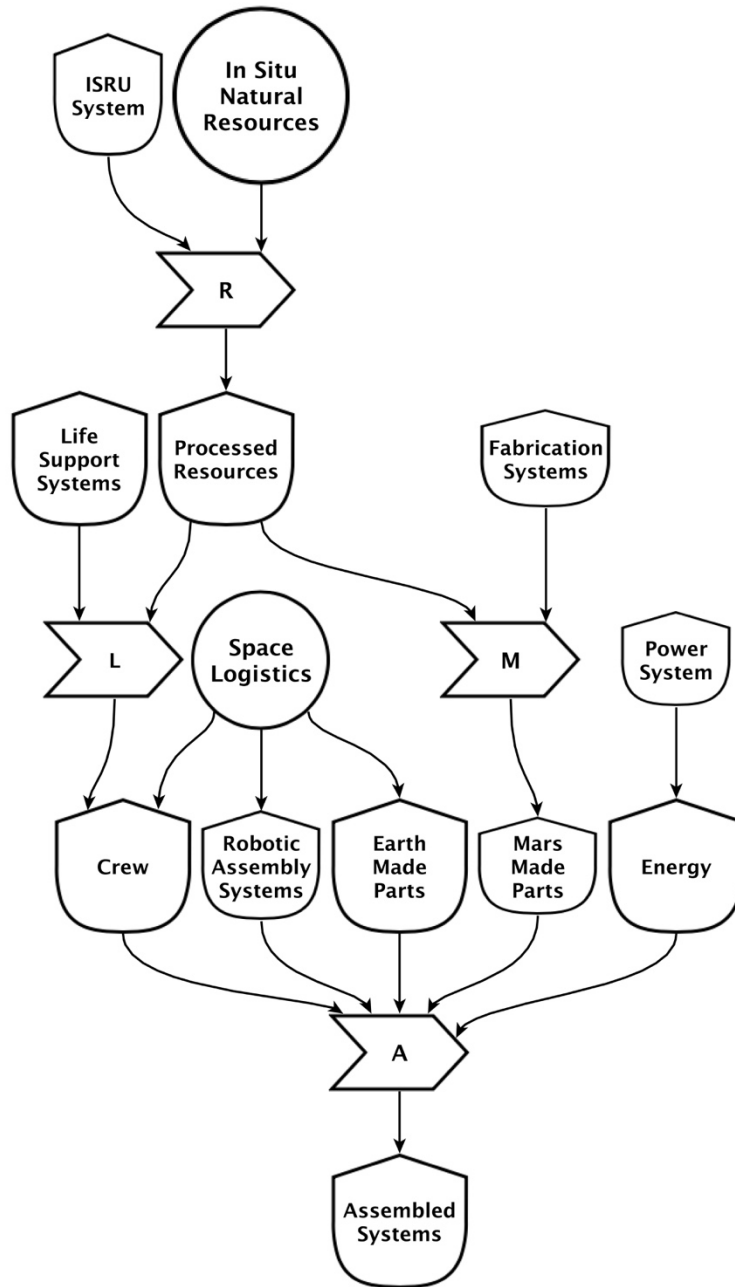


Figure 14 : Direct and Indirect Sources of Embodied Energy for Assembled Systems on Mars

4.1.4 Habitation and Life Support Sector

The Habitation sector is special in that it is both a part of the overall objective function (e.g. science, or settlement), and also the main source of indirect embodied energy for Crew labor. If the crew were to spend 100% of their time on ISRU and ISM activities, the cost of their time would become an integral part of the production function, and therefore all support systems required to keep them alive and productive become indirect inputs to the production function, as

well. Thus, the embodied energy associated with life support and habitation must be allocated to the various products of the Crew's labor, according to the same principle of pairwise fraction calculation described in 4.1.2 above. This allows the comparison between robotic and crewed modes, again using a metric which is based on a common denominator.

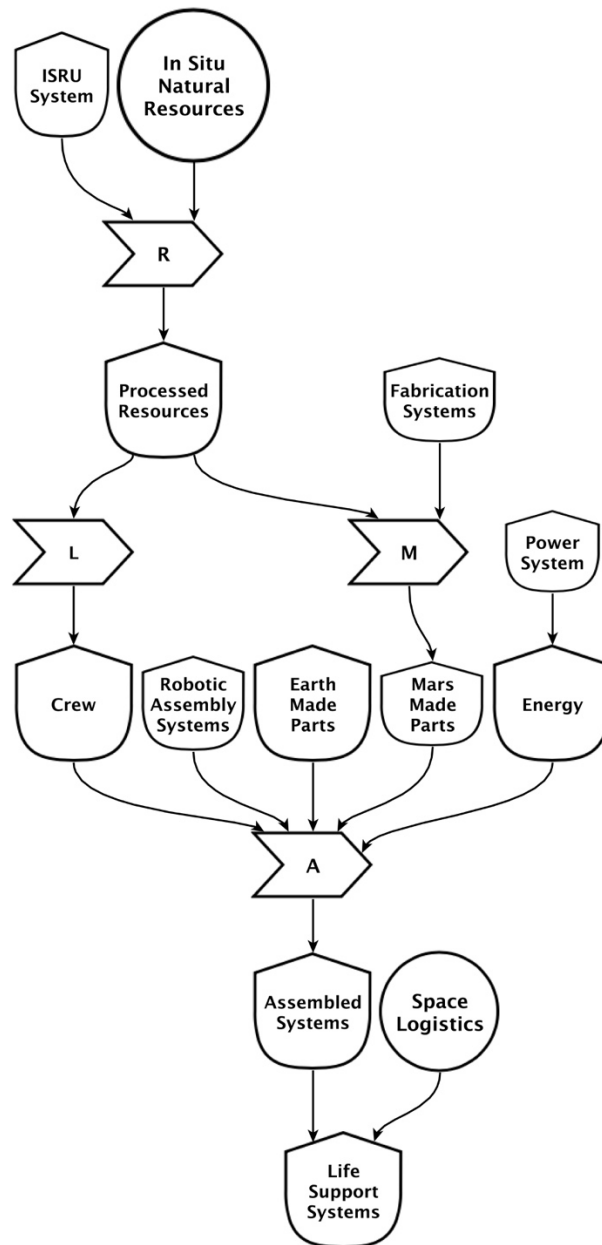


Figure 15 : Direct and Indirect Sources of Embodied Energy for Life Support Systems. Note that life support in this context follows the NASA Advanced Life Support (ALS) definition.

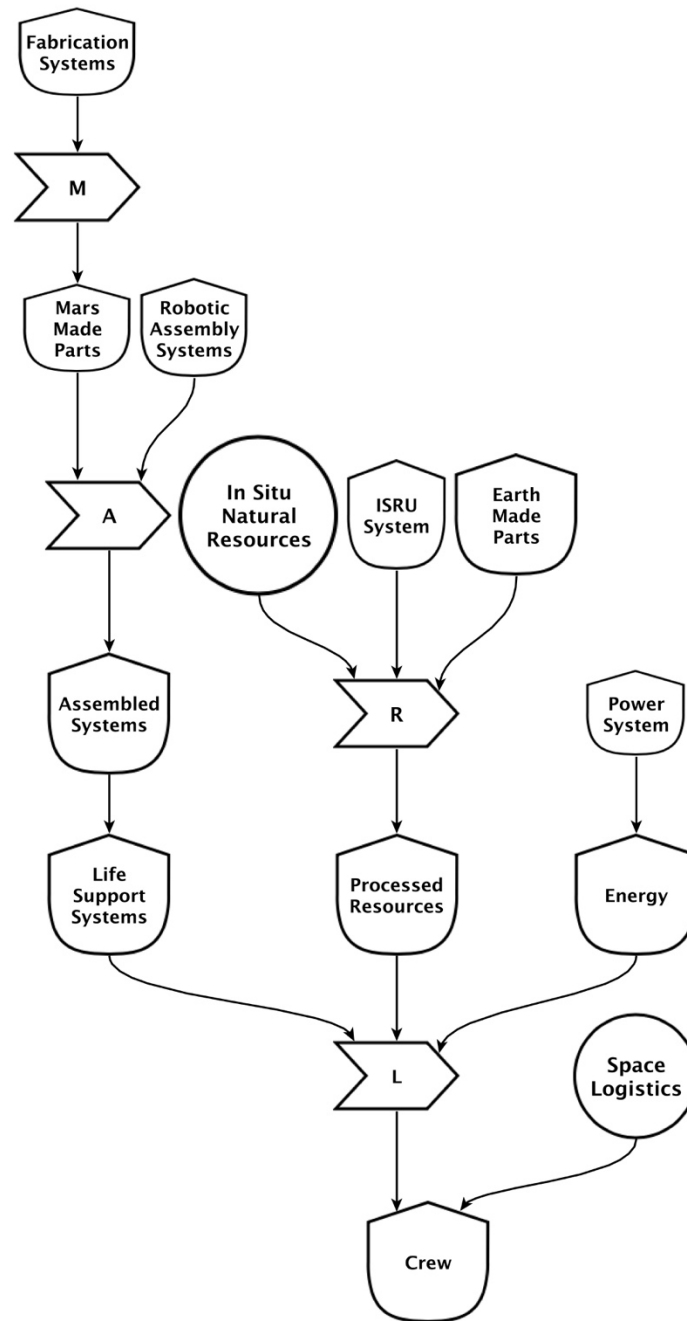


Figure 16 : Direct and Indirect Sources of Embodied Energy for Crew. Notice from the tops of all the upstream branches that the crew literally depends on all the technology brought to Mars, as well as on the in situ natural resources.

Figure 15 and Figure 16 indicate the substantial upstream sources of embodied energy for the habitation sector and for crew. This is consistent with Odum's finding that human labor almost always has by far the highest embodied energy (Odum, 1983, p. 490).

4.2 Excel Model with Embodied Energy Equations³¹

An Excel based model has been created which permits the generation of simple Mars surface mission architectures featuring a choice of nuclear or solar energy, whether to adopt recycling, ISRU, ISM, at different levels of automation and versatility. The starting point was to specify the variables that the model should maintain for each system or process, as shown below:

Table 5 : Model Variables Tracked for Each System, Sector or Process

Sector i (System / Process, or Sector)			
$\mathbf{m_{lf,i}}$	Lifetime mass of system, process or sector i including spare parts (kg)	$\mathbf{L_{i}}$	Lifetime labor hours required by sector i
$\mathbf{m_{is,i}}$	Of which, lifetime mass manufactured on Mars from in situ resources	$\mathbf{m_{is,i}/m_{lf,i}}$	Fraction of lifetime mass manufactured on Mars
$\mathbf{O_{lf,i}}$	Lifetime output of system, process or sector i		Output units (e.g. MJ, kg)
$\mathbf{E_{m,i}}$	Lifetime Embodied Energy (LEE) of mass transport for i (MJ) $\mathbf{E_{m,i} = e_m \cdot (m_{lf,i} - m_{is,i})}$	$\mathbf{E_{s,i}}$	Lifetime energy input OR output of sector i (MJ)
$\mathbf{\Sigma E_{m,ij}}$	All direct allocated inputs of LEE into sector i from upstream sector(s) j (MJ)	$\mathbf{E_{s,i} / E_b}$	Energy consumed by this sector as fraction of total energy budget
$\mathbf{E_{lf,i}}$	Total LEE of system, process or sector i from all sources (MJ) $\mathbf{E_{lf,i} = E_{m,i} + E_i}$	$\mathbf{E_{lfsp,i}}$	Specific LEE (MJ per unit of output) $\mathbf{E_{lfsp,i} = E_{lf,i} / O_{lf,i}}$

As the input options are changed, the model recalculates the lifetime useful mass emplaced on Mars, as well as the embodied energy cost of the architecture. These input options are the following:

- Fraction of surface power from nuclear energy (Pn, from 0% to 100%)
- Is ISM enabled? (True/ False)
- Is ISRU enabled? (True/ False)
- Is Material recycling enabled? (True/ False)
- Level of automation in ISRU and ISM (from 0% to 80%)
- Level of versatility³² of the ISM systems (LOW / MEDIUM / HIGH)

³¹ The equations and model in this section will be featured in a paper by George Lordos, which was submitted and accepted for presentation to AIAA Space 2018. The author gratefully acknowledges the comments, feedback, and suggestions made by SDM fellows John Mehrman, Sarah Summers and Shawn Vasichak. Any errors are the responsibility of the author.

³² A more *versatile* ISM system can produce a broader selection of different systems and components, thereby allowing the outpost to aim for higher levels of “manufacturability”.

In the case of no ISRU, the lifetime mass (m_{lf}) of systems accumulated on Mars is the same as the mass of systems brought from Earth; it is equal to the lifetime mass transported through space over a 20-year campaign, which is also known as ‘logistical mass’. The actual amount of lifetime mass can only exceed the logistical mass if ISRU is enabled. In all scenarios, a fixed amount of logistical mass is transported from Earth to Mars, to enable comparison of outcomes. The energy of space logistics embodied into this logistical mass is found by multiplying mass by the ‘LEE Exchange Rate’, which for the purposes of this case study is 206 MJ/kg³³.

The lifetime mass of a system made from in-situ resources is given by $m_{is} = m_{lf} \cdot P_n \cdot w_n$ in the case of nuclear energy systems, where P_n is the fraction of nuclear (Kilopower) systems in the energy mix, and w_n is the average lifetime mass fraction of the nuclear power system that is manufacturable from in-situ natural raw materials. This choice signals the expectation that heavy energy systems which require substantial structural or thermal mass can be partially constructed out of in situ materials. However, for resource processing, manufacturing, labor and assembly operations, in this case study m_{is} is assumed to be zero, signaling that for those productive sectors, which will directly be generating other mass, the equipment will be optimized for performance and reliability from Earth, and the outpost will rely on having sufficient spares.

The projected lifetime output of the different systems, processes or sectors is estimated in a different way for each sector, according to the physics and economics of the situation:

Solar Panels

$$O_{lfp} = O_{pk} \cdot t \cdot 365 \cdot lh \cdot 60 \cdot 60$$

In the above equation, O_{pk} is the peak power of the solar panels in W, t is the time horizon of the campaign (20 years), lh is the hours of daylight per day, typically 12.

Resource Processing³⁴

$$O_{lfrp} = \frac{O_{lfm}}{eff_m}$$

$$O_{lfrp} = \frac{O_{lfm}}{eff_m}$$

$$O_{lfrp} = O_{lfm} \cdot eff_m$$

³³ Please see Appendix I for the calculations.

³⁴ For simplicity, it is assumed that demand from manufacturing directly drives the production output of resource processing. In turn, manufacturing need is determined by the availability of extra Earth Made Parts which are deemed to be needed in fixed proportions to Mars Made Parts; counter-intuitively, the mass of Earth Made Parts increases as the outpost becomes more self-sufficient, because of the fixed logistical mass.

Manufacturing

$$O_{lfm} = m_{system} \cdot \frac{m_{output}}{m_{system}} \cdot t \cdot eff_m \cdot prod$$

Labor and Assembly Operations

$$O_{lfl} = C \cdot H \cdot t$$

In the above equations, O_{lf} is the lifetime output of the system, eff_m is the efficiency of production in terms of mass of inputs used, m_{output} is the total output mass over the campaign, m_{system} is the mass of the resource or manufacturing system, $prod$ is an average productivity multiplier based on versatility (the higher the versatility, the lower the productivity), C is the number of crew, H is the number of labor hours per year, and L is the fraction of manufacturing that is carried out manually rather than autonomously. The resource processing output is sized to the required inputs of the manufacturing sector.

Lifetime embodied energy of mass transport: $E_m = (m_{lf} - m_{is}) \cdot e_t$

This is calculated for each sector, to allocate the embodied energy of space logistics to its downstream sectors, according to logistical mass. In this equation, e_t is the exchange rate between mass and embodied energy, which is calculated in Appendix I. It is constant for a given route and given propulsion technology, and analogous to the gear ratio, but with a change of units to energy.

Lifetime embodied energy of energy inputs

Here, we use energy consumed as a fraction of the total energy budget as our allocation mechanism to divide the embodied energy of nuclear and solar energy among all the sectors, systems and processes that make use of it.

$$\text{For resource processing, } E_i = O_{lfrp} \cdot \frac{e_{rp}}{E_B} \cdot O_{lfe}$$

$$\text{For manufacturing, } E_i = O_{lfm} \cdot \frac{e_m}{E_B} \cdot O_{lfe}$$

$$\text{For labor, } E_i = O_{lfl} \cdot \frac{e_L}{E_b} \cdot O_{lfe}$$

Where: e_{rp} is the energy per kilogram required to process the natural resource into a Processed Resource, E_B is the total energy budget, O_{lfe} is the total energy sector output, e_m is the

energy per kilogram required to manufacture a component, and e_L is the energy required to sustain human life for the portion of time they are offering labor services to the ISRU or ISM sectors.

Lifetime embodied energy of a sector, system or process is captured by $E_{lf} = E_m + E_i$ where E_m is the direct lifetime embodied energy of space logistics, and E_i is the indirect lifetime embodied energy of space logistics, allocated using cost drivers such as fractional allocations of energy. It must be noted that other cost drivers can be used as well, such as fractional allocations of a material flow consumed, labor used, and so on.

4.3 Chapter 4 Summary

Two lifetime embodied energy modeling approaches for a prototype human settlement on Mars with an industrial focus were presented. The first was a primarily graphical approach using Howard Odum's energy language diagrams and featuring four sectors: energy, ISRU, ISM and habitation. For the key output of each sector, a diagram of its predecessors, or upstream sources of embodied energy was shown. This supports the hypothesis made in earlier chapters that all physical value creation can be traced through flows of embodied energy. The development of equations for energy language diagrams of a Mars outpost remains open for future work.

An Excel-based model tracing the flow of LEE through a toy model of a Mars outpost was also created, using a simplified lifetime-basis input-output method. This model, with its simplifications and approximations, is helpful for easily running alternative scenarios and plotting the results in terms of increased useful mass at the destination and reduced specific embodied energy, which is ultimately reduced economic cost per unit of economic value gained. In this case, economic value corresponds to the amount of useful mass emplaced on Mars.

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5 Model Results and Discussion

The models described in the previous chapter represent typical tools that a space mission architect might use to evaluate architectures for a long-term crewed campaign to the surface of Mars. For the purposes of this thesis, these models were developed to illuminate the potential applications and usefulness of Lifetime Embodied Energy as a value or cost metric for long-term crewed space exploration campaigns. We are especially interested in the application of LEE in contexts where the system designer has opportunities to accumulate infrastructure and utilize a broad range of in situ resources to establish an off-Earth industrial base, such as in the case of Mars.

5.1 Simulation Results

A number of simulation scenarios for our fledgling Mars industrial outpost, each with different levels of reliance on ISRU and ISM, were generated using the same set of assumptions and parameters³⁵. The main assumptions common across all scenarios were crew size (8), a fixed amount of mass delivered to Mars (1,600 tons, spread over 20 or 40 years as needed), campaign length (either 20 or 40 years), average power rating (640KW or 720KW) and an exogenously set production capacity³⁶, the latter depending *only* on the versatility of the equipment as set by the user. The total mass of the resource processing, fabrication and assembly systems was deliberately *not* made endogenous for this simple model, so as to isolate and illuminate the first-order productivity differences implied by the various alternative industrial development scenarios, without relying on the second-order endogenous growth of production capacity. Growth trajectories of autocatalytic (self-reinforcing) systems are likely to be highly sensitive to initial assumptions. Thus, endogenizing growth may unnecessarily complicate the verification of the hypothesis of this thesis that the new metric of LEE adds value to the art of space systems architecture.

Seven different scenarios were run, representing alternative strategies for the first multi-decade campaign of crewed missions to Mars. These were set across the industrial development

³⁵ Please see Appendix II for a listing of the assumptions and parameters.

³⁶ In the model, the ISRU and ISM systems are treated as being maintained using parts brought from Earth and parts fabricated on Mars from in situ resources, such that total productive capacity stays constant throughout the campaign horizon.

spectrum, ranging from no efforts to industrialize, up to high technology strategies which include ISRU, ISM, recycling and substantial automation with highly versatile, small-footprint smart manufacturing platforms. The seven scenarios were as follows:

Flags & Footprints (# 1): The Flags and Footprints scenario is Apollo-like, meaning there is no ISM and no ISRU. As a result, the sole source for all requirements is space logistics, and therefore the specific embodied energy cost of this scenario stays very close to the ‘exchange rate’ between Payload mass / IMLEO and Embodied Energy³⁷. The purpose of this scenario is to provide an embodied energy baseline, against which we can evaluate the other six scenarios.

Hard labor (# 2): The Hard Labor scenario introduces basic, low-versatility ISRU and ISM capabilities together with recycling, with almost no automation in the assembly phase. The energy mix is predominantly solar backed up with batteries, with some nuclear.

Simple Mining (# 3): In this scenario, the ISRU / ISM equipment is upgraded to medium versatility, which in practice translates to the mining of more classes of resources and the fabrication of more types of systems. As a result, the outpost can import larger quantities of fewer types of ready-made complex subassemblies from Earth which it can combine with the new resources mined and processed to produce a higher mass fraction of their needs from local resources, at a slight cost to their productivity. The energy mix is solar plus batteries, and there is no recycling of metals and plastics.

Medium Tech (# 4): has medium versatility equipment, more robotic automation at the assembly stage, plus recycling of metals and plastics and an all-nuclear energy mix.

Robotic Tech (# 5): is similar to medium tech, but has even higher levels of robotic automation at the assembly stage.

High Tech (no robots) (# 6): is a control scenario with high versatility, meaning that the flexible manufacturing systems could make almost anything, but with zero automation, where all

³⁷ This exchange rate is analogous to the gear ratio concept. Given an interplanetary transfer orbit, a propulsion technology and an EDL technology, it is possible to calculate gear ratios of mass required in LEO to mass delivered to a planetary surface. Typical gear ratios for LEO to Mars are of the order of 7.5 to 11. An exchange rate of ~210 MJ / kg was calculated in App. I

the assembly input is manual labor³⁸. This selection forces the model to allocate all habitat embodied energy costs to the production function, and embody all the costs of keeping humans alive into the energy cost of the outpost's economic output. The energy mix is all nuclear.

High Tech (# 7): is a scenario with high versatility, high automation at the assembly stage, and a balanced energy mix.

Table 6 : Results of Lifetime Embodied Energy Simulation

Scenario number	1	2	3	4	5	6	7
Scenario name	Flags & Footprints Baseline	Hard labor	Simple Mining	Medium Tech	Robotic Tech	High Tech No droids	High Tech
Energy mix: Nuclear %	50%	20%	0%	100%	50%	100%	50%
Energy mix: Solar %	50%	80%	100%	0%	50%	0%	50%
ISM?	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
ISRU?	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Use of robotic automation in assembly operations	5%	10%	20%	50%	80%	0%	80%
Use of manual labor in assembly operations	95%	90%	80%	50%	20%	100%	20%
Versatility of ISRU / ISM equipment (range, types of outputs that can be made)	LOW	LOW	MED	MED	MED	HIGH	HIGH
Mass Index for ISRU/ISM equipment (LOW versatility = 1)	1	1	5	5	5	12	12
Productivity Index for ISRU/ISM equipment (LOW versatility = 1)	1	1	0.9	0.9	0.9	0.8	0.8
Recycle scrap metal and plastic?	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE
Final Useable Mass (kg)	1.36E+06	1.91E+06	2.63E+06	2.90E+06	2.79E+06	4.06E+06	4.00E+06
% Useable Mass Produced In-Situ	0%	25%	52%	49%	52%	66%	67%
Specific Lifetime Embodied Energy of Useable Mass (20 years) MJ/kg	212.8	150.4	108.8	99.5	89.7	80.8	68.3
Specific Lifetime Embodied Energy of Useable Mass (40 years) MJ/kg	208.0	113.8	88.9	59.0	49.2	49.2	34.0

³⁸ Which means that the crew of 8 would have to assemble systems at an average rate of ~58kg per person per day for 20 years, accumulating a useable mass of 4,000 tons of infrastructure. Assuming they could keep up with such a rate, this hypothetical crew is unlikely to have much leisure time for exploration or science.

The model was first run to replicate these seven scenarios with a campaign length of 20 years. The campaign length was then doubled to 40 years, and the same seven scenarios were run again, to quantify the impacts of longer time horizons on long-term, forward-looking lifetime embodied energy costs. The results of the simulations together with the input parameters are shown in Table 6 above. Among other things, these results show that doubling the analysis horizon from 20 years to 40 years, which is the same as saying that the decision maker's investment horizon is 40 years instead of 20, leads to significant reductions in the specific lifetime embodied energy costs. It is also clear from Table 6 above and from Figure 18 below that these LEE reductions due to extension of the analysis time horizon are greater for the more capital intensive, high-industrialization strategies (scenarios 4-7).

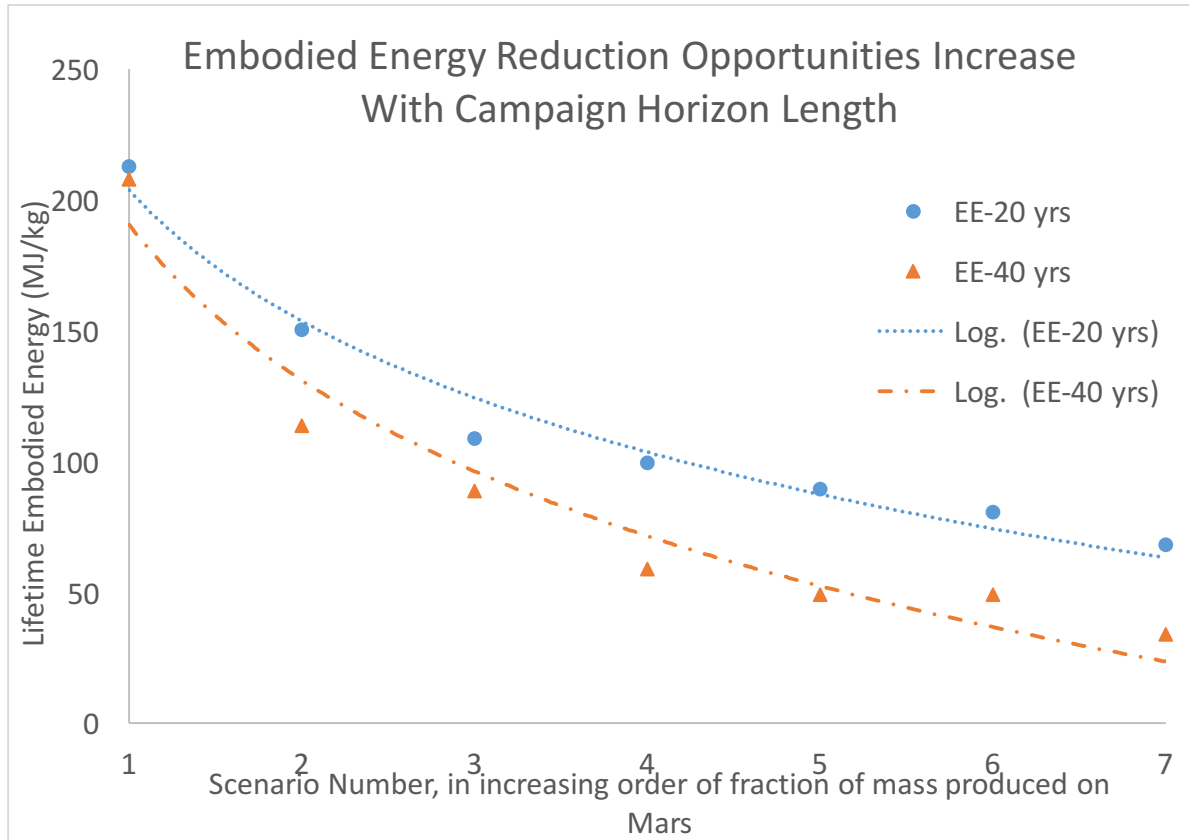


Figure 18 : Lifetime Embodied Energy Reduction Opportunities Increase with Length of Campaign Horizon

5.2 Discussion of Simulation Results

5.2.1 Model Output

The findings above, namely that specific lifetime embodied energy costs fall with increasing investment in industrial capabilities and also with the length of the amortization

horizon, are not surprising. All high-industrialization strategies aiming to reduce unit cost require up front investments in manufacturing capability, and the longer-lived this equipment is, the more output it can produce over its lifetime. As a result, longer time horizons mean that the embodied energy of the initial investment is spread over more output mass, reducing the embodied energy cost per unit mass which flows downstream to the output mass³⁹.

5.2.2 Model Limitations

The Energy Diagram version of the model, as described in 4.1 above, Figure 10, is clearly rich in dynamics. However, a quantitative treatment of the Energy Language Diagrams developed here, for the purpose of creating models of space mission architectures, remains as future work. Odum's energy accounting formulations, which were and remain masterpieces of intellectual construction, were reviewed by later writers who recommended a variety of ways to adapt, simplify or re-interpret them (Hornborg, 1998; Tilley, 2014). A set of equations, associated notation and methodologies for quantifying the flows of embodied energy through Odum's energy diagrams all remain as work to do in the future.

The Excel version of model, in 4.2, Figure 17 above, though fully quantified and parameterized, has no dynamics and no time dimension. The time horizon under study (either 20 or 40 years) is treated as a single instantaneous period, and all equations are solved analytically and instantaneously for the entire time horizon. This limitation is to some extent a benefit, in that risky assumptions about growth dynamics are sidestepped for now; only the first-order capacity of each alternative industrial configuration to produce useful mass is calculated, along with associated metrics such as the lifetime embodied energy and the fraction of cumulative useful mass produced from in situ resources.

5.2.3 Model Findings

It is clear that the *ex ante* modeling of entire industrial ecosystems on other worlds is a profitable and interesting exercise, at least from the point of view of the system designer of an extended human exploration spaceflight campaign. The designer in such cases generally is (or

³⁹ If the average cost of using capital equipment goes up rather than down as time passes, that is almost always a signal that it is costing more to maintain it rather than replace it. That is how most people decide when it's time to buy a new car.

should be) interested in reducing logistical mass, and in increasing the mass of useful infrastructure emplaced at the destination world, among other targets and goals. More efficient rockets, clever in-space refueling schemes and the ISRU of propellant can only take us so far in the quest to increase the efficiency of transporting mass through space. Beyond those limits, we are (finally) increasingly exploring whether we should be transporting more *capabilities* through gravity wells instead of *mass*, and using these capabilities together with the mass available at the destination to emplace the infrastructure needed for our activities (Rapp, 2018; Sanders, 2018).

What is not clear, however, is whether the space systems designer can continue using mass-based metrics for the purpose of optimizing the long-term sustainability prospects of a human outpost on another world, or whether a switch to an energy-based metric is indicated at this time. We turn to the energy language diagrams for insight on this question.

5.3 Insights from Energy Language Diagrams

As we saw in Chapter 1, the mass-based approach was satisfactory and successful in past decades when rockets were expendable and/or too expensive, when every mission was unique, and when no habitation infrastructure was being accumulated on Mars or the Moon.

However, now, at the dawn of the ISRU and ISM eras of human spaceflight, it is proposed that an energy based metric is more appropriate to architects of off-Earth outposts.

An energy based metric can do everything a mass-based metric can do, and more that a mass-based system cannot do.

Specifically, as we found from our analysis of predecessor nodes in the energy diagram model, from Figure 11 to Figure 16, the same energy diagrams used to set up the embodied energy calculation also reveal all the linkages and dependencies between nodes, clearly illustrating the role every system or process plays in the effort to keep crews alive and productive.

This side benefit was not accidental or fortuitous. It emerged precisely because energy is the natural metric to measure any and all efforts to sustain systems in the struggle against the relentless attacks from the Second Law of Thermodynamics. Keeping order requires energy, and maximizing the flows of energy in self-reinforcing ways is what all dominant forms of life have evolved to do. Therefore, when we model networks of energy flows in order to measure the

embodied energy costs at various nodes, we are *also* automatically recreating the pathways which keep the natural or artificial system functional. Going forward, this alignment between nature's ways and ours is likely to lead to more insights and discoveries on the evergreen topic of maximizing system performance, which is of interest to all system architects and systems engineers.

Moreover, in modeling lifetime embodied energy (with energy expended in space logistics as the primary source), we are actually working with a metric which simultaneously optimizes not just for minimum lifetime logistical mass, but also for the maximum lifetime energy efficiency of the systems under consideration. Given that the industrial revolution only really began in earnest when James Watt started raising the energy efficiency of the steam engine, the space systems architect who would like to design self-sustaining cities on other worlds should be interested in metrics which can be used to optimize both logistical cost and lifetime energy efficiency at the same time. The importance of keeping an eye on in-space energy efficiency cannot be overstated: as we saw in earlier chapters, all human activity in space must be paid for out of our own expensive energy sources that we will bring or make there. Far from the cradle of our birth planet, we will also be far from its free life support system which sustains the lives of billions of us.

In fact, the optimizations delivered by the LEE framework go beyond mass and energy. The mechanics of measuring the cost of past effort in the way we described for embodied energy are generalizable to any type of effort, not just energy. Thus, the embodied energy cost of labor can be incorporated into the modeled flows of embodied energy simply by considering the LEE of all systems that the crew depend upon, such as Habitat and ECLS. In so incorporating it, labor becomes a consequential input variable to the in-space production function, and the designer can vary the amount of high-cost, high-value labor input along with inputs of resources, capital and energy of different kinds. If the principle of diminishing marginal utility applies, the optimum design will be consistent with equal marginal returns of all these inputs. In other words, the optimum design will reveal not just the minimum amount of embodied energy, but also the optimum mix of capital, labor and materials. Hence, the LEE metric and the associated energy language diagrams can provide holistic insights to inform Make vs. Take decisions and all kinds of architecting decisions.

The systemic viewpoint afforded by the lifetime perspective of LEE and the associated easy-to-use energy language diagrams emphasize another dimension that the architect should pay attention to. Namely, that past “make vs. take” decisions will alter the trajectory of future decision options, and can create both negative and positive lock-in. Thus, if the first outposts on Mars are constructed using life support systems which are very difficult to manufacture on Mars, these outposts will end up being dependent on a constant flow of very specific spare parts, and future mission architects will face both overt and subtle⁴⁰ switching costs which will discourage them from adopting radical new designs. Such constraints, or ‘limits to growth’ will likely be everywhere to be found in our system designs for Mars. It will be the job of the architect to target a self-consistent set of growth rates for any variables threatening to become constraints to the future growth of the outpost into a city. The ability to model all interactions and measure the impact on a single objective cost metric will assist in that task of balancing the growth rates of important state variables. Again, the natural energy linkages between nodes on the energy language diagrams tell the story of the interacting growth trajectories of the main state variables, too, with little effort.

5.4 Chapter 5 Summary

The Excel model of the initial Mars outpost was run under seven scenarios, representing increasing investment in a variety of modeled industrial capabilities, for campaign durations of 20 and 40 years. The resulting distribution of specific lifetime embodied energy confirms reasonable assumptions about the high return on investment in manufacturing capabilities in space. It also shows that LEE captures other characteristics that IMLEO will miss, because all seven scenarios start with exactly the same IMLEO but vary widely in lifetime embodied energy, almost by an order of magnitude. These characteristics which can also be optimized using LEE-based models include energy efficiency as well as the optimal mix of capital and labor for the in-space production function. Odum’s energy diagrams, as applied to the design of space missions, help illuminate these and more insights as they represent the natural energy pathways which create and sustain both life and technological systems. The quantification of energy language diagrams for space logistics and space industrialization remains as future work.

⁴⁰ How many would put their careers on the line to insist that, e.g., a TRL 9 Carbon Dioxide Removal Assembly (CDRA) which has been matured on the ISS for years should now be cast aside and a new design created, because the new design would be highly manufacturable on Mars, whereas the existing design would not be?

6 Conclusion

6.1 Summary of Findings

The objective function in space mission architecting almost always includes the minimization of total mass, whether for a single mission or across a campaign of missions. However, minimizing mass does not guarantee the minimization of cost, opening a research gap for the exploration of suitable non-mass, non-dollar metrics which can serve as improved proxies for costs. This thesis has made the following findings which add to the body of knowledge in this regard:

6.1.1 True Space Mission Cost is Progressively Being Decoupled from IMLEO

IMLEO has been and still is widely accepted as a reliable proxy for the cost of activities in space. However, reusable rockets, ISRU and ISM and other factors are reshaping the landscape of space economics. When the ongoing changes are completed, IMLEO will have lost most of its past status and relevance as a reliable proxy for space mission cost. It must be noted that IMLEO minimization is a hidden assumption in advanced costing systems such as ESM and GMCNF.

6.1.2 Energy is the Natural Metric of Cost

It is often repeated in the Aerospace engineering profession that “mass attracts cost”. While this is generally true, it is also more likely to be indicative of a mere correlation rather than causation. Cost in fact attaches to *work*, and in physics energy is the metric of the capacity to do work. More mass often requires more work, which requires more energy and therefore more cost. However, more or less mass does not always mean more or less cost, or more or less energy⁴¹. Energy is the natural metric for cost because it is the natural metric for work.

6.1.3 Embodied Energy is a Measure of Past Work

Since energy measures the capacity to do work, embodied energy – a concept which Howard Odum described as “the memory” of past work – is a measure of all the past work that was required for the creation or sustainment of a product or system. Given the physical basis of

⁴¹ In 1999, NASA’s Space Science News web page quoted the figure of **\$62.5 trillion** per gram as the ‘cost’ of antimatter. (https://science.nasa.gov/science-news/science-at-nasa/1999/prop12apr99_1, retrieved May 16, 2018)

work in thermodynamics, the embodied energy of objects or systems comes close to being an ideal objective measure of their value or cost.

6.1.4 Embodied Energy is a Skilled Metric of Space Mission Cost

The embodied energy of systems at a destination in space can easily be converted to IMLEO using well-known gear ratios and a Lifetime Embodied Energy (LEE) exchange rate calculated using a method similar to that shown in Appendix I. Therefore, all IMLEO-based calculations and methodologies can be replicated with LEE. Beyond this, LEE does not come with the implicit assumption that payload mass will always be something that must be minimized: it is the lifetime embodied energy which must be minimized, *not necessarily* the mass. This makes LEE a native-language metric for designing multi-decade campaigns which will rely on ISRU and ISM, where the embodied energy of space logistics and *in situ* raw mass combine to produce *in situ* useful mass, which in turn may displace future payload mass from manifests.

6.1.5 Energy Language Diagrams are useful for Space Mission Design

The diagrams shown in Figure 7; Figure 8; and Figure 10 to Figure 16 are drawn using Howard Odum's Energy Language (Odum, 1983, 1996). They were first created for applications in ecology, but their creator showed how the energy language can handle natural and artificial systems, as well as their interactions. In mapping the flows of embodied energy through a system, from sources to sinks, energy language diagrams provide unique insight to the space mission architect as well. These insights can lead to increased savings in lifetime logistical mass, increased energy efficiency and longevity and increased sustainable growth rates.

6.1.6 Increasing Returns on ISRU / ISM Investment

As we saw in Figure 18 above, increased up-front investment in ISRU and ISM capabilities is correlated with a reduced specific lifetime embodied energy cost, and these reductions increase still further as the time horizon of analysis is increased.

6.2 Recommendations

6.2.1 Adoption of LEE as a Metric for Estimating Space Mission Cost

As LEE can replicate and go beyond IMLEO-based costing estimates, for instance by its native connection to energy efficiency or the ease and accuracy with which it can allocate labor

cost to outputs, it is recommended that it should be adopted as a metric for space missions, especially for long campaigns to the same crewed outpost or destination on the Moon or Mars.

6.2.2 Embodied Energy Metadata and Digital Twins for In-space Supply Chains

Currently, embodied energy is in widespread use in the measurement of the energy performance of buildings. This measurement of performance has been mandated by law in the European Union and elsewhere. A literature search showed that the most extensive database of embodied energy for common building materials is an Excel sheet maintained by an academic in the United Kingdom (Hammond & Jones, 2008).

As the in-space supply chain has yet to be created, the opportunity arises to structure this supply chain in such a way as to make it easy to calculate embodied energies for all manners of in-space systems, products and processes. It is a matter of tagging every material system or subsystem intended for use in space with the required metadata, and creating a universal framework where every in-space system has a digital twin, from where all the required metadata would of course be accessible. This recommendation is well aligned with current trends towards model-based systems engineering (MBSE).

This metadata would also be useful not only to the space architect, but also to the logistics team of a mining or in-space fabrication operation on the Moon or Mars. Again, the Earth makes up many of our losses to entropy with free gifts of energy; this won't be the case in space. So in future there will be operational uses to accurately tracking the energy cost of complex development activities, such as in the month-to-month planning to balance the energy budget of a fast-growing settlement on Mars. Such uses are supportive of the development and growth of human activities in space and go well beyond the architect's initial interest in mass, dollars or energy numbers for the purpose of designing a space system.

6.2.3 LEE Analysis Informing Key NASA TRL Development Decisions

NASA may use LEE to quantify the benefits of important decisions regarding TRL development for ISRU, ISM and life support systems. Specifically, a LEE analysis could assist NASA to determine whether they should consider setting aside legacy system designs (including

for TRL 9 systems) in favor of adding extensive “design for manufacturability” requirements to all habitat and life support systems.

6.2.4 LEE Analysis Informing the Field of Space Economics

Space economists interested in modeling the future growth of the space economy may use LEE-based models, such as systems dynamics models, to study the growth dynamics of the space economy and related potential constraints. Variables to be studied may include:

- Transported mass per person
- Pressurized volume per person
- Manual labor required per unit of systems mass, or per unit of pressurized volume
- Energy required per person, or per unit of pressurized volume, or per unit of systems mass
- Stock of consumables required per person, or per unit of pressurized volume

6.2.5 Standardizing Sector Breakdown of Space Economy to aid in mapping LEE flows

It will be useful to agree early on to a comprehensive, standard categorization and mapping of sectors of economic activity for the space economy, so that all participants gather data in the same way. This will facilitate later analysis of space economic activities using LEE.

6.3 Limitations

The recommendations made above aim in part to help address limitations in the application of LEE to practical space mission design problems.

Modelling and methodological limitations revolve mainly around data gathering difficulties. These might affect data or projections on system lifetime, productivity, manufacturability, materials and labor requirements. The impact of lack of data is multiplied because of the practice of truncation of hierarchical process trees. Truncation is a technique used to facilitate the calculation of embodied energy from process trees. Lack of data often leads to excessive pruning and truncation, which negatively affects the accuracy of the embodied energy estimate.

Another limitation is that embodied energy calculations remain a time consuming process and are less relevant to most people than mass or dollar costs. They are certainly not immediately and intuitively tangible. Mass-based approaches are very well established in the space industry. This gives rise to resistance to change established methodologies.

6.4 Future Work

A number of important streams of future work arise from this thesis, chief among them the need to develop elegant notation and simple equations streamlining the translation of Odum energy language diagrams into mathematical models, using Odum's own equations and selected principles of economics and accounting as the starting point. The key would be to use principles of double entry accounting to robustly guarantee that embodied energy is never double counted, and to assist the analyst in keeping track of everything through the unavoidable complexity of more detailed sector and process graphs with hundreds or thousands of elements.

Using the digital twins mentioned above, one may usefully inform the manufacturability, decomposition of form and lifetime estimates which would be required to make forward-looking lifetime embodied energy analysis an easier proposition.

The analysis can be reframed with different system boundaries and different primary sources of energy. For example, the primary source of energy can be changed to assign a LEE cost to all mass launched from Earth. This can bring the cost of manufacturing of space systems on Earth within the system boundary, allowing tradeoffs between making a system on Mars vs. making it on Earth. This is the power afforded by the built-in flexibility of the energy language methodology: the system boundary can easily be extended at any time, primary sources can be endogenized, and transformities used to re-baseline the embodied energy to be in the emjoules of a higher-level source.

The principles and approach used in developing Lifetime Embodied Energy may also be used to develop extensions to existing mass-based costing methods such as ESM and GMCNF. Such extensions would explicitly take into account the potential for investments in ISRU and ISM to reduce long term mission and campaign costs. An advantage of extending existing, accepted methods is that adoption and application by the community is significantly increased.

6.5 Summary of Thesis

From the Apollo era to the present day, various mass-based metrics such as payload mass, system dry mass and IMLEO have served as proxies or key inputs into calculations of total mission cost. However, IMLEO is being progressively decoupled from cost due to changes including the advent of reusable rockets and the inclusion of ISRU in design reference missions. At the same time, cost reductions arising from new forms of contracting and new investments are starting to undermine the validity of old cost databases and CER's.

A natural and objective metric of past work is energy, and specifically the *embodied energy*, which is the sum of past work that went into the creation or maintenance of a system and its predecessors. This concept was first created in the 1970's amidst the oil crises, and has found limited application, mainly in the study of the energy efficiency of buildings. Its use in a space application is novel. Flows of embodied energy were represented using Odum's energy language diagrams, and also with equations in a simple Excel model. The key result is the ability to measure all costs on the same denominator of embodied Joules of energy from the selected primary energy source, which in our case is the energy of space logistics. This makes it possible to compare all types of diverse human spaceflight architectures, with or without investment in ISRU and ISM, without unfairly disadvantaging any one family of concepts. This graphical and quantitative analysis demonstrated the usefulness of the proposed new metric in the architecting of human space exploration campaigns and other types of space missions.

7 Appendix I – Specific Embodied Energy of Payload to Mars

We present a method to calculate an approximate specific embodied energy cost of space logistics, to transport a kg of mass to Mars. Such a cost can be used as a LEE to mass exchange rate.

We start with a cost analysis from (Musk, 2017) showing the calculation of the long-term cost per ton to Mars, once the BFR / BFS system is fully reusable. The future cost per ton to Mars is estimated at \$140k / ton, or \$140 per kg. However, we note from Figure 19 below that this low price is only realizable if the BFS can achieve 12 lifetime flights, a question which won't be settled for 25 years or more after the first flight to Mars. For the purposes of this analysis, we will assume that the initial price will be 10 times the minimum quoted by Musk, or \$1,400 per kg, including the profit for SpaceX and recovery of the development costs. We note that the cost per flight of the BFS can be as much as \$500 per kg if the ship cannot be reused.

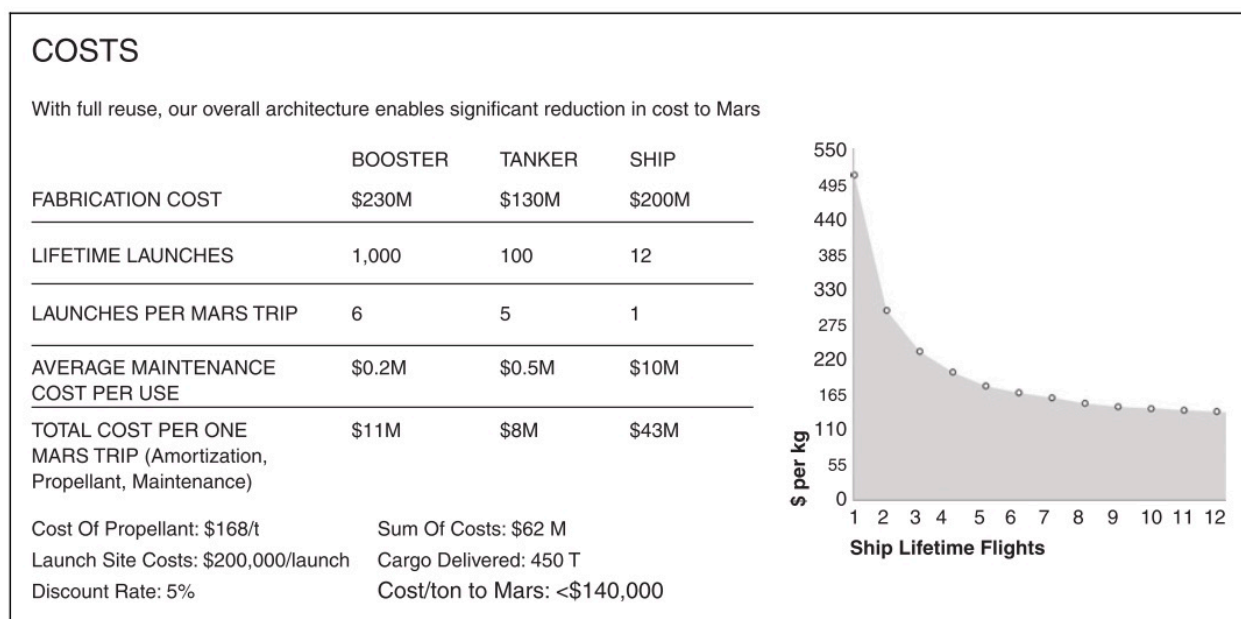


Figure 19 : Projected cost of transportation to Mars (Credit: Elon Musk)

The total primary energy consumption of the US economy in 2016 was given as 10^{15} BTU⁴² which is approximately 1.06×10^{12} MJ. This does not include energy services from the environment which have been valued as approximately twice the size of the US economy. The

⁴² From https://www.eia.gov/energyexplained/index.php?page=us_energy_home, retrieved on 16 May 2018

total GDP of the US economy in 2016 was given as \$18.57 trillion⁴³. Thus, including the free energy services from the environment, the embodied energy intensity of the US economy in 2016 was ~ 0.15 MJ / \$.

Multiplying this embodied energy intensity by the adjusted Elon Musk estimate for the near-term cost of transportation to Mars (\$140 per kg \times 10 = \$1,400 per kg), we obtain the figure of 210 MJ / kg as the embodied energy of transportation to Mars.

The above figure is close to reasonable physical limits. Starting from the total ΔV from Earth surface to Mars surface, which is about 18.91 km/s, we can calculate the kinetic energy that must be imparted to the mass using the conservation of energy equation $\frac{1}{2}mv^2$. Adding 15% for losses and inefficiencies of the propulsion system, we obtain the figure of 205.6 MJ / kg as the embodied energy of transportation to Mars.

The latter figure was used in the calculations for the model, because it required fewer assumptions and because these assumptions were physical in their nature. The actual figure is not critical because the method works equally well with only relative comparisons between embodied energies.

⁴³ Data source: World Bank, last updated Apr 24, 2018, retrieved from Google public data search on 16 May 2018

8 Appendix II - Model Assumptions and Parameters

<u>Assumptions</u>	<u>Value</u>	<u>Unit</u>	<u>Excel Name</u>	<u>Notes</u>	<u>Reference</u>
Energy to transport 1kg of mass from Earth to Mars	205.6	MJ kg-1	MJPERKG	See Appendix I	
Energy intensity of plastics feedstock production on Mars	56	MJ kg-1	MJPLASTICS	Author estimate 10KW for 2 hours.	
Energy intensity of metals feedstock production on Mars	108	MJ kg-1	MJMETALS	Author estimate 30KW for 1 hour	
Energy intensity of 3D printing plastics on Mars	129.6	MJ kg-1	MJ3DPLASTIC	Author estimate 3KW for 12 hours	
Energy intensity of CNC milling metals on Mars	28.8	MJ kg-1	MJCNCMETAL	Author estimate 4KW for 2 hours	
Energy intensity of Laser cutting metals on Mars	30	MJ kg-1	MJLASER	Author estimate	
Energy intensity of production of consumable food	579	MJ kg-1	MJFOOD	Based on BPS system sized by S. Do 2016 (137 lights per 4 people)	(Do, 2016 Thesis)
Energy intensity of life support systems	20	MJ person-1 hour-1	MJLIFESUPPORT	See Sydney Do thesis	(Do, 2016 Thesis)
Energy intensity of robotic assembly systems	18	MJ kg-1	MJROBOTS	Estimate 5KW for 1 hour	
Energy Intensity of Recycle Systems	81	MJ kg-1	MJRECYCLE	Estimate 75% of Metal Feedstock Production	
Logistical mass cost per human to Mars	1000	kg person-1	TRANSIT_MASS_PERSON	Including consumables in transit	(Do, 2016 Thesis)
Food consumed per person per Earth day	1.878	kg person-1 day-1	FOOD_CONS	including spoilage	(Do, 2016 Thesis)
Crew Hours Worked per person per Earth year	2087	hours person-1 year-1	HOURSPERYEAR	Working hours per year (excluding sleep, leisure)	(Do, 2016 Thesis)
Mass of habitats & ECLS per person incl spares for 20 years	80000	kg person-1	HAB_ECLSS_MASS	based on Sydney Do's Minimum Continuous Presence + BPS Case	(Do, 2016 Thesis)
Rocket Payload	80000	kg		based on current plans for BFS	Elon Musk, IAC 2017
# of Rocket Launches per Year	1	Launches /year		two launches every ~2 years = ~one launch per year	Elon Musk, IAC 2017

Parameter	Value	Unit	Excel Name	Notes
Number of crew on surface of Mars	8	persons	CREW_SIZE	Persons supported by habitat.
Targeted imported Feedstock Percentage	75%	(local:total)	STOCK_IMPORT	Amount of feedstock developed in-situ.
Targeted in situ mass fraction for systems "Made on Mars"	60%	(local mass:total mass)	MOM_MF	Average, only for subsystems to be made on Mars. This encodes the average local mass content of all subsystems, spares etc. which will be made on Mars
Fraction of crew working hours absorbed by "Made on Mars"	0%	(MoM hours:total wrkg hrs)	CREW_MOM	Implicit labor productivity (output not driven by this). Changing this will change the embodied energy of habitat & crew allocated to final outputs
Min Productivity of plastic feedstock manufacturing system	200%	(output mass:system mass)	PRODPLASTICS	Every year, system output = X% of system mass . Changing this will change output of raw materials, import of subassemblies & output of systems.
Min Productivity of metal feedstock manufacturing system	200%	(output mass:system mass)	PRODMETALS	Every year, system output = X% of system mass . Changing this will change output of raw materials, import of subassemblies & output of systems.
Duration of entire campaign (=lifetime of nuclear reactor)	20	years	CAMPAIGN	A finite lifetime for the analysis. For all systems, the mass shown is cumulative lifetime mass; a 3D printer can be changed several times
Duration of mission (crew rotation every X Earth years)	4	years	CREW_ROTATION	Every X years, the crew is replaced by a new crew.
Mass of Nuclear Reactors	136382.4	kg	MASS_NUC	Lifetime mass, including all future spare parts. 72 Kilopower systems
Energy Output of Nuclear Reactors	0.72	MW		Power output, including heat and electrical. 72 Kilopower systems
Mass Fraction of Nuclear Reactor manufacturable locally	90%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Mass of Water + CO2 to Plastics Resource Processing System	10000	kg	MASS_PLASTIC	Lifetime mass, including all future spare parts. Since output is linked to system mass via minimum productivity, changes here also change output
Mass Fraction of Plastics RPS manufacturable locally	0%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.

Mass of Regolith to Metals Resource Processing System	30000	kg	MASS_METAL	Lifetime mass, including all future spare parts. Since output is linked to system mass via minimum productivity, changes here also change output
Mass Fraction of Metals RPS manufacturable locally	0%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Mass of 3D Printing Manufacturing System	2000	kg	MASS_3D	Lifetime mass, including all future spare parts.
Mass Fraction of 3D Printing system manufacturable locally	0%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Min Productivity of 3D Printing System	300%	(output mass:system mass)/yr		Every year, system output = X% of system mass .
Mass of CNC Milling Manufacturing System	2000	kg	MASS_CNC	Lifetime mass, including all future spare parts.
Mass Fraction of CNC Milling system manufacturable locally	0%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Min Productivity of CNC Milling System	300%	(output mass:system mass)/yr		Every year, system output = X% of system mass .
Mass of Robotic Assembly System	10000	kg	MASS_ROBOT	Lifetime mass, including all future spare parts.
Mass Fraction of Robotic system manufacturable locally	0%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Mass of Laser Cutting System	2000	kg	MASS_LASER	
Min Productivity of Laser Cutting System	300%			
Mass Fraction of Laser cutting system manufacturable locally	0%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Efficiency of 3D printing, including recycling of scrap	95%	mass_out mass_in-1	EFF3DP	out of feedstock, how much is ultimately converted to useful mass.
Efficiency of CNC milling, including recycling of scrap	95%	mass_out mass_in-1	EFFCNC	out of feedstock, how much is ultimately converted to useful mass.

Efficiency of laser cutting, including recycling of scrap	95%	mass_out mass_in-1	EFFLASER	out of feedstock, how much is ultimately converted to useful mass.
Mass of Solar Panels	153771.156	kg	MASS_SOLAR	Lifetime mass, including all future spare parts. Source - NASA Report. Same power as nuclear but less than half the mass
Mass of Batteries for Solar System to provide overnight cover	140000	kg		https://www.tesla.com/powerpack
PEAK Energy Output of Solar Panels	1.476	MW		Peak power output, which is not the same as average sustained output. System overproduces during day and charges batteries such that same output as nuclear is made available.
Mass Fraction of Solar Panels manufacturable Locally	95%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM. Linked via formula to "high versatility"
Mass Fraction of Batteries manufacturable Locally	30%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Mass of Recycle System	10000	kg	MASS_RECYCLE	System mass of recycling system
Min Productivity of Recycle System	50%	(output mass:system mass)	PRODRECYCLE	every year, system output = X% of system mass . Changing this will change output of raw materials, import of subassemblies & output of systems.
Mass Fraction of Recycle system manufacturable locally	0%	(local mass:total mass)		
Percentage of Recycled Material for Feedstock	0%			

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