Technology Development Targets
for Commercial In-Space Manufacturing

by
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Abstract

In-Space Manufacturing (ISM) promises to revolutionize space systems by reducing mass, lowering costs, and enabling entirely new designs through the orbital fabrication of components in the space environment in which they are intended to operate for their entire life. Because ISM changes many long-standing launch-related design constraints, a new approach for the design and fabrication of space systems must be developed. Technology development planning for ISM is complicated by the existence of various proposed commercial ISM architectures, each with their own technologies, products, and costs. Instead of attempting to estimate these highly uncertain quantities, this analysis informs ISM technology targeting by identifying the key system drivers, maximum allowable lifecycle cost, and minimum required performance for an ISM architecture to be cost-effective relative to the existing launched approach.

This analysis is accomplished by first forming generalized classes of ISM applications based on the design constraints relaxed using ISM, such as launch loads, fairing volume, standard gravity, and launch schedule. These generalized classes, which include structurally optimized systems, larger-than-launchable systems, Earth-return systems, and on-demand manufactured systems, are shown to be collectively exhaustive, but not mutually exclusive. For each of these classes, a bottom-up cost model is developed that captures the impact of key system drivers on lifecycle cost. Then, Buckingham Pi theorem is used to identify nondimensional groups of input design variables, such as the ratio of areal density of launched components to that of ISM components, the ratio of ISM facility mass to that of ISM components, the ratio of ISM product sale price to launch cost, or the ratio of launch cost to material cost. The breakeven point between launched and ISM components is identified as a function of these parameters and nondimensional groups, which serve as technology development targets for commercial viability.

It is shown that the presented approach can inform technology development efforts by evaluating the commercial viability of historical, current, proposed, and notional ISM concepts across a broad application space. The best ISM applications can be identified as having a high allowable facility cost without requiring a large
total ISM product mass. For the structurally optimized class, ISM of solar arrays appears promising because structural mass can be reduced by up to 85% relative to the technology goal for launched solar arrays. However, ISM solar array mass savings are fundamentally limited by solar cell mass, which can total 5 kg/kW. Of the Earth-return concepts considered, ISM of ZBLAN optical fiber appears most promising with an allowable facility cost of $1.35B based on just 125 kg produced over a five year period at its sale price of $11M/kg. The commercial viability of ISM of ZBLAN is relatively insensitive to launch costs. Interestingly, falling launch costs improve the business case of Earth-return ISM concepts, while weakening that of ISM for structural optimization.

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"I can do all things through him who strengthens me." — Phil. 4:13, NRSVCE

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Nomenclature

$\alpha$  Density performance parameter [kg/m, kg/m$^2$, or kg/m$^3$]  

$\beta$  Parameter capturing relationship between $m_{produced}$ and $C_{facility,allowable}$ for structurally optimized case study  

$\Gamma$  Mass efficiency [Ex: W/kg]  

$\kappa$  Nondimensional material cost, which is given by $c_{matl,SO}/c_{launch}$  

$\lambda$  Linear density [kg/m], areal density [kg/m$^2$], or volume density [kg/m$^3$]  

$\lambda_{NSO}$  Linear/areal/volume density of non-structurally optimizable components  

$\lambda_{SO}$  Linear/areal/volume density of structurally optimizable components  

$\lambda_{SO,ISM}$  Linear/areal/volume density of structurally optimizable components in the ISM case  

$\lambda_{SO,LV}$  Linear/areal/volume density of structurally optimizable components in the existing launch case  

$\mu$  Scrap part ratio, which is given by $m_{feedstock}$ divided by $m_{produced}$  

$\nu$  Structural optimization mass fraction, which is given by $\lambda_{SO,ISM}/\lambda_{SO,LV}$  

$\psi$  Value adding quantity per unit scale parameter [Ex: W/m$^2$]  

$a$  Proportionality constant in CERs  

$b$  Exponent on mass in CERs
$C_1, C_2$ Generic cost contributions

$C_{1,ISM}, C_{2,ISM}$ Generic cost contributions for ISM case

$C_{1,LV}, C_{2,LV}$ Generic cost contributions for existing launched case

$C_{company}$ Cost burden carried by private company

$C_{facility}$ Realized ISM facility cost

$C_{facility,allowable}$ Allowable facility cost

$C_{facility,allowable}$ Nondimensional allowable facility cost. For the structurally optimized case study, this quantity is given by $C_{facility,allowable}/(x_{BE} \lambda_{SO,LV} c_{launch})$. For the Earth-return case study, this quantity is given by $C_{facility,allowable}/(m_{produced}(c_{launch} + c_{mat}))$.

$C_{feedstock}$ Cost contribution due to providing feedstock to orbit for Earth-return case study

$C_{government}$ Cost burden carried by government investment

$C_{launch, facility}$ Launch cost for ISM facility

$c_{launch}$ Specific launch cost [$/kg$]

$c_{mat}$ Specific material cost [$/kg$]

$c_{mat,NSO}$ Specific material cost of non-structurally optimizable components [$/kg$]

$c_{mat,SO}$ Specific material cost of structurally optimizable components [$/kg$]

$C_{NSO}$ Cost contribution due to non-structurally optimizable components

$C_{NSO,ISM}$ Cost of non-structurally optimizable components in the ISM case

$C_{NSO,LV}$ Cost of non-structurally optimizable components in the existing launch case

$C_{ops, facility}$ Operations cost for ISM facility
$C_{RDTE, facility}$ RDTE cost for ISM facility

$\Delta C_{RDTE, ISM, components}$ Additional RDTE cost required to validate new ISM spacecraft components

$c_{reentry}$ Specific reentry cost, which is the cost of returning payload from orbit to the surface of Earth [$/kg]

$\hat{c}_{reentry}$ Nondimensional specific reentry cost, which is given by $c_{reentry}/(c_{launch} + c_{mat})$

$C_{return}$ Cost contribution due to returning the ISM product to Earth for Earth-return case study

$c_{revenue}$ Specific sale price for product in Earth-return case study [$/kg]

$\hat{c}_{revenue}$ Nondimensional specific sale price, which is given by $c_{revenue}/(c_{launch} + c_{mat})$

$C_{SO}$ Cost contribution due to structurally optimizable components

$C_{SO, ISM}$ Cost of structurally optimizable components in the ISM case

$C_{SO, LV}$ Cost of structurally optimizable components in the existing launch case

$C_{TFU, facility}$ Theoretical first unit cost for ISM facility

$C_{total}$ Total system lifecycle cost

$C_{total, ISM}$ Total system lifecycle cost for ISM case

$C_{total, LV}$ Total system lifecycle cost for existing launched case

$f, g$ Generic cost model functional form

$f_n$ Fundamental frequency

$m$ mass

$m_{facility}$ ISM facility mass

$m_{feedstock}$ Mass of feedstock for Earth-return case study
$m_{\text{produced}}$ Total mass fabricated by ISM facility

$\dot{m}_{\text{produced}}$ Mass production rate of ISM facility

$m_{SO, LV}$ Mass of structurally optimizable components in the existing launch case

$M_{\text{total}}$ Total mass of system produced, including both SO and NSO components

$N$ Number of ISM facilities produced

$P$ Power produced by solar array [W]

$P_{\text{total}}$ Total profit

$R&D$ Research and development

$R_{\text{total}, ISM}$ Total revenue generated through sale of ISM product

$t_{\text{life}}$ Lifetime of ISM facility

$u_n$ Generic cost model independent variable

$V^*$ Stowed volume efficiency

$V_{\text{facility}}$ Volume of ISM facility

$V_{NSO}$ Volume of NSO components

$V_{SO}$ Volume of SO components

$V_{\text{stowed}}$ Stowed volume

$x$ Scale parameter [m, m², m³]

$x_{BE}$ Scale parameter at desired breakeven point

$x_{\text{demand}}$ Scale parameter demanded by market

$y_n$ Generic cost model independent variable

ADAM Able Deployable Articulated Mast
AI&T Assembly, Integration, and Testing

CER Cost estimating relationship

CF/PEEK Carbon fiber reinforced polyether ether ketone

CFRP Carbon fiber reinforced polymer

CIRAS Commercial Infrastructure for Robotic Assembly and Services

COPV Composite overwrapped pressure vessel

CRS Commercial Resupply Services

FAST Folding Articulated Square Truss

GEO Geostationary orbit

GRA Government Reference Array

HEOMD Human Exploration and Operations Mission Directorate

ISM In-space manufacturing

ISRU In-situ resource utilization

ISS International Space Station

LEO Low Earth orbit

LV Launch vehicle, used as a subscript to denote quantities pertaining to the existing launch case

MEO Medium Earth orbit

MIS Made in Space, Inc.

MOCET Mission Operations Cost Estimation Tool

NASA National Aeronautics and Space Administration
NRC  National Research Council
NSO  Non-structurally optimizable
RDTE  Research, development, test, and evaluation
SAW  Solar array wing
SBIR  Small Business Innovation Research
SCAFEDS  Space Construction Automated Fabrication Experiment Definition Study
SiC  Silicon carbide
SMAD  Space Mission Analysis and Design
SME-SMAD  Space Mission Engineering: The New SMAD
SO  Structurally optimizable
SRTM  Shuttle Radar Topography Mission
SSL  Space Systems Loral
STTR  Small Business Technology Transfer
SWaP  Size, weight, and power
TFU  Theoretical first unit
TUI  Tethers Unlimited, Inc.
USAF  United States Air Force
USCM8  Unmanned Spacecraft Cost Model, version 8
V&V  Verification and Validation
WSF  Wake Shield Facility
ZBLAN  A heavy metal fluoride glass made of ZrF$_4$-BaF$_2$-LaF$_3$-AlF$_3$-NaF
Chapter 1

Introduction

1.1 What is In-Space Manufacturing (ISM)?

Currently, space systems are constrained by the fact that all components are built on Earth, launched aboard a rocket, and then operated in orbit for years with little to no opportunity for repair. Even though a spacecraft spends its entire operational life in orbit, some of the most stringent design constraints are driven by the short ride to orbit aboard a launch vehicle. One promising new technology that can revolutionize spacecraft design is in-space manufacturing (ISM), where the fabrication, assembly, and integration of products takes place outside of the Earth’s atmosphere [54]. With ISM, components are fabricated in the space environment in which they are intended to operate for their entire life. These components are no longer constrained by launch loads, fairing volume, or gravity. In addition, ISM opens the possibility of acquiring feedstock via orbital material recycling or in-situ resource utilization (ISRU), in addition to the traditional launch of raw material from Earth.

ISM can leverage these relaxed design constraints to potentially lower the mass and cost of spacecraft with current capabilities or, perhaps more interestingly, provide improved performance and entirely new capabilities that are not currently possible [40]. Due to these perceived benefits, ISM has long been sought after, but commercially viable operations have remained elusive [9]. Commercially viable operations are crucially important because they will provide cost sharing opportunities for NASA. In
addition, the development of technologies for commercially viable ISM feed directly into NASA’s Congressionally-mandated role to "seek and encourage, to the maximum extent possible, the fullest commercial use of space" [66]. As seen in numerous historical and ongoing experimental ISM studies and proposed commercial ISM concepts, there is significant interest in ISM and a wide variety of design concepts and applications. However, achieving commercially viable ISM will require the correct combination of application area and manufacturing technology.

1.2 History of ISM

Although space-based assembly and integration has been practically performed during construction of Mir and the International Space Station (ISS), in-space fabrication has been largely limited to experimental investigation. Several historical programs have investigated the material science of manufacturing in-space. For example, in-space welding was performed on Soyuz 6 [47, 53]. Experiments on Skylab investigated electron beam welding, crystal growth, metal alloying, and brazing [72]. In the 1979, Grumman Aerospace completed ground testing of their Beam Builder concept capable of creating aluminum trusses in space [4]. Thin film semiconductors were produced in the orbital wake vacuum of the Wake Shield Facility flown on STS-60, STS-69, and STS-80 [24].

Recently on ISS, Made In Space completed its 3D Print Experiment and is currently operating the Additive Manufacturing Facility to produce both test articles and useful plastic components for ISS astronauts and commercial customers [48, 30]. In addition, the Tethers Unlimited Refabricator is scheduled to demonstrate plastic recycling on-orbit in 2018 [12]. Furthermore, ISS is planning to add metal 3D printing capabilities in the near future [49].

Beyond these ISS operations, there are several presently proposed ISM mission concepts. Made in Space’s Archinaut and Tethers Unlimited’s SpiderFab are two proposed free-flying facilities, where the spacecraft uses its additive manufacturing capability, robotic arms, and rendezvous and proximity operations to create struc-
tures in space [46, 21]. Tethers Unlimited is also currently developing its Trusselator for the manufacture of large, lightweight carbon fiber trusses. The Trusselator can be hosted on-board a customer spacecraft to create large baseline sensors or deploy flexible blanket solar arrays [22, 29]. The Space Systems Loral (SSL) Dragonfly is a spacecraft proposed to self-assemble its antenna reflectors on orbit and demonstrate ISM activities [35, 59]. Orbital ATK’s Commercial Infrastructure for Robotic Assembly and Services (CIRAS) will create large space structures through in-orbit manufacturing and assembly [43, 7, 36]. The recent Axiom Space Station concept envisions manufacturing as a main source of revenue [6].

Many ISM concepts require the delivery of components to customer spacecraft. Thus, any pursuit of ISM should be aware of historical and current on-orbit servicing mission concepts, which can help to develop key enabling technologies for ISM, such as autonomous operations, space robotic arms, and rendezvous and proximity operations. Completed on-orbit servicing missions include DARPA Orbital Express, Solar Maximum Mission, and Hubble Space Telescope servicing missions [33]. DARPA Phoenix also investigated on-orbit servicing related activities [13]. Current projects include DARPA Robotic Servicing of Geosynchronous Satellites (RSGS) and NASA Restore-L [14, 34].

1.3 Literature Review

After surveying the literature, several studies were found that conducted investigations regarding in-space manufacturing. Skomorohov provides a good assessment of ISM, but only performs qualitative analysis [54]. The Commercial Space Transportation Study investigated ISM applications, but largely limited itself to return-to-Earth products. Additionally, this study assumed an ISM facility cost and focused on the specific products and the sale price required to achieve the desired return on investment [9]. The National Research Council (NRC) "3D Printing in Space" study provides a good overview of the current state of additive manufacturing and ISM, a vision for future capabilities, and provides recommendations to NASA and USAF.
Regarding research investments. However, the NRC report did not perform quantitative analysis to justify plans for particular ISM applications or technologies [40]. Literature on detailed ISM facility designs, along with some performance metrics, exist for past, current, and proposed ISM facilities, such as the Grumman Aerospace Beam Builder, Made In Space Additive Manufacturing Facility, and Tethers Unlimited Trusselator [4, 30, 22]. These papers focus on the detailed design or performance of one type of ISM facility or application, but fail to address the question of which application or facility would be best.

1.4 Motivation

To fully capture the potential benefits of ISM, space systems must be designed to take advantage of their newly relaxed design constraints. Because existing launch-related design constraints have become ingrained in space system design, systematic thinking is necessary to explore all available design options under the new ISM paradigm. Failure to fully explore the new ISM design space could lead to missed opportunities for commercial ISM operations.

As seen by the numerous experimental ISM studies and proposed commercial ISM concepts, there is significant interest in ISM and a wide variety of proposed concepts and applications. Currently, ISM is at a point in its development where it is not immediately clear what ISM manufacturing technology or products will look like and what their benefits will be. This leads to significant uncertainty in future ISM facility cost and performance. Instead of attempting to estimate these highly uncertain quantities, a systematic analysis of ISM should bound the maximum allowable ISM facility cost and the minimum required performance to become cost-effective relative to the existing launched approach. These results can serve to levy requirements on commercially viable ISM facility design. This will provide insights into the design considerations for both ISM components and facilities.
1.5 Problem Statement

This thesis proposes to analyze the trade space of ISM applications and technologies to answer the research question: "What are the key system drivers and ISM facility properties for an ISM operation that surpasses current launch alternatives in cost or performance?" This research question can be decomposed into the following objectives:

1. Develop an ontology to systematically discuss ISM application areas
2. Determine the properties that make a system commercially viable for ISM operations
3. Bound the required ISM technology development in cost and capability required for commercially viable ISM operations
4. Establish screening metrics for evaluation of proposed ISM applications, technologies, and facility concepts

This thesis will present a framework to determine the most promising ISM application areas and set technology targets for commercially viable operations in those areas. This involves performing quantitative analysis for various ISM applications and design choices. These technology targets can be used for preliminary design of a commercial ISM facility.
Chapter 2

Methodology

2.1 Overview

This thesis aims to present a framework with which one can evaluate the commercial viability of proposed ISM facility concepts in a changing landscape of potential ISM application areas. The process presented allows for identification of the cost and performance targets beyond which ISM surpasses the current launch approach. The methodology applied in this thesis is outlined in Figure 2-1.

2.2 From Relaxed Constraints to Generalized Classes

The first step in this thesis is the development of generalized classes of ISM applications, which is presented in Chapter 3. These generalized classes will only prove useful for informing technology development if they (1) are collectively exhaustive of all known, and unknown ISM concepts and (2) allow for detailed analysis to identify key parameters and metrics for commercial viability of any ISM concept that may fall into that class. For these reasons, the generalized classes were developed by first identifying the design constraints existing under the current launch paradigm using references such as launch vehicle payload user guides. These constraints were then compared to the design constraints existing when ISM is used, which are based on knowledge of the space environment. Constraint categories were then formed for each
Figure 2-1: This thesis roadmap presents the methodology used to develop technology targets for commercially viable ISM. First, the design constraints for the existing launch approach and for ISM are determined and compared. Based on the constraint categories relaxed by ISM, a set of generalized classes of ISM applications is formulated into which historical, current, and future ISM concepts can be mapped. Commercial viability for generalized classes hinges upon the relationship between allowable facility cost and actual realized ISM facility cost. Detailed analysis of this commercial viability in two of the generalized classes is then conducted. This process involves developing a cost model that captures the potential cost savings when using ISM and/or predicting the performance benefit of ISM. This modeling is used to evaluate proposed concepts, identify key system drivers, which include nondimensional parameters found through Buckingham Pi theorem, and inform technology development.
instance where ISM relaxes design constraints relative to launch. Any commercially viable ISM concept must necessarily take advantage of one of these relaxed constraints. Thus, a collectively exhaustive classification can be developed by formulating the generalized classes from the constraint categories. This classification was then validated by mapping existing ISM concepts into the generalized classes. However, its applicability is not just limited to existing ISM concepts because the classes were formulated without regard for existing concepts. These generalized classes are useful in this analysis because they allow for abstraction of the problem to allow for detailed analysis of classes of ISM concepts, instead of having to conduct detailed analysis for every possible ISM concept.

2.3 Cost Modeling for ISM Concepts

In order to assess commercial viability of ISM concepts, a technique had to be developed for cost modeling of generalized classes of ISM applications, as detailed in Chapter 4. While cost estimating relationships (CERs) exist for current space systems, it is infeasible to use or develop statistical cost estimating relationships for ISM components or ISM facilities because of the lack of historical commercial operations. It would be ill-advised to attempt to estimate the highly uncertain cost of a future ISM facility because, at this point, it is still unclear which ISM applications are best and which manufacturing processes will be used.

Instead of attempting to estimate ISM facility cost in the above way, the concept of allowable facility cost is developed, which is the maximum development effort that can be expended by a company pursuing ISM in order to breakeven. This allowable facility cost is determined through bottom-up cost estimating in each generalized class to capture the impact of key factors on the lifecycle cost of ISM components relative to launched components. When ISM components have significant cost savings, or revenue gains, relative to existing launched components, then that particular ISM

*In many cases, ISM also adds new constraints. In particular, constraints are often added due to the limitations of the manufacturing equipment and remote operations.
concept has a high allowable facility cost. This approach allows for evaluation of commercial viability of ISM concepts (by comparing allowable facility cost to the actual realized ISM facility cost) while still allowing for flexible interpretation of how much the ISM facility actually costs and how much government investment is provided in support of the endeavor. Examples are presented of how this flexible interpretation can be performed by established a formulation for expected realized ISM facility cost, which is based on the Unmanned Spacecraft Cost Model, version 8 (USCM8) and the Mission Operations Cost Estimation Tool (MOCET), and showing the sensitivity to mass production of ISM facilities with learning curve effects as well as to the level of government investment. With this approach, the allowable facility cost can be used as a measure of the strength of ISM concepts in any of the generalized classes. The true potential of an ISM concept will depend on the margin between the expected actual facility cost and the allowable facility cost. In this way, allowable facility cost can be used as a screening metric to evaluate the commercial viability of a newly proposed ISM concept.

2.4 Case Studies of Generalized Classes

The formulated generalized classes of ISM applications are used to guide subsequent detailed analysis. In particular, two of the generalized classes were selected as case studies for detailed evaluation of commercial viability (see Chapter 5 and Chapter 6). The generalized classes were quantitatively analyzed in comparison to the existing launch paradigm to identify breakeven points and the impact of key system parameters on the requirements for commercial viability of an ISM facility. The results of this analysis serve to bound the required ISM facility development, both in terms of maximum allowable cost and minimum performance, for commercially viable operations. With key system drivers identified, existing proposed ISM concepts will be evaluated for commercial viability and the most promising ISM applications will be determined. This same process, as described below, can be applied to any of the generalized classes developed.
By defining the scope of concepts pertaining to a given generalized class, a parametric formulation for allowable facility cost within that class was developed. This involved developing a cost model that captures the potential cost savings when using ISM relative to launch and/or predicting the revenue generated through improved performance of ISM relative to launch. By design, any ISM concept within the generalized class can be described, regarding its allowable facility cost, using the identified parameters. Using the expression for allowable facility cost, trends and insights are reported with regards to the impact of input parameters on allowable facility cost. Then, the input parameters are evaluated for various example cases of ISM. This allows the ISM concepts to be evaluated for commercial viability (i.e. a high allowable facility cost) to show which concepts are better and to report any interesting findings. These results can also show how much technology development is needed in this generalized class in order to increase allowable facility costs to acceptable levels, given some expected realized ISM facility cost and level of government investment. This technology development can take the form of either improving the value of input parameters for existing concepts or developing technology for entirely new concepts with more favorable input parameter values. The sensitivity of results to parameters beyond the control of ISM facility technology, such as launch costs, is also evaluated. Lastly, specifications, such as size, weight, power, and production rate, for some actual ISM facility hardware that has been developed or proposed is reported. Consideration of this hardware provides insight into the current state of ISM technology and gives an idea of the performance and scale of production, which can serve as a proxy for expected cost.

Within the analysis, the expression for allowable facility cost is nondimensionalized to identify physically relevant key system drivers. This nondimensionalization is significant because, according to the Buckingham Pi theorem, these key nondimensional parameters will still be relevant regardless of the functional form of the cost model used, as long as the correct input variables were considered. Thus, even if simplifying assumptions are made in the cost modeling in this thesis, the resulting nondimensional parameters would still be expected to apply when higher-fidelity cost
models are developed in later work. Additionally, nondimensionalizing the results reduces the number of independent variables to plot and also allows for industry readers to easily interpret the model nondimensional result using their own proprietary data. Nevertheless, in some cases, the results are still presented in dimensional form to explore the sensitivity to particular parameters.
Chapter 3

Formulation of Generalized Classes of ISM Applications

3.1 Constraint Comparison and Categorization

When considering ISM designs, it takes significant effort and a systematic thought process to produce designs that are free from the launch paradigm constraints that have ingrained themselves in modern space system design. To aid systematic thinking about potential ISM applications, we consider the constraints typically imposed on launched components and identify the change in those constraints when ISM is used. Constraints related to operation in the space environment, which includes the impact of radiation, atomic oxygen, thermal radiation, vacuum, micrometeoroids, and microgravity, will remain in place regardless of whether ISM is used or not [16]. New constraints will inevitably appear through the use of ISM, particularly regarding the capabilities of the ISM technology. However, many typical launched component constraints, such as those driven by the launch vehicle, remote operations, and Earth gravity, are significantly relaxed when ISM is used. The relaxation of these constraints is described and categorized in Table 3.1. This categorization forms the basis of the subsequent analysis of generalized classes of ISM applications. The tradeoff between the benefits of the relaxed constraints and the newly imposed constraints will be explored throughout this thesis.
Table 3.1: Constraint Categorization for Launch and ISM Paradigms

<table>
<thead>
<tr>
<th>Generalized Class</th>
<th>Constraint Category</th>
<th>Launch Paradigm Constraint</th>
<th>ISM Paradigm Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structurally Optimized Systems</td>
<td>Structural Loads</td>
<td>Launch, transportation, AI&amp;T, deployment, and in-space operational loads</td>
<td>In-space operational loads</td>
</tr>
<tr>
<td>Larger-than-Launchable Systems</td>
<td>Volume</td>
<td>Launch vehicle fairing volume</td>
<td>ISM fabrication volume</td>
</tr>
<tr>
<td>Earth-Return Systems</td>
<td>Environmental Conditions</td>
<td>Manufacturing in 1 g, atmospheric pressure</td>
<td>Manufacturing in microgravity, near perfect vacuum</td>
</tr>
<tr>
<td>Repairable Systems</td>
<td>Reliability &amp; Redundancy</td>
<td>Mission life drives required component reliability and redundancy</td>
<td>Mission life drives required spare parts manufacture and on-orbit servicing, which are limited by available feedstock and manufacturing capability</td>
</tr>
<tr>
<td>Recycling Orbital Debris as Feedstock</td>
<td>De-orbiting</td>
<td>At end of life, perform controlled reentry, uncontrolled reentry, or move to graveyard orbit</td>
<td>At end of life, become recyclable material source in orbit</td>
</tr>
<tr>
<td>On-Demand Manufactured Systems</td>
<td>Resupply Time</td>
<td>Launch windows, launch delays, launch schedule, and orbital transit times</td>
<td>Availability of feedstock and manufacturing equipment, production rate, delivery from manufacturing to use location</td>
</tr>
<tr>
<td>Accurately Tested Systems</td>
<td>Verification and Validation</td>
<td>Stringent pre-launch testing in simulated space environment</td>
<td>Manufacturing, check-out, and operation all in the space environment; challenges of autonomous V&amp;V; ability to quickly space-qualify new designs</td>
</tr>
<tr>
<td>Planetary Surface Systems</td>
<td>Total Mass</td>
<td>Launch vehicle payload capacity to LEO and gear ratio to final orbit</td>
<td>Available raw material stock is either from launch, recycling, or ISRU</td>
</tr>
</tbody>
</table>
3.2 Generalized Classes of ISM Applications

Table 3.1 showed the constraint categories that are used to form a set of generalized classes of ISM applications that capitalize on a particular relaxed constraint as a competitive advantage over the existing launch paradigm. These generalized classes are briefly described in Table 3.2, which also shows example concepts that fall in each class. A listing of all Small Business Innovation Research (SBIR) projects related to ISM, along with their mapping into the generalized classes, is provided in Table A.3. The following sub-sections provide a more in-depth description of each generalized class and its associated constraint category, the impact of the constraint on both the launch and ISM paradigm, and the possible avenue for application of ISM in light of the relaxed constraint. Examples of historical and proposed ISM concepts in each generalized class are provided. The generalized classes presented below will form the framework for subsequent analysis.

3.2.1 Structurally Optimized Systems

Spacecraft are often designed for a multi-year life, over which only about ten minutes are subjected to launch loads. However, this short journey to orbit aboard a launch vehicle is typically the driving structural design constraint on spacecraft. After enduring the strenuous ride to orbit, a spacecraft spends the rest of its operation life in the relatively structurally benign in-space environment (see Table 3.3). The reported values for launch loads are based on data from payload user guides for existing launch vehicles. The complete loading data set for these vehicles can be found in Table A.2.

Some of the primary loading environments on a spacecraft are quasi-static acceleration, sinusoidal vibration, acoustics, and shock. Quasi-static acceleration typically peaks at stage burnout, when the engine is still providing nearly constant thrust but the mass of the launch vehicle, having consumed all of its propellant, is now at a minimum. The time history of quasi-static acceleration for a typical launched spacecraft (see Figure 3-1) is quite telling with regards to the orders of magnitude difference in acceleration and duration for which a spacecraft experiences launch loads com-
<table>
<thead>
<tr>
<th>Generalized Class</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structurally Optimized Systems</td>
<td>Fabrication of lighter structures that only need to survive in-space loading</td>
<td>TUI Trusselator, MIS Archinaut, Grumman Beam Builder</td>
</tr>
<tr>
<td>Larger-than-Launchable Systems</td>
<td>Fabrication of large structures that no longer need to fit inside launch vehicle fairings</td>
<td>TUI SpiderFab, MIS Archinaut, Orbital ATK CIRAS, Convair SCAFEDs, Grumman Beam Builder</td>
</tr>
<tr>
<td>Earth-Return Systems</td>
<td>Fabrication of products that require some unique aspect of the space environment, i.e. micro-gravity or ultravacuum</td>
<td>MIS Fiber, MIS Industrial Crystallization Facility, ACME SiC, Wake Shield Facility, Skylab</td>
</tr>
<tr>
<td>Repairable Systems</td>
<td>Fabrication of replacement components for failed systems on-orbit</td>
<td>MIS 3D Print Experiment, MIS Additive Manufacturing Facility</td>
</tr>
<tr>
<td>Recycling Orbital Debris as Feedstock</td>
<td>Recover components and feedstock from defunct spacecraft for use as an alternative to launched mass</td>
<td>DARPA Phoenix, Northrop Grumman Space Recycler, MIS EAGLE</td>
</tr>
<tr>
<td>On-Demand Manufactured Systems</td>
<td>Fabrication of components, i.e. spare parts, in a responsive way without the need for a cache of spare parts or the delay of waiting for a launch and orbital transfer of components</td>
<td>MIS 3D Print Experiment, MIS Additive Manufacturing Facility, MIS Vulcan</td>
</tr>
<tr>
<td>Accurately Tested Systems</td>
<td>Fabrication of components that can be tested and calibrated in the orbital environment in which they will be used</td>
<td>N/A (No existing concepts were found in this application area)</td>
</tr>
<tr>
<td>Planetary Surface Systems</td>
<td>Fabrication of components using locally available raw material, either through ISRU or recycling of on-board components</td>
<td>TUI Refabricator, MIS Plastic Recycling System, Altius ISP3</td>
</tr>
</tbody>
</table>
pared to in-space loads. The sine vibration environment is driven by low frequency structure-borne vibrations in the launch vehicle, which are often caused by an imbalance in rotating turbomachinery. Acoustic loading is manifested as high frequency broadband vibration, which is significant when the vehicle is transonic and is maximum at liftoff. A shock environment is experienced as a brief, broadband vibration due to impulse loading, such as stage separation, fairing separation, and spacecraft deployment [69].

With ISM, a component is built and operated in space, so it spends its entire life merely subjected to in-space loads. These in-space loads are, in general, much more benign than the launch loads. However, the exact in-space loads depend on the spacecraft and its mission profile. For example, all spacecraft will experience small accelerations due to orbital perturbations, such as aerodynamic drag and solar radiation pressure, as well as due to orbital eccentricity. However, some spacecraft will experience higher acceleration due to thruster firings, spin stabilization, or entry, descent, and landing operations. A key factor determining the acceleration experienced on orbit is whether high thrust chemical propulsion or low thrust electric propulsion is used. Additional in-space loads, such as plume impingement, thermal snap, pressurization, reaction wheel imbalance, and deployment events, must also be considered. These sources of in-space loads can be seen to limit the potential applications of structurally optimized systems, or can be thought of as informing the design choices for a spacecraft that uses structurally optimized systems.

ISM can achieve significant mass savings through structural optimization in cases where in-space loads are significantly reduced over launch loads. For example, Tethers Unlimited seeks to use its Trusselator concept to capitalize on the possibility of using ISM to create structurally optimized trusses for spacecraft solar arrays and long baseline sensors. The potential mass savings is fundamentally limited by the degree to which loads are reduced on-orbit, as well as the degree to which the original component’s mass is driven by structural loading.
Table 3.3: Comparison of Launch and In-Space Loading Environment

<table>
<thead>
<tr>
<th>Loading Type</th>
<th>Launch Loads</th>
<th>In-Space Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-Static</td>
<td>3.7 to 6.6 g</td>
<td>Drag: $10^{-7}$ g</td>
</tr>
<tr>
<td>Acceleration</td>
<td></td>
<td>Gravity gradient: $0.3 \times 10^{-6}$ g/m [15]</td>
</tr>
<tr>
<td>Sine</td>
<td>5 Hz: 0.5 to 1 g</td>
<td>&lt;6 Hz: $8.4 \times 10^{-6}$ g RMS [15]</td>
</tr>
<tr>
<td>Vibration</td>
<td>100 Hz: 0.8 to 1 g</td>
<td>100 Hz: $1 \times 10^{-3}$ g RMS [15]</td>
</tr>
<tr>
<td>Acoustics</td>
<td>130.8 to 144.7 dB OASPL</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

Figure 3-1: Time history of quasi-static acceleration for a launched spacecraft. The data shown is taken from a Falcon 9 launch webcast, and the data for orbit is modeled as aerodynamic drag on the spacecraft. The acceleration experienced by a spacecraft during launch is orders of magnitude higher than the acceleration it will experience while on orbit. Additionally, the duration of in-space loading is orders of magnitude longer than that of launch loading. Thus, in-space loads are relatively benign and make up the overwhelming majority of a spacecraft’s operational life.
Table 3.4: Target Size for Desired Component Performance

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Arrays</td>
<td>Power generated: $P = n_{cells}I_dL_d\Phi_{solar}A\cos(\theta)$</td>
<td>$A \approx 1,500 \text{ m}^2$ for $P = 300 \text{ kW}$</td>
<td>HEOMD Solar-EP Missions</td>
</tr>
<tr>
<td>Antenna Reflectors</td>
<td>Gain: $G = \eta\left(\frac{e\Lambda}{D}\right)^2$</td>
<td>$D &gt; 10 \text{ m}$</td>
<td>SWOT, ONEP, ACE, SCLP, Mars-28, Mars 30</td>
</tr>
<tr>
<td>Optics</td>
<td>Angular resolution: $\theta_r \approx 1.22\left(\frac{\lambda}{D}\right)$</td>
<td>$D &gt; 8 \text{ m}$</td>
<td>Extremely Large Space Telescope (EL-ST), TPF-C</td>
</tr>
<tr>
<td>Trusses</td>
<td>Fundamental frequency of first free-free bending mode:</td>
<td>$L = 20 \text{ to } 500 \text{ m}$ with $f_n &gt; 0.1 \text{ Hz}$</td>
<td>Structure-Connected Sparse Aperture, TPF-I, SPECS</td>
</tr>
<tr>
<td>Radiators</td>
<td>Radiative power: $Q_{rad} = \sigma\epsilon A(T_{rad}^4 - T_{space}^4)$</td>
<td>$A \approx 6,000 \text{ m}^2$ for $Q_{rod} = 2 \text{ MW}$</td>
<td>HEOMD Nuclear-Electric Missions</td>
</tr>
<tr>
<td>Solar Sails</td>
<td>Thrust: $F = \frac{\Phi}{e}\cos(\theta)$</td>
<td>$A &gt; 1,000 \text{ m}^2$</td>
<td>Solar Sail Space Demo, Interstellar Probe</td>
</tr>
</tbody>
</table>

### 3.2.2 Larger-than-Launchable Systems

Large structures are often desired for spacecraft subsystems where performance scales with size. For example, larger solar arrays generate more power, larger antenna reflectors have higher gain, larger optics have better diffraction-limited angular resolution, longer trusses enable larger baseline sensors, larger radiators can reject more heat, and larger solar sails produce a larger force due to solar radiation pressure. The governing equations relating size to performance for these systems, along with current subsystem targets for size, are reported in Table 3.4.

The launch vehicle fairing volume constraint limits the maximum size of launched components. At present, the largest launch vehicle fairing diameter is 5.4 m on the Ariane 5 ECA. Once operational, the Space Launch System will claim the largest diameter fairing at 8.4 m, followed by the proposed New Glenn vehicle at 7 m. The
Figure 3-2: This figure details the potential method by which an on-orbit capability can be achieved, as a function of the desired length on-orbit and the stowed volume of the component. The niche for ISM within the larger-than-launchable systems class is for systems requiring deployed lengths larger than existing deployables, but with raw material stowed volumes below fairing volume constraints. Extremely large structures are ultimately limited by the fundamental frequency of the resulting structure, which must be kept high enough to avoid adverse interaction with the spacecraft’s attitude control system.

The longest fairing length is 26.5 m, which is currently offered by the Atlas V 5 m Extra Extended Payload Fairing [10]. A listing of fairing dimensions for other launch vehicles is reported in Table A.1.

If fixed components are launched, the scale is limited by the fairing dimensions. Deployment mechanisms enable larger-than-fairing dimensions, but add complexity and must be designed and tested to ensure reliable operation after launch. The largest truss deployed to date is the 60 m Able Deployable Articulated Mast (ADAM)
Figure 3-3: Fixed, deployable, and in-space assembled components and spacecraft are seen to be distinguished by their stowed volume and longest deployed dimension in relation to launch vehicle fairing dimensions. In-space manufacturing presents opportunities to push into larger dimensions while still keeping stowed volume below existing fairing constraints.
on the Shuttle Radar Topography Mission (SRTM). The largest inflatable structure deployed is the Echo 2 spacecraft, which was a 41 m diameter sphere. When ISM is used, no deployment mechanisms are required even for components that achieve much larger deployed lengths than possible under the existing launch paradigm. ISM can achieve these larger dimensions because the parasitic mass and volume of the deployment mechanism is eliminated. In addition, the raw material for fabrication can be packaged much more compactly than in its stowed deployable state.

In-space assembly is another approach that can be used for emplacement of large systems, oftentimes larger than existing deployables, in orbit. In-space assembly, which was performed during the construction of Mir and the ISS, is necessary when the final structure has a mass or stowed volume larger than the capability of existing launch vehicles. These operations necessitate multiple launches with subsequent assembly and integration in orbit, but do not involve fabrication in orbit. With the use of ISM, large structures that would have otherwise required in-space assembly can potentially fit within existing launch vehicle fairing constraints. This is because the bulk raw material for ISM will package according to its density, which is much more compact than existing spacecraft components or deployables can be packaged. However, in-space assembly would still be needed if the raw material has a volume larger than the fairing or if the final structure in orbit has a mass larger than the available single-launch capability.

Additive manufacturing is often found appealing for ISM. Although conventional Earth-based 3D printers typically can only produce parts smaller than their internal volume, there exist concepts capable of producing parts larger than the manufacturing equipment itself. Some notable examples include the historical Grumman Beam Builder and Convair Space Construction Automated Fabrication Experiment Definition Study (SCAFEDS) concepts, as well as currently proposed concepts such as the Made In Space Archinaut and the Tethers Unlimited Trusselator and SpiderFab. In addition, there are manufacturing methods other than additive manufacturing, such as extrusion, that can produce parts larger than the machine volume.
Table 3.5: Unique Features of the Space Environment

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Space</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultravacuum</td>
<td>$10^{-7}$ Torr in LEO</td>
<td>760 Torr</td>
</tr>
<tr>
<td></td>
<td>$10^{-14}$ Torr in LEO orbital wake</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-15}$ Torr halfway to the Moon</td>
<td></td>
</tr>
<tr>
<td>Microgravity</td>
<td>Drag: $10^{-7}$ g</td>
<td>$1$ g</td>
</tr>
<tr>
<td></td>
<td>Gravity gradient: $0.3 \times 10^{-6}$ g/m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vibration: $8.4 \times 10^{-6}$ g RMS</td>
<td></td>
</tr>
<tr>
<td>Solar Flux</td>
<td>1367 W/m²</td>
<td>550 W/m² to 1,025 W/m²</td>
</tr>
<tr>
<td>Temperature</td>
<td>40 K (passive)</td>
<td>184 K to 330 K</td>
</tr>
<tr>
<td></td>
<td>Deep Space: 2.7 K</td>
<td></td>
</tr>
</tbody>
</table>

### 3.2.3 Earth-Return Systems

Earth-based manufacturing occurs in a 1-g environment at atmospheric pressure, whereas ISM would occur in a nearly 0-g environment with access to extremely low pressures, if needed. This unique manufacturing environment could enable completely new manufacturing methods that are not possible on Earth, and also enable the fabrication of high-value products that can be made better in space. Table 3.5 shows some of the unique features of the space environment that could potentially be utilized for manufacturing.

Regarding particular manufacturing methods, 3D printers could benefit from microgravity by eliminating the need for support material on overhanging features and by enabling the use of multiple print heads around a part suspended in the middle of the machine, thus allowing faster build times [40]. The lack of natural convection in microgravity can also be exploited to enable more even cooling of parts, which can aid in crystallization. Microgravity can also allow for new alloys to be formed that would otherwise separate due to differences in specific gravity in their molten state under Earth-gravity conditions. The possibility of producing higher quality parts through ISM, augmented by the potential use of ISM-specific methods, opens an interesting possibility of applying ISM to build components in space for return to Earth, where they can be sold and used.
The interest in ISM of high-value products for return to Earth has a rich history. Experiments on Skylab focused on metallurgy, composite preparation, and welding processes. The first product made in space for sale on Earth was monodisperse latex particles made on STS-6 [28]. Later, the Wake Shield Facility utilized the orbital wake vacuum to perform thin film epitaxy on-orbit [24]. Recently, Made In Space has launched an optical fiber manufacturing capability to the ISS [55]. Prior research has indicated that ZBLAN fiber optic cable fabricated in microgravity exhibits fewer impurities than fiber manufactured on Earth [11]. Another example of a high-value product that requires microgravity fabrication is silicon carbide wafers, which are currently being pursued by ACME Advanced Materials [3].

3.2.4 Repairable Systems

A spacecraft typically reaches its end of life either due to limited propellant or due to component failure. To protect against premature end of life, components are designed with high reliability, and oftentimes redundancy as well. This stems from the launch paradigm precluding, except for in the most extreme circumstances, the repair or replacement of components in orbit. Thus, spacecraft often require functional redundancy to avoid the loss of their space assets. This high reliability and redundancy comes at a high cost, both in dollars and mass. With ISM, the component reliability constraint can be relaxed (while still ensuring the same system reliability) through the fabrication of in-orbit spares on demand. However, the ability to manufacture these spares is limited by the available feedstock mass and the ISM capabilities.

3.2.5 Recycling Orbital Debris as Feedstock

Under the current paradigm, responsible orbital operations are driven by the 25-year rule for de-orbit of spacecraft. Orbital debris removal is also an active field of research to combat the growing debris population. The risk due to orbital debris is a serious concern and could lead to a cascade effect rendering space unusable, in a Kessler Syndrome situation, if left unchecked. ISM presents an interesting opportunity because it
Figure 3-4: As of February 2018, there is about 7.7 million kg of mass in Earth orbit and the number is growing. This mass largely consists of spacecraft and rocket bodies, which could potentially be scavenged for parts or raw materials. Just by applying existing launch costs to LEO (~$10,000/kg) to the mass currently in orbit, we find that the orbiting mass has a value of $77B. By recycling orbital debris, this type of ISM operation would also be serving as an active debris removal system, which would help reduce the risk of orbital debris and potentially act as an additional source of revenue for the ISM operation. This figure is taken from [39].

allows for the recycling of the large amount of mass in orbit (see Figure 3-4) from defunct satellites, rocket bodies, and orbital debris. This provides the benefit of cheaply acquired mass already in orbit, which eliminates the launch cost associated with that mass, while simultaneously reducing the orbital debris population. Additionally, the spacecraft that did not need to expend its propellant to de-orbit can get additional operational life (and revenue) because it knows it does not need to de-orbit, since it will be recycled. An important consideration for this ISM application is the accessibility of the mass on orbit and its proximity to the desired final orbit, which is shown in Figure 3-5.
Figure 3-5: The total effective mass at various orbital altitudes is shown. For most effective orbital debris recycling, the ISM application should acquire the mass in the orbit in which it will ultimately be used. Presently, there is about 2.7 million kg available in LEO, 1.8 million kg in MEO, 1.6 million kg in GEO, and 0.6 million kg in GEO graveyard orbits. Because launch costs to GEO are higher (~$36,000/kg) than LEO (~$10,000/kg), the mass in GEO has a higher value than that in LEO. Additionally, the mass in GEO is confined to a smaller range of orbital planes than in LEO.
3.2.6 On-Demand Manufactured Systems

Extended human presence in space on ISS has been enabled through regular resupply from Earth. Even with an ISS logistics strategy in LEO, the ability to manufacture spare parts on-orbit when needed has the potential to significantly reduce cost and spares logistics mass. In addition, as efforts are made to pursue extended duration deep space missions, the importance of on-demand manufacture of spare parts becomes even more important because the mission endurance, or maximum time between resupply opportunities, increases. Under the current launch paradigm, resupply is constrained by launch windows, transit times, and the inevitable schedule delays and overload of launch service providers. With on-demand ISM, the time to deliver components is a function of the manufacturing production rate, manufacturing queue, and the time to deliver completed components from the ISM facility to the needed location. However, the ability of ISM to produce needed components is limited by the available feedstock and the manufacturing technology used. Made In Space has made great strides through its 3D Printing in Zero-G Technology Demonstration and its currently operating commercial Additive Manufacturing Facility [48, 30]. Both of these concepts have developed additive manufacturing technology for on-demand manufactured systems.

3.2.7 Accurately Tested Systems

Spacecraft are typically subjected to rigorous testing prior to launch to ensure reliable operation in the space environment. This is performed both to validate the design, via qualification testing, and to assess the manufacturing quality of the flight unit, via acceptance testing. One of the challenges with testing is the simulation of the space environment. Thermal vacuum chambers are used to simulate the vacuum and thermal environment of space. Deployment mechanisms are tested using gravity off-loading devices to simulate the microgravity environment in which deployment will occur. Sometimes, drop tests are conducted in vacuum chambers to simulate vacuum and microgravity conditions. However, the test results are limited by both
the accuracy achieved in representing the space environment, as well as the fact that, between testing and operation, the spacecraft will be subjected to a strenuous rocket launch. Thus, it is possible that damage could occur during launch after which testing cannot identify and correct problems, as it can on the ground.

If ISM is used, components are built and testing in the actual space environment in which they will then be used. Additionally, no launch loads are endured between testing and operation. In this way, ISM opens the possibility to more accurate testing. ISM also opens the possibility for rapid space-qualification of new prototypes in orbit. However, performing autonomous verification and validation in orbit presents a significant challenge for ISM and should not be overlooked.

3.2.8 Planetary Surface Systems

Regardless of whether the launch paradigm or ISM paradigm is used, the mass for components must come from somewhere. In the launch paradigm, the available mass is limited by the maximum launch vehicle payload mass, as well as the gear ratio to reach the destination orbit, which is driven by the rocket equation. At present, the maximum single-launch mass is 63.8 mT to LEO and 26.7 mT to GTO on SpaceX’s Falcon Heavy [10]. A complete listing of launch vehicle payload mass capability for other vehicles, including planned vehicles, such as the Space Launch System with a payload to LEO of up to 130 mT, can be found in Table A.1. The use of ISM expands the mass source from solely Earth launch to also include recycling of components and the use of in-situ resources. Recycling allows for the repurposing of mass throughout a journey, while ISRU can eliminate both the Earth launch and gear ratio constraints, which significantly increases the available mass and reduces the cost of that mass. For ISM to use these new mass sources, material recycling and ISRU mining technology will need to be developed. One example where this work has begun is the Tethers Unlimited Refabricator, which can recycle components into feedstock for additive manufacturing.

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1 This is the limit for a single launch. Multiple launches could be used, but then in-space assembly will be required.
3.3 Overlap between Generalized Classes

For the generalized classes of ISM applications presented above, the question arises as to whether the classification is both exhaustive and mutually exclusive. This is a critical consideration for determining whether these generalized classes can be used for conducting detailed analysis and informing decisions for ISM technology development.

This classification is, in fact, expected to be collectively exhaustive of all potential ISM application areas. This means that at least one of the generalized classes applies to any conceivable ISM concept. This claim has been validated, at least for known concepts, by showing that known ISM concepts (including historical, current, and proposed concepts) can be adequately classified according to the generalized classes. Selected examples of ISM concepts are shown in Table 3.2 with their mapping into the generalized classes. The complete listing of known SBIR ISM concepts, along with their mapping into the generalized class framework, is presented in Table A.3. Beyond known ISM concepts, the generalized classes are expected to be collectively exhaustive even for yet-to-be-considered ISM concepts. This is because the generalized classes were not developed based on known concepts, but instead were developed based on fundamental differences in constraints between the launch and ISM paradigms. Thus, the applicability of the classes is not expected to be limited to just known concepts. Additionally, any future proposed commercially viable ISM application must necessarily take advantage of at least one of the relaxed design constraints. If an ISM application did not take advantage of a relaxed design constraint, then it may not fit within any of the generalized classes. However, this sort of ISM application would never be able to provide improved cost or performance over existing launched alternatives and, thus, would not prove commercially viable. The question of collective exhaustiveness of generalized classes for yet-to-be-considered ISM concepts then becomes a question of whether all of the relaxed constraint categories have been considered. It is claimed that Table 3.1 is a complete listing of relaxed constraint categories. If a new constraint category were to be found, it would then need to be added there as a new generalized class. However, no such constraint category
### Table 3.6: Effect of ISM Concepts Operating in Multiple Generalized Classes

<table>
<thead>
<tr>
<th>Generalized Classes</th>
<th>Concept</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larger-than-Launchable and Structurally Optimized Systems</td>
<td>Fabricate large, lightweight components</td>
<td>Structural optimization aids the ability to build large structures by reducing the required feedstock mass and volume such that it can fit on the launch vehicle. Additionally, reducing structural mass helps to keep the fundamental frequency of the large structure above the minimum limit.</td>
</tr>
<tr>
<td>Planetary Surface and Structurally Optimized Systems</td>
<td>Fabricate lightweight components using either recycled or in-situ feedstock</td>
<td>By acquiring mass other than through launch, the component produced by ISM can actually be heavier than the launched alternative and still provide net benefit.</td>
</tr>
<tr>
<td>Planetary Surface and On-Demand Manufactured Systems</td>
<td>Fabricate components on-demand using recycled or in-situ feedstock</td>
<td>Spares logistics mass can be reduced by fabricating only the parts that are needed, when they are needed. Recycling failed parts into feedstock for spares fabrication saves even more mass.</td>
</tr>
</tbody>
</table>

is thought to exist.

The generalized classes are clearly not mutually exclusive. There exist several known ISM facility concepts that fall into multiple generalized classes (see Table 3.2 and Table A.3). For example, the TUI Trusselator produces both structurally optimized and larger-than-launchable trusses. As another example, the TUI Refabricator accomplishes on-demand manufacturing by first recycling material into feedstock. ISM concepts such as these, which operate in more than one generalized class, can produce interesting benefits, as shown in Table 3.6. However, the case studies presented in this thesis will only consider one generalized class at a time. The analysis can later be adapted to identify commercial viability of ISM concepts that operate within multiple generalized classes, meaning that they take advantage of multiple relaxed design constraints compared to the launched alternative.
3.4 Detailed Analysis of Generalized Classes

Using the generalized classes formulated above, the design space for ISM applications can be explored. In this thesis, a method for determining commercial viability of ISM facility concepts will be presented. The method will be applied in a case study for the class of Structurally Optimized Systems and for the class of Earth-Return Systems. Detailed analysis of other generalized classes of ISM applications, such as for the class of Planetary Surface Systems and Larger-than-Launchable Systems, is left for future work. However, the method used in this thesis is applicable to any of the generalized classes of ISM applications discussed above.
Chapter 4

Cost Modeling for Generalized Classes of ISM Applications

4.1 Contributions to Lifecycle Cost

Throughout this study, the total system lifecycle cost, $C_{total}$, is estimated within various case studies. This lifecycle cost is the total cost required to provide a required capability. Under the conventional Earth-launch paradigm, this is simply composed of the required cost to manufacture and launch a component into orbit. However, under the new ISM paradigm, this lifecycle cost will include the development, manufacture, launch, and operations of an ISM facility, as well as the recurring cost for raw material and launching that raw material to fabricate a component on-orbit.

For each generalized class of ISM application, the lifecycle cost is decomposed into additive contributions. For example, the lifecycle cost could be thought of as the sum of the ISM facility cost, $C_{facility}$, and two other cost contributions, $C_1$ and $C_2$, for example. These cost contributions, in turn, can be expressed as functions of key driving input variables without expressing the functional form. The functional form can then be taken to be that of a typical cost estimating relationship (CER) where cost is proportional to a power of the mass of the fabricated component ($C = am^b$). Finally, in some cases, it is acceptable to make the linearizing assumption that cost is linearly proportional to the mass of the fabricated component. By building up the
cost model in this way, several insights can be garnered at each level, as shown in Table 4.1.

4.2 Allowable Facility Cost

Throughout this study, the idea of an allowable facility cost, $C_{\text{facility,allowable}}$, is developed. This allowable facility cost represents the maximum amount of money that can be spent developing, manufacturing, and operating an ISM facility such that the concept breaks even. This breakeven point is either based on the lifecycle cost savings achieved using ISM relative to the existing launch paradigm when providing similar performance, or through revenue generated by selling the ISM product with better performance than existing approaches.

For concepts that use ISM to produce similar components for cheaper than the current launch approach, the allowable facility cost is given as the facility cost at which the lifecycle cost under the ISM paradigm equals the lifecycle cost under the existing launch paradigm, i.e. $C_{\text{total,ISM}} = C_{\text{total,LV}}$. If the ISM capability can be achieved for cheaper than the allowable facility cost, then ISM will be preferred over the launch paradigm in this case. Otherwise, the current launch approach will prove to be a cheaper alternative. The existence of this breakeven point for a positive ISM facility cost requires that the quantity $C_1 + C_2$ is reduced when components are fabricated with ISM (denoted by a subscript ISM) compared to when they are fabricated under the current launch approach (denoted by a subscript LV). This can be expressed as follows:

$$C_{\text{facility,allowable}} \leq (C_{1,\text{LV}} - C_{1,\text{ISM}}) + (C_{2,\text{LV}} - C_{2,\text{ISM}})$$  \hspace{1cm} (4.1)

For concepts that use ISM to generate revenue by selling a product with better performance than currently available, the allowable facility cost is given as the facility cost at which revenue, $R$, equals cost, meaning that zero profit is earned. If the ISM capability can be achieved for cheaper than this allowable facility cost, then ISM will yield a net profit. Otherwise, there is not an incentive to perform ISM in this case.
Table 4.1: Insight Gained from Various Levels of Cost Model Fidelity

<table>
<thead>
<tr>
<th>Cost Model Formulation</th>
<th>Insight</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{total} = C_{facility} + C_1 + C_2$</td>
<td>Most general identification of mechanism for cost reduction through the use of ISM.</td>
</tr>
<tr>
<td>$C_{total} = C_{facility} + f(y_1, ..., y_n) + g(u_1, ..., u_n)$</td>
<td>Allows for identification of nondimensional groups through Buckingham Pi theorem without assuming a functional form for the cost model. These nondimensional groups serve as key metrics for ISM concepts regardless of the eventual functional form of the cost model.</td>
</tr>
<tr>
<td>$C_{total} = C_{facility} + a_1 m_1^{b_1} + a_2 m_2^{b_2}$</td>
<td>Nonlinear cost model formulation with respect to mass of fabricated components provides a more detailed cost prediction, albeit with additional assumptions regarding the functional form of cost model.</td>
</tr>
<tr>
<td>$C_{total} = C_{facility} + a_1 m_1 + a_2 m_2$</td>
<td>Linear cost model formulation with respect to mass of fabricated components provides simplest, yet most limited cost analysis. In some cases, it is safe to assume a linear cost model based on historical space system costs. The nondimensional quantities resulting from the linear formulation still hold for a general functional form through Buckingham Pi theorem.</td>
</tr>
</tbody>
</table>
This can be expressed as:

\[ C_{\text{facility, allowable}} \leq R_{ISM} - (C_{1,ISM} + C_{2,ISM}) \]  

(4.2)

Thus, instead of computing what an actual ISM facility would cost, this analysis finds the upper limit on what the maximum allowable facility cost could be for an ISM application to be commercially viable. This serves as an indicator of the strength of an ISM concept without having to make assumptions on the highly uncertain cost of future manufacturing technology and its associated costs. A concept with a very high allowable facility cost increases the likelihood that the ISM capability can be implemented, in practice, for less than that cost. The difference between the allowable facility cost and the actual facility cost can become profit, or it can provide margin for cost growth during ISM facility development. Thus, the best ISM concepts will have a high allowable facility cost, but will be able to be implemented for very low facility cost.

4.3 Realized ISM Facility Cost

Even though allowable facility cost is used throughout this thesis, it is important to gain insight into what the actual realized ISM facility cost will be once implemented. This allows for a determination of the steps that can be taken to ensure the actual facility cost comes in below the allowable facility cost for a particular concept. Potential ways to reduce the unit cost of an ISM facility include mass production, reducing the mass of the ISM facility, receiving government funding, and balancing the need for a high ISM production rate and a long operational life. The ISM facility cost is defined as the total cost required to develop, manufacture, launch, and operate an ISM facility. The unit facility cost, \( C_{\text{facility}} \), can be thought of as being composed of the following summation of costs:
As seen in the equation above, the cost of the ISM facility is made up of several factors. The research, development, test, and evaluation (RDTE) costs, $C_{RDTE,facility}$, and the theoretical first unit (TFU) cost, $C_{TFU,facility}$, are typically related through cost estimating relationships to increase with increasing spacecraft mass. If $N$ copies of the same ISM facility are produced, the RDTE costs for the program can be amortized over each facility while unit costs will be reduced based on the TFU cost and a learning curve effect. Figure 4-1 shows this reduction in per unit ISM facility cost as the number of facilities produced is increased. By including the launch cost of the facility, $C_{launch,facility}$ this formulation for $C_{facility}$ implicitly penalizes more massive facilities, which will incur higher launch costs when being placed in orbit. Additionally, placing an ISM facility in a higher orbit will also incur a higher launch cost. This launch cost term also accounts for the case where ISM facilities themselves could be used to build other ISM facilities. If the raw material for this manufacturing is launched, then the launch cost term remains unchanged. However, if recycled mass or in-situ resources are used for fabrication of the new ISM facility, then the launch cost would be adjusted according to the cost of acquiring that raw material mass. Operations costs of the ISM facility, $C_{ops,facility}$, are a fixed cost per unit time required to operate the spacecraft from the ground. Increased automation of the ISM facility can reduce the cost of operation. The additional research, development, testing, and evaluation (RDTE) required to validate new designs for spacecraft components that can be fabricated using ISM is captured in $\Delta C_{RDTE,ISM,components}$. This cost is present because ISM components will likely be modified to take advantage of the unique ISM constraints, which requires validation to space-qualify the designs. Even if an ISM facility were used to fabricate identical components to the existing launch paradigm, the use of this new manufacturing process would require validation. All of the above
cost contributions combine to give the total facility cost.

The facility cost, broken down into each of the cost contributions discussed, is shown in Figure 4-2 for varying facility mass, $m_{\text{facility}}$. The numerical value for each of the cost contributions was computed using available spacecraft cost models, such as the Unmanned Spacecraft Cost Model version 8 (USCM8) and the Mission Operations Cost Estimation Tool (MOCET), as shown in Table 4.2. The cost models used here are based on historical spacecraft data, which means that particular ISM facility concepts can, and likely will, have costs that differ from the prediction of these models and depend on factors other than just the mass of the facility, such as the power, production rate, and operational life of the ISM facility. However, this

1These factors will typically manifest themselves in the ISM facility mass. For example, fa-
Table 4.2: Cost Estimating Relationships for Each Cost Contribution

<table>
<thead>
<tr>
<th>Cost Contribution</th>
<th>Cost Estimating Relationship</th>
<th>Applicable Range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Recurring (RDTE)</td>
<td>FY2010 $108,000m_{facility}$</td>
<td>114 to 5,127 kg</td>
<td>USCM8 [68]</td>
</tr>
<tr>
<td>Recurring (TFU)</td>
<td>FY2010 $283,500(m_{facility})^{0.716}$</td>
<td>288 to 7,398 kg</td>
<td>USCM8 [68]</td>
</tr>
<tr>
<td>Launch</td>
<td>$10,000m_{facility}$</td>
<td>-</td>
<td>LEO launch costs</td>
</tr>
<tr>
<td>Operations</td>
<td>$987,000m_{months}$</td>
<td>-</td>
<td>MOCET [18]</td>
</tr>
</tbody>
</table>

calculation of the ISM facility cost is intended merely to show the general trend in how $C_{facility}$ is expected to grow as the mass of the facility becomes large, as well as to show the relative contributions of RDTE, TFU, launch, and operations costs to the total.

The commercial viability of an ISM concept rests upon the the relative values of $C_{facility, allowable}$, $C_{facility}$, and the level of government investment, as summarized in Table 4.3. When government investment, $C_{government}$, is provided, the required investment by a company hoping to pursue ISM, $C_{company}$, can be thought of as given by $C_{company} = C_{facility} - C_{government}$. An inherently commercially viable ISM concept would have a positive allowable facility cost that is greater than the actual facility cost. If the allowable facility cost is less than the actual facility cost, then the commercial concept can still be realized, but only if some government subsidy is provided, if the allowable cost is increased, or the actual cost is reduced. If the allowable facility cost is negative, then it is impossible to be commercially viable regardless of quantity of good produced or any potential reduction in actual facility cost. The only way for industry to realize the ISM concept is if government pays for all of the facility cost and provides an additional stimulus. These ISM concepts are effectively deemed infeasible.

*facilities requiring high production rates will likely require large amounts of power, which leads to heavy electrical power subsystems consisting of solar arrays, secondary batteries, fuel cells, and/or radioisotope thermoelectric generators.*
Figure 4-2: ISM facility cost vs. mass of facility. Cost estimated based on USCM8 [68] and MOCET [18] cost models assuming only a single ISM facility is produced and neglecting $C_{RDTE.ISM,components}$.

Table 4.3: Commercial Viability of ISM Concepts for Various Levels of $C_{facility}$ and $C_{facility,allowable}$

<table>
<thead>
<tr>
<th>Relative Cost</th>
<th>Commercial Viability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{facility} &lt; C_{facility,allowable}$</td>
<td>Commercial ISM naturally pursued</td>
</tr>
<tr>
<td>$C_{facility} &gt; C_{facility,allowable}$, and $C_{company} &lt; C_{facility,allowable}$</td>
<td>Government has taken enough of the financial burden to allow commercial pursuit of ISM</td>
</tr>
<tr>
<td>$C_{company} &gt; C_{facility,allowable}$</td>
<td>Government investment is insufficient to encourage commercial ISM</td>
</tr>
<tr>
<td>$C_{facility,allowable} &lt; 0$</td>
<td>Commercial ISM will only be realized if government continues to subsidize the effort</td>
</tr>
</tbody>
</table>
Figure 4-2 reveals the relative contribution of each of the cost factors that add up to give ISM facility cost. Some of these cost factors could potentially be reduced by government investment in R&D, whereas other costs would likely remain and need to be paid for by the commercial space company trying to have commercially viable ISM operations. The usefulness of the formulation for $C_{facility}$ is that depending on the circumstances, one can think of $C_{facility}$ as comprising any subset of the cost contributions shown. For example, in NASA Tipping Point solicitations, NASA can treat $C_{facility}$ as only including the recurring costs that the company will incur building, launching, and operating an ISM capability, because the government funding will cover the RDTE costs to get them to the tipping point. This can reduce the ISM company's required investment to below the allowable facility cost for that ISM application. In this way, government funding will have enabled the pursuit of commercial ISM. The impact of varying levels of government investment in RDTE on the required investment from commercial industry is shown in Figure 4-3. Another, more extreme funding case would require government subsidies to help alleviate recurring operations costs to allow for commercially viable operations. Concepts requiring this type of government support are unlikely to be pursued because a self-sustaining commercial ISM capability is not enabled.
Figure 4-3: ISM facility cost vs. company investment for various levels of NASA investment in RDTE costs. By investing in RDTE for ISM technologies, NASA can push commercial industry past the tipping point to where a company’s required investment is less than the allowable facility cost for their application, thus allowing commercial ISM to be pursued.
Chapter 5

Structurally Optimized Systems

5.1 Overview

Consider a system where some fraction of its components can be structurally optimized for in-space loads to reduce mass, while the rest of the system cannot be structurally optimized. The former could be structural supports that are sized for launch loads, and the latter could be electronics components that could not be made any lighter even if they were made in space. In this class of ISM applications, only the structurally optimizable components would be built in space. The non-structurally optimizable components would still be launched from Earth and then integrated with the ISM components in orbit. While the analysis developed below is for a generalized structurally optimized system, some potential examples will be explored, including ISM of trusses, solar arrays, and propellant tanks.

This analysis will begin by producing a cost model that captures the primary cost drivers. The model will be parametrized such that the inputs can be varied to produce the expected cost for both a launched system and a system produced through ISM. Then, the breakeven cost point can be determined as a function of the system drivers. This analysis will identify important screening metrics that can be used to aid decision-making regarding the suitability of ISM in various applications where ISM enables structural optimization for in-space loads. Models that capture the system performance as a function of system drivers will also be developed. A
sample application of this decision-making process will be applied to a set of space systems to determine which appears most promising for ISM.

5.2 Cost

The most general form of total system lifecycle cost, $C_{total}$, that can be developed under the assumptions of this analysis is composed of the following cost contributions: non-structurally optimizable (NSO) components, $C_{NSO}$, structurally optimizable (SO) components, $C_{SO}$, and the ISM facility itself, $C_{facility}$. In the subsequent analysis, a structurally optimizable component is one that is capable of being structurally optimized through ISM, but would not be structurally optimized if launched from Earth. Thus, it will only save on mass if ISM is used. When a baseline cost for a conventionally launched space system is computed, the cost of the ISM facility, $C_{facility}$, will be set equal to zero. This simple expression for $C_{total}$ is given as:

$$C_{total} = C_{facility} + C_{NSO} + C_{SO}$$

(5.1)

Even from this very simplified formulation of a cost model, we can begin to gain insights. In order to find the maximum allowable facility cost for commercial viability, we equate the total cost for a conventionally launched system, $C_{total, LV}$, to the total cost for a system where the structurally optimizable components have been produced using ISM, $C_{total, ISM}$, and solve for the facility cost. Here we assume that $C_{facility, LV} = 0$ and that non-structurally optimized components cost the same in both cases because the same component would be used in either case, so $C_{NSO, LV} = C_{NSO, ISM}$. The following result is then obtained:

$$C_{facility, allowable} \leq C_{SO, LV} \left(1 - \frac{C_{SO, ISM}}{C_{SO, LV}}\right)$$

(5.2)

Based on this result, the allowable facility cost is limited by the cost of the components in the launched case which can be structurally optimized if ISM is used, $C_{SO, LV}$. However, this limit can only be reached when the ratio $C_{SO, ISM}/C_{SO, LV}$
approaches zero, which means that the cost of the ISM structurally optimized components must be very much less than the launched components they are replacing. Thus, a preliminary finding is that systems that are well-suited for ISM are ones where the current launched components are costly, but they can be made in space rather cheaply through structural optimization.

To gain more understanding and see how this can be accomplished, we must add more detail to the cost model. We can define that $C_{SO}$ and $C_{NSO}$ are functions of several input parameters without identifying a particular functional form. Under the assumptions for this case study, $C_{SO}$ and $C_{NSO}$ are determined to be functions of the scale parameter, $x$ [m, m², m³], the linear/areal/volume density, $\lambda$ [kg/m, kg/m², kg/m³], the specific material cost, $c_{matl}$ [$/kg$], and the specific launch cost, $c_{launch}$ [$/kg$]. Generality to the type of space system being modeled is maintained through the definition of the scale and density parameters, however their units must be consistent within any given analysis. It should be noted that the scale parameter represents the total quantity produced by the ISM facility over its operational life, which could include multiple copies of the same component. The expression for total cost thus becomes:

$$C_{total} = C_{facility} + f(x, \lambda_{SO}, c_{matl,SO}, c_{launch}) + g(x, \lambda_{NSO}, c_{matl,SO}, c_{launch})$$  \hspace{1cm} (5.3)$$

It should be noted that the scale parameter and the specific launch cost are assumed to be the same regardless of whether a component is one that is structurally optimizable or not and regardless of whether the component is launched or made using ISM. The scale parameter is taken to be the same in each case because we are assuming that the ISM component should be a drop-in replacement for the existing launched component, which means that it will need to have the same scale. The launch cost is taken to be the same because the use of in-situ resource utilization (ISRU) or material recycling is not included in this case study as a means of reducing the cost of obtaining mass on orbit.
With the functional inputs identified above, Buckingham Pi theorem can be applied to generate nondimensional groups that are relevant for describing the problem regardless of the functional form of the cost model. Thus, the resulting nondimensional groups will hold for any cost model form that takes the identified parameters as inputs. These nondimensional parameters will be reported later once the cost model is linearized, for convenience.

Typical cost estimating relationships (CERs) take a functional form where cost is related to a coefficient times the mass of the system raised to some power, such as $C = am^b$. With this cost model functional form for $C_{NSO}$ and $C_{SO}$ we get the following expression for total cost:

$$C_{total} = C_{facility} + (x\lambda_{NSO})^{b_1}(c_{matl,NSO} + c_{launch}) + (x\lambda_{SO})^{b_2}(c_{matl,SO} + c_{launch})$$  \hspace{1cm} (5.4)

To understand what the exponents $b_1$ and $b_2$ should be, we can look at existing space system cost models for reference. According to the Unmanned Spacecraft Cost Model, version 8 (USCM8), the recurring theoretical first unit costs for structures, electrical power, and propulsion subsystems scale linearly with the mass of the sub-system [68]. Thus, for these subsystems of interest, we can safely assume $b_1 = b_2 = 1$.

The resulting cost model, which gives cost as a linear function of system mass, results in the following equation for total cost:

$$C_{total} = C_{facility} + x[\lambda_{NSO}(c_{matl,NSO} + c_{launch}) + \lambda_{SO}(c_{matl,SO} + c_{launch})]$$  \hspace{1cm} (5.5)

### 5.2.1 Allowable Facility Cost

Figure 5-1 shows a representative plot of the total cost as a function of scale parameter, as given by Equation 5.5, for an ISM system and a launched system. A breakeven point exists because an ISM system will have a higher fixed cost, due to the cost of the ISM facility, but a lower variable cost, due to the reduced linear/areal/volume
density through structural optimization, compared to a launched system.

The breakeven point is found by equating the total cost of systems carried to orbit by a launch vehicle (LV) and those built using in-space manufacturing (ISM), which is given by $C_{total,LV} = C_{total,ISM}$. Evaluating this and solving for the allowable facility cost to breakeven at a desired scale, $x_{BE}$, gives the equation below. Recall that the cost contribution from NSO components will cancel out in the breakeven analysis because those components are the same in launched and ISM cases. This yields the following expression for allowable facility cost, where we define $\nu = \frac{\lambda_{SO,ISM}}{\lambda_{SO,LV}}$:

$$C_{facility,allowable} \leq x_{BE} \lambda_{SO,LV} (c_{matl,SO} + c_{launch})(1 - \nu) \quad (5.6)$$

Where the total mass of the ISM components produced is given by:
The mass produced, \( m_{produced} \), must also be equal to the mass production rate, \( \dot{m}_{produced} \), multiplied by the lifetime over which the ISM facility will operate, \( t_{life} \):

\[
\begin{align*}
    m_{produced} &= \dot{m}_{produced} t_{life} \\
    (5.8)
\end{align*}
\]

It should be noted that Equation 5.6 can be equivalently written as

\[
C_{facility, allowable} \leq C_{SO, LV}(1 - \nu).
\]

This result has the same form as Equation 5.2, which reveals that, under the given assumptions, the ratio \( \frac{C_{SO, ISM}}{C_{SO, LV}} \) is numerically equivalent to \( \frac{\lambda_{SO, ISM}}{\lambda_{SO, LV}} \). This confirms that the cost reduction achieved by using ISM for structural optimization is manifested in the reduced linear, areal, or volume density of the component produced relative to the existing launched component. In the limiting case where \( \nu = 0 \), meaning that ISM has removed all mass from components that could be structurally optimized, we see the extreme limiting case. This gives the maximum possible allowable facility cost for a given system. In this case, the total ISM system cost is driven by the cost of components that cannot be structurally optimized. This means that, in order to breakeven, the facility cost must be less than the total cost of structurally optimizable components in the launched case, such that \( C_{facility, allowable} \leq C_{SO, LV} \). From this result, we see that the cost of structurally optimizable components in the launched case is an important driver of an ISM application’s commercial viability.

Equation 5.6 can be nondimensionalized using Buckingham Pi theorem to give the following:

\[
\hat{C}_{facility, allowable} \leq (\kappa + 1)(1 - \nu)
\]

(5.9)

Where we define the nondimensional allowable facility cost, \( \hat{C}_{facility, allowable} \), material cost, \( \kappa \), and structural mass fraction, \( \nu \), as follows:
The nondimensional Equation 5.9 is plotted in Figure 5-2 to identify the trends in allowable facility cost as parameters are varied. In the plot, we have quantified how increasing structural optimization (i.e., reducing structural mass fraction) leads to increased nondimensional allowable facility cost. The nondimensional material cost increases the sensitivity of facility cost to structural mass fraction and places an upper limit on the maximum allowable facility cost for a particular design even if all structural mass is removed through optimization. The dimensional allowable facility cost is increased at higher breakeven scale parameters, when launch costs are high, and when the launched alternative of the structurally optimized component is heavy.

This particular nondimensional plot is only valid to compare ISM concepts within one application area, such as different concepts for solar array manufacture, where the quantities within \( \hat{C}_{\text{facility, allowable}} \), including \( X_{BE} \), \( \lambda_{SO, LV} \), and \( c_{\text{launch}} \), are the same for all concepts being compared. In order to compare across different application areas, such as comparing ISM of trusses and of solar arrays, the dimensional allowable facility cost must be computed.

Based on the equations above for allowable facility cost, a few interesting conclusions can be drawn. First, the structural mass fraction, \( \nu \), is an important performance parameter for mass-reducing ISM facilities. It is an evaluation of the performance of both the ISM facility, as well as the ISM design of a component. It has direct impacts on the allowable facility cost to breakeven. Interestingly, reduced launch costs make mass-reducing ISM less favorable. This could equivalently be interpreted as showing that the use of ISM to take advantage of structural optimization for in-space loads is most beneficial when far from Earth’s gravity well, where the
Figure 5-2: Nondimensional plot of allowable facility cost vs. structural mass fraction for various values of nondimensional material cost.
delivery of mass is more expensive. We also see that systems where the structurally optimizable part of the system is expensive, i.e. high $C_{SO, LV}$, are good candidates for ISM because they have a higher maximum possible allowable facility cost. Under the given assumptions, the allowable facility cost, $C_{facility, allowable}$, is seen to increase linearly with desired breakeven point. Assuming that the actual realized facility cost is a function of total production capacity, which is driven by breakeven point, we would expect to see an optimal combination of $\nu$ and $C_{facility}$. We see that ISM becomes completely infeasible (i.e. $C_{facility, allowable} \leq 0$) when $\nu = 1$ (because this means no structural optimization was performed), when $\lambda_{SO, LV} = 0$ (because there is very little initial mass to structurally optimize), and when $c_{mati, SO} + c_{launch} = 0$ (because there is very little cost savings available).

5.3 Application of Cost Analysis

Now that we have identified a procedure by which allowable facility cost can be determined for the class of structurally optimized systems, this analysis proceeds to evaluate the commercial viability of ISM of the following structurally optimizable systems: trusses, solar arrays, and pressure vessels.

5.3.1 Trusses

Trusses are a spacecraft component modeled as having a scale parameter expressed in meters and a linear density expressed in kg/m. Spacecraft can utilize trusses to deploy and support synthetic aperture radar like on the Shuttle Radar Topography Mission (SRTM) and long focal lengths like on NuStar. While these deployable trusses successfully provide long baselines, they do so with the mass penalty of a deployment canister and joints that enable deployment, see Figure 5-3. At the very least, ISM trusses could eliminate this parasitic mass, thus providing the needed stiffness and baseline at reduced mass and volume.

The total system mass, which includes the truss itself and the deployment canister, for existing launched deployable trusses grows as a function of the length of truss
SRTM truss and canister [25].

Stowed 10 m NuStar mast [57].

Figure 5-3: Existing deployable trusses in deployed (left) and stowed (right) configurations. The deployment canister represents a significant parasitic mass and volume compared to the truss structure itself.

required for a given application, as shown in Figure 5-4. Based on this data, the fraction of the total system mass that is attributed to the canister as a function of truss length can be determined. This represents the amount of structural optimization readily achievable through ISM and leads to a relatively constant value of $\nu = 0.6$ for ISM of trusses over the length range considered.

5.3.2 Solar Arrays

Solar arrays are a spacecraft component modeled as having a scale parameter expressed in m$^2$ and an areal density expressed in kg/m$^2$. Nearly all spacecraft rely on photovoltaic solar arrays to generate power in orbit. There is significant interest in improving solar array performance by designing arrays that are cheaper, lighter, more compactly stowed, and generate more power [8]. Supporting high-power spacecraft requires large solar arrays that must survive launch loads (such as acoustics, vibrations, and acceleration) and have complex deployment mechanisms that drive up mass. With ISM, the solar arrays can be designed for in-space loads, such as thruster acceleration, plume impingement, and aerodynamic drag, and no deployment mechanisms are needed. Even if no loading at all were experienced, solar arrays
Figure 5-4: Truss mass vs. length. This plot was generated using specifications for the Able Deployable Articulated Mast (ADAM) with a bending stiffness selected to provide a fundamental frequency of 0.15 Hz. The deployment canister, which is seen to account for about 40% of the total system mass, can be eliminated when ISM is used.
Figure 5-5: Solar array mass vs. area. By eliminating launch loads, significant potential reduction in solar array mass is enabled. However, ISM arrays are still typically limited by thruster acceleration. Tethers Unlimited (TUI) Trusselated solar array concepts aim to reach this limit using ISM, thus achieving significant mass reduction over traditional Earth-launched solar arrays, including the Government Reference Array (GRA).

are still limited by the areal density of the solar cells themselves.

Figure 5-5 shows solar array mass as a function of solar array area, which can be related to power generation capability. The figure shows a curve based on a SME-SMAD reported average solar array areal density of 2.5 kg/m², which agrees well with the data points for three historical spacecraft (Dawn, Hubble, and Juno) and the Orbital ATK MegaFlex Array [68, 8, 44]. Thruster acceleration, which was taken to be 0.1 g, is seen to be the driving requirement of launch loads for ISM solar arrays. Based on the mass savings shown, ISM solar arrays on average, over the area range considered, are expected to have $\nu = 0.24$.

The Government Reference Array (GRA) and Tethers Unlimited (TUI) aim to
achieve solar arrays near the limit imposed by thruster acceleration [45, 22]. Two TUI solar array concepts of interest (shown in Figure 5-6) are a Trusselated GRA, which involves fabricating the GRA design using high structural efficiency CF/PEEK trusses produced by the Trusselator, and a Tensioned SpiderWeb, where a new design is fabricated to meet GRA requirements using Trusselator trusses with additional stiffening wires.

### 5.3.3 Pressure Vessels

Pressure vessels and propellant tanks are a spacecraft component modeled as having a scale parameter expressed in MPa-m$^3$ and a volume density expressed in kg/MPa-m$^3$. While launched pressure vessels are subjected to launch loads, their design is typically driven by the hoop stress caused by the contained pressure. Figure 5-7 shows propellant tank mass as a function of pressure-volume for both metallic and composite pressure vessels. The SME-SMAD curves are based on statistical data from historical spacecraft propulsion subsystems [68]. The other curves shown are computed based on the tank thickness required to keep the hoop stress at the given pressure-volume below the yield stress of the tank material. Based on this result, the structural optimization achievable for pressure vessels is, on average, about $\nu = 0.8$. While pressure vessels likely do not present a great opportunity for structural optimization with ISM, there is interest nonetheless in considering the possibility and identifying
Figure 5-7: Pressure vessel mass vs. pressure-volume. Even if pressure vessels are designed solely for the hoop stress they will experience in orbit and not for launch loads, only a small degree of mass savings is even theoretically achievable. The SME-SMAD data shown above are curve fits to statistical pressurant tank data, whereas the hoop stress curves were computed analytically from first principles [68].

whether the fabrication of metallic or composite tanks would prove more favorable for ISM.

5.3.4 Results

In order to compute the allowable facility cost for various different concepts, numeric values must be assigned to each of the parameters in the cost model. For all concepts considered, we will assume operations occur in LEO with $c_{\text{launch}} = $10,000/kg. The rest of the parameter values are dependent on the particular ISM concept, and are reported in Table 5.1. The computed value for $C_{\text{facility, allowable}}$ is a point estimate based on the scale parameter reported in the table. Figure 5-8 plots these results of
allowable facility cost vs. structural mass fraction and shows lines of constant $m_{SO,LV}$. Figure 5-9 treats $m_{produced}$ as an independent variable to show the effect of altering the scale parameter to produce more or less of the component than is considered in the point design. Figure 5-10 shows the sensitivity of allowable facility cost for each concept to launch cost. ISM for structural optimization is seen to become less favorable as launch costs fall.

![Graph showing allowable facility cost vs. structural mass fraction for various concepts.](image)

Figure 5-8: Allowable facility cost vs. structural mass fraction for various concepts. This figure shows that even within this structural optimization case study, the best ISM concepts are not just the ones that reduce structural mass the most. The overall objective for a strong ISM concept is to have a high allowable facility cost, which can happen at higher mass fractions for applications with a higher mass of components available for structural optimization. However, within any one application area, as we have seen, it is always preferable to achieve more structural optimization, as long as it doesn’t require increased complexity of the manufacturing equipment, which could drive up the actual facility cost.
Table 5.1: Parameter Values for Selected Structurally Optimized ISM Concepts

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NuStar Truss</th>
<th>ISS SAW FAST Mast</th>
<th>TUI Truss-related GRA</th>
<th>TUI Tensioned SpiderWeb</th>
<th>Theoretical Solar Array</th>
<th>Metallic Tank</th>
<th>Composite Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu = \frac{\lambda_{SO,.ISM}}{\lambda_{SO,LV}} )</td>
<td>0.6</td>
<td>0.6</td>
<td>0.44 [22]</td>
<td>0.15 [22]</td>
<td>0.24</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>( c_{matr,SO} )</td>
<td>$2.13/\text{kg}^*</td>
<td>$2.13/\text{kg}^*</td>
<td>$22/\text{kg}^{†}</td>
<td>$22/\text{kg}^{†}</td>
<td>$2.13/\text{kg}^*</td>
<td>$3.84/\text{kg}^{†}</td>
<td>$22/\text{kg}^{†}</td>
</tr>
<tr>
<td>( x_{BE} = x_{demand} )</td>
<td>10 m [29]</td>
<td>264 m [27]</td>
<td>1500 m² [45]</td>
<td>1500 m² [45]</td>
<td>2,080 m² §</td>
<td>273.4 MPa-m³ ¶</td>
<td>273.4 MPa-m³ ¶</td>
</tr>
<tr>
<td>( \lambda_{SO,LV} )</td>
<td>2.35 kg/m ‡</td>
<td>9.27 kg/m †</td>
<td>0.283 kg/m² [22, 45]</td>
<td>0.283 kg/m² [22, 45]</td>
<td>2.13 kg/m² ***</td>
<td>13.1 kg/MPa-m³ ‡‡</td>
<td>5.5 kg/MPa-m³ ‡‡</td>
</tr>
<tr>
<td>( m_{produced} )</td>
<td>14 kg</td>
<td>1,468 kg</td>
<td>187 kg</td>
<td>64 kg</td>
<td>1,065 kg</td>
<td>2,866 kg</td>
<td>1,203 kg</td>
</tr>
<tr>
<td>[ Eqn 5.7 ]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_{facility,allowable} )</td>
<td>$0.094M</td>
<td>$9.79M</td>
<td>$2.38M</td>
<td>$3.62M</td>
<td>$33.7M</td>
<td>$7.21M</td>
<td>$3.01M</td>
</tr>
<tr>
<td>[ Eqn 5.6 ]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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* Aluminum commodity pricing [71].
† Standard modulus carbon fiber pricing [50, 52].
‡ Stainless steel pricing [31].
§ Based on capturing one-fourth of the GEO market for solar arrays. In GEO, there is currently an approximate total of 2,500 kW of solar power production using arrays which can be assumed to generate about 300 W/m².
* Based on manufacturing the SpaceX BFR tanks of 568 m³ for LCH4 and 754 m³ for LOX, which are both assumed to be stored at 30 psi [32].
** Based on performance of the Able Deployable Articulated Mast (ADAM) at the corresponding truss length.
*** Based on the areal density for typical rigid deployable solar arrays with the mass of solar cells themselves, which are considered non-structurally optimizable, subtracted out [68].
¶ Determined from historical data of the relationship between propulsion system tank mass and pressure-volume [68].
Figure 5-9: Allowable facility cost vs. mass produced by ISM for various concepts. An ideal ISM concept would have a very high allowable facility cost but only require a very small amount of mass to be fabricated. For any one concept, which is defined by the parameter $\beta = (c_{\text{mat}} + c_{\text{launch}})(\gamma - 1)$, increasing the mass produced increases the allowable facility cost. The ideal design point in terms of mass produced will depend on the demand for the product being manufactured and on how the actual realized ISM facility cost increases with mass.
5.4 Performance

Now that the impact of structural optimization through ISM has been addressed in regards to cost, we consider the impact on system performance, or the benefit delivered. We define three different performance metrics: density performance, mass efficiency, and stowed volume efficiency. Each of these performance metrics will be related back to the achieved structural mass fraction, $\nu$, and the fraction of the existing system that can be structurally optimized, $\lambda_{SO,LS}/\lambda_{NSO}$, as well as the size and weight of the ISM equipment itself, which are given as $V_{facility}$ and $m_{facility}$, respectively. The
degree of structural optimization will depend upon the difference in loading between
launch and on-orbit conditions as well as the capabilities of the manufacturing pro-
cess used to accomplish ISM. The fraction of the system that can be structurally
optimized depends both on the complexity of the system being manufactured and the
capability of the manufacturing equipment.

5.4.1 Density Performance

Density performance, \( \alpha \), is a measure of how the mass of a system increases with
the scale parameter, \( x \). For example, for systems that rely on area to accomplish
their function, such as solar panels and radiators, the important metric is kg/m\(^2\). We
compute the density performance as the sum of the mass of the ISM facility, \( m_{\text{facility}} \),
normalized by the total scale produced, \( x \), and the densities of both the NSO and
SO components, which were assumed to both scale equally with the scale parameter.
If the ISM equipment is located on a free-flier spacecraft that merely delivers the
fabricated component to a customer spacecraft, we can set \( m_{\text{facility}} = 0 \). However,
retaining \( m_{\text{facility}} \) as a term in the formulation enables evaluation of spacecraft with
on-board ISM facilities for their own use.

\[
\alpha = \lambda_{\text{NSO}} + \lambda_{\text{SO}} + \frac{m_{\text{facility}}}{x}
\]

We can now consider the ratio of density performance between ISM and launched
systems, \( \alpha_{\text{ISM}}/\alpha_{\text{LV}} \), where a smaller ratio is better and the ratio must be less than
1 for ISM to have a net performance benefit. The result is shown graphically in
Figures 5-11 and 5-12, and expressed analytically below:

\[
\frac{\alpha_{\text{ISM}}}{\alpha_{\text{LV}}} = \frac{1 + \nu \left( \frac{\lambda_{\text{SO,LV}}}{\lambda_{\text{NSO}}} \right) + \frac{m_{\text{facility}}}{x \lambda_{\text{NSO}}}}{1 + \left( \frac{\lambda_{\text{SO,LV}}}{\lambda_{\text{NSO}}} \right)}
\]

We find that the density performance can be improved (i.e. reduce the ratio
\( \alpha_{\text{ISM}}/\alpha_{\text{LV}} \)) by increasing the ratio \( \lambda_{\text{SO,LV}}/\lambda_{\text{NSO}} \), which is a property of the system
selected for ISM and the capability of the manufacturing equipment. The density
Figure 5-11: Density performance vs. fraction available for structural optimization. The data shown assumes \( \frac{m_{\text{facility}}}{\lambda_{\text{NSO}}} = 1 \), which limits the regime over which a net performance benefit can be achieved with the on-board ISM facility. The parameters \( \nu \) and \( \lambda_{\text{SO, LV}}/\lambda_{\text{NSO}} \) are dependent on both the component that is fabricated (i.e. solar arrays) and on the capability of the ISM equipment.
Figure 5-12: Density performance vs. nondimensional ISM facility mass. The data shown is for $\nu = 0.4$. Lightweight facilities that produce large quantities of product improve density performance. The best density performance is achieved when a free-flying ISM facility is used, because no ISM facility mass is added to the system receiving the ISM component. Furthermore, in order to have a net reduction in component mass ($\alpha_{ISM}/\alpha_{LV} < 1$), there is a maximum nondimensional facility mass which depends on the ratio $\lambda_{SO, LV}/\lambda_{NSO}$. 
performance can also be improved by reducing \( \nu \), which depends on the structural optimization accomplished. Lastly, having lightweight manufacturing equipment and fabricating a large quantity of a component improves density performance. This result shows that performance gains are most easily achieved on systems where the structurally optimizable components are comparatively heavy and where it can be easily structurally optimized. The achievable density performance is limited by the ratio \( \lambda_{SO, LV}/\lambda_{NSO} \) of the system selected for ISM because, even with full structural optimization and a zero mass ISM facility, the non-structurally optimizable components limit the density performance:

\[
\frac{\alpha_{ISM}}{\alpha_{LV}} \bigg|_{\text{max}} = \frac{1}{1 + \left( \frac{\lambda_{SO, LV}}{\lambda_{NSO}} \right)}
\]  

(5.12)

5.4.2 Mass Efficiency

Mass efficiency, \( \Gamma \), is a measure of how the value adding quantity is delivered per unit mass. For solar arrays, the value adding quantity is the number of watts of power produced, \( P \). The mass efficiency metric would then be given in W/kg as the total power produced divided by the total mass of solar array, \( M_{\text{total}} \). In the equation below, the variable \( \psi \) is a measure of the value adding quantity per unit scale parameter. For example, for solar arrays we would have \( \psi \) in W/m\(^2\) given by the amount of power produced by a unit area of solar panel.

\[
\Gamma = \frac{P}{M_{\text{total}}} = \frac{x \psi}{x(\lambda_{NSO} + \lambda_{SO}) + m_{\text{facility}}} = \frac{\psi}{\alpha]
\]  

(5.13)

The ratio of mass efficiency for ISM systems compared to launched systems, \( \Gamma_{ISM}/\Gamma_{LV} \), where the higher the ratio is the better the application of ISM, is evaluated as follows:

\[
\frac{\Gamma_{ISM}}{\Gamma_{LV}} = \frac{\psi_{ISM}}{\psi_{LV}} \left( \frac{\alpha_{LV}}{\alpha_{ISM}} \right)
\]  

(5.14)

We see that mass efficiency is subject to the same sensitivities as the density performance ratio, i.e. better density performance leads to better mass efficiency.
However, there is an additional dependency on the ratio $\psi_{ISM}/\psi_{LV}$ which accounts for any performance penalty incurred by ISM at the expense of mass reduction. For the case of solar panels, we assumed that only the solar panel support structure is made through ISM and the solar cells are launched from Earth. In this case, we would expect $\psi_{ISM}/\psi_{LV} = 1$ because in both cases the solar cells have the same efficiency and are exposed to the same solar flux (approximately 1,367 W/m$^2$ at 1 AU) and, thus, will generate the same power for a given solar panel area.

### 5.4.3 Stowed Volume Efficiency

Stowed volume efficiency, $V^*$, is a measure of the value adding quantity delivered per unit of stowed volume on launch. ISM presents a great opportunity to improve stowed volume efficiency over existing systems because raw material can be packaged much more compactly than pre-fabricated or deployable structures. In addition, by reducing the structural mass required for a system, the capability can be packaged in an even smaller volume. Stowed volume efficiency is important for ISM because, although the manufacturing occurs in space, the raw material feedstock is often still delivered from Earth. Although this would not be the case when feedstock is acquired through recycling or ISRU, stowed volume efficiency would still be important during storage of the feedstock onboard the spacecraft. The stowed volume efficiency is computed as follows:

$$V^* = \frac{P}{V_{stowed}} = \frac{P}{V_{NSO} + V_{SO} + V_{facility}} = \frac{x\psi}{V_{SO}(1 + \frac{V_{NSO}}{V_{SO}} + \frac{V_{facility}}{V_{SO}})} \quad (5.15)$$

### 5.5 Hardware Specifications

Now that the allowable facility cost for each concept as a function of total mass of product has been determined, and the performance benefits of structural optimization have been explored, we can look at the specifications of the hardware required to accomplish the manufacturing of these systems. Table 5.2 reports specifications for
Table 5.2: Hardware Specifications for Selected Structurally Optimized ISM Concepts

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Rate Capability</td>
<td>7.34 kg/day</td>
<td>7.34 kg/day</td>
<td>2,732 kg/day</td>
</tr>
<tr>
<td>Mass</td>
<td>12 kg</td>
<td>1,495 kg</td>
<td>7,200 kg</td>
</tr>
<tr>
<td>Volume</td>
<td>0.003 m³</td>
<td>2 m³</td>
<td>39.1 m³</td>
</tr>
<tr>
<td>Power</td>
<td>20 W</td>
<td>300 W</td>
<td>617 W (22 kW peak)</td>
</tr>
</tbody>
</table>

ISM of trusses using TUI MakerSat (see Figure 5-13) and Grumman Beam Builder (see Figure 5-14), as well as ISM of solar arrays (see Figure 5-15) and antenna reflectors using TUI SpiderFab (see Figure 5-16). This data shows the wide range of production rate, mass, volume, and power for structural optimization ISM concepts. Additionally, by comparing the SWaP of the Grumman Beam Builder concept to the TUI concepts, it becomes clear how recent technological advancements have improved the potential for ISM by reducing the mass, volume, and power of manufacturing equipment. Reducing SWaP helps to limit ISM facility recurring costs while also improving the potential performance benefit of an on-board facility, as previously discussed. The TUI Trusselator concept that forms the foundation of MakerSat and SpiderFab operations performs a very similar task to that of Beam Builder, namely, producing truss structures. However, Trusselator forms trusses using pultrusion of CF/PEEK in a CubeSat form factor, whereas Beam Builder produced much larger trusses using forming and welding of aluminum strips in a Space Shuttle payload bay form factor. This technology advancement has resulted in reduced size and mass of truss fabrication ISM hardware.
Figure 5-13: Tethers Unlimited MakerSat-1 concept for a 6U CubeSat demonstrating long-baseline synthetic aperture radar using a 50 m truss fabricated by a 3U Trusselator system. In the rendition above, the truss has only just begun to be fabricated [23].

Figure 5-14: The Grumman Beam Builder ground demonstration unit for production of welded aluminum trusses underwent testing at Marshall Space Flight Center in 1979 [40].
Figure 5-15: Tethers Unlimited Trusselator demonstrating the deployment of an emulated flexible blanket solar array using a fabricated CF/PEEK truss [22].

Figure 5-16: The Tethers Unlimited SpiderFab features Trusselator technology for fabrication of composite trusses as well as robotic arms for precision assembly of those trusses into higher order structures [20].
Chapter 6

Earth-Return Systems

6.1 Overview

Consider the case where a product is manufactured in space to take advantage of some unique aspect of the space environment, such as persistent microgravity or vacuum, and is then returned to Earth to be sold and used. A thorough discussion of these and other unique attributes of the space manufacturing environment is provided in [15]. In this Earth-return class of ISM applications, the raw material would be launched from Earth to orbit, where it will be fabricated into a product, which will then be returned to Earth for sale and use. The following analysis applies for an ISM product that possesses the following attributes: (1) better than what can possibly be built on Earth, (2) truly requires the space environment for fabrication because it cannot be produced any other way, and (3) retains its favorable properties once returned to an Earth environment for sale. Because, by definition, no Earth-manufactured alternative exists for these products, this analysis cannot compare the manufacturing cost to a non-ISM alternative. Instead, the manufactured product is assumed to provide a performance benefit over existing Earth-based products, which is manifested in a high selling price to terrestrial customers. Then, the breakeven point is based on achieving a positive profit through sale of this product.

A major programmatic risk for any Earth-return ISM application is the emergence of a lower cost, ground-based technique to fabricate a product with performance
equal to that of the ISM product. For example, if a particular ISM application (such as metal alloying or crystal growth) requires a microgravity environment, various potential approaches exist for providing that environment, including using a drop tower, a parabolic aircraft, a sounding rocket, or an automated spacecraft platform. As shown in Figure 6-1, only applications that require very low acceleration levels for very long durations will require processing onboard a spacecraft. Otherwise, the cheaper options of parabolic aircraft or sounding rockets would be selected to provide the required microgravity exposure. Even for ISM applications that are deemed to require spacecraft microgravity levels and durations, there remains the risk that companies will eventually learn, through R&D activities in space, how to move the operation back to the ground where fabrication costs are inherently lower.

An ideal product for Earth-return ISM is one where it can only be made in microgravity and the business case closes considering launch costs, manufacturing costs, and sale price. To date, no large-scale commercial operation for Earth-return ISM has proven successful. However, over time, a wide variety of potential high-value Earth-return ISM products have been proposed and continue to be proposed. Back in 1994, [9] identified promise in the fields of drug production, biotechnology, and materials processing. Since 2012, the NASA Emerging Space Office has been investigating a variety of potential markets for commercial Earth-return ISM and determining how development efforts on ISS or commercial platforms can benefit American industry [17]. Some examples of potential ISM products include ZBLAN optical fiber, silicon carbide wafers, epitaxial thin films, pharmaceuticals, and metal alloys. The following analysis will evaluate historical and existing concepts, while establishing a generalized framework by which future concepts can be evaluated as they arise.

The analysis will begin by producing a cost model that captures the primary cost drivers. The model will be setup to compute the expected cost and revenue for the ISM operation. Then, the breakeven point, where revenue equals cost, can be determined as a function of the system drivers. This analysis will identify important screening metrics that can be used to aid decision-making regarding the suitability of ISM in various applications for products for use on Earth that can only be fabricated
Figure 6-1: The various potential techniques for conducting microgravity research are shown with respect to the acceleration level achieved and the duration of reduced gravity. Autonomous spacecraft platforms are seen to be necessary when true microgravity (10^{-6} g) is required for durations on the order of months. This figure was reproduced from [60] with data from [61].
in the space environment. System performance will be indicated by expected sale prices for ISM products. A sample application of this decision-making process will be applied to a set of proposed ISM products to determine which appears most promising for ISM application.

6.2 Cost, Revenue, and Profit

The most general expression for lifecycle cost for this case study is the sum of cost contributions due to the ISM facility, $C_{\text{facility}}$, the cost of providing feedstock to orbit, $C_{\text{feedstock}}$, and the cost of returning the ISM product to Earth, $C_{\text{return}}$:

$$C_{\text{total}} = C_{\text{facility}} + C_{\text{feedstock}} + C_{\text{return}}$$

(6.1)

More detail can be added to this cost model by identifying the inputs driving the individual cost contributions to give Equation 6.2. The cost of delivering feedstock to orbit is expected to be a function of the mass of feedstock, $m_{\text{feedstock}}$, the specific launch cost, $c_{\text{launch}}$, and the specific material cost of feedstock, $c_{\text{mat}}$. The cost of returning the manufactured product to Earth is expected to be a function of the mass of product, $m_{\text{produced}}$, and the specific cost of returning payload from orbit, $c_{\text{reentry}}$. By bookkeeping the launch and reentry costs separately, the model retains the possibility of only a fraction of the launched feedstock mass being successfully converted into the final product for return to Earth, while the rest of the scrap product could burn-up on reentry. In this framework, the specific launch cost is given by the total launch cost divided by the payload capacity of the launch vehicle with a standard payload fairing. The specific reentry cost on the other hand, is given by the additional cost required to put a capsule capable of reentry on the launch vehicle divided by the return payload of the capsule. This identifies the cost contribution due to the need to return payload from orbit.

$$C_{\text{total}} = C_{\text{facility}} + f(m_{\text{feedstock}}, c_{\text{launch}}, c_{\text{mat}}) + g(m_{\text{produced}}, c_{\text{reentry}})$$

(6.2)
It should be noted that the mass of product, \( m_{produced} \), can be computed from the mass production rate, \( \dot{m}_{produced} \), multiplied by the lifetime over which the facility will operate, \( t_{life} \).

\[
m_{produced} = \dot{m}_{produced}t_{life} \quad (6.3)
\]

Next, we assume a typical CER functional form with cost being proportional to the mass raised to a power. This gives the following result:

\[
C_{total} = C_{facility} + (m_{feedstock})^{b_1}(c_{launch} + c_{mat}) + (m_{produced})^{b_2}(c_{reentry}) \quad (6.4)
\]

The functional form above allows for nonlinear behavior of cost in response to changes in mass. This would be the case if an ISM operation became large enough to receive bulk discounts from material vendors or launch service providers, but this will be deemed a second order effect in this analysis. Thus, we now assume that the exponential constants are both equal with \( b_1 = b_2 = 1 \), whereby costs become linear with respect to the mass term. This is a reasonable assumption because it is unlikely that the cost per unit mass for launch, material, or reentry will depend strongly on the total mass of feedstock or the mass of product for the small-scale fabrication of high-value products being considered.

The cost model to be used is then given by:

\[
C_{total} = C_{facility} + m_{feedstock}(c_{launch} + c_{mat}) + m_{produced}(c_{reentry}) \quad (6.5)
\]

Now that an expression for the lifecycle cost of the ISM application has been developed, the amount of revenue generated by the Earth-return products must be determined. This revenue is solely made up of the quantity of product sold times the price at which that product can be sold.

\[
R_{total} = (\text{Qty})(\text{Price}) \quad (6.6)
\]
For this case study, we take the quantity to be given as the mass of product, $m_{produced}$. Based on the inverse demand function for the product of interest, we know that sale price will be a function of the quantity.

$$R_{total} = m_{produced}f(m_{produced})$$ (6.7)

However, for simplicity we can assume that the sale price per unit mass is fixed at $c_{revenue}$ over the range of production masses to be considered in this analysis. Here, $c_{revenue}$ is given in $$/kg and tells the price per unit mass for which the ISM product can be sold. This sale price will be driven by the economics of the market, which depends on the demand on Earth for this new product. In addition, the sale price will depend on the performance benefit achieved by this product through ISM compared to the ground-based alternative that is currently used. The revenue is then given by:

$$R_{total} = m_{produced}c_{revenue}$$ (6.8)

Combining the revenue and cost models yields the following equation for profit:

$$P_{total} = R_{total} - C_{total} = m_{produced} \left[c_{revenue} - c_{entry} - \frac{m_{feedstock}}{m_{produced}} (c_{launch} + c_{mat}) \right] - C_{facility}$$ (6.9)

### 6.2.1 Allowable Facility Cost

Now that a model for the profit of an Earth-return ISM operation has been developed, the maximum allowable facility cost for which positive profit will be generated can be determined. By targeting a break-even point where $P_{total} \geq 0$, we find the allowable facility cost is bounded by:

$$C_{facility, allowable} \leq m_{produced} \left[c_{revenue} - c_{entry} - \frac{m_{feedstock}}{m_{produced}} (c_{launch} + c_{mat}) \right]$$ (6.10)
Note that in the above expression, there is an implicit constraint that \( \frac{m_{\text{feedstock}}}{m_{\text{produced}}} \geq 1 \) because all of the produced mass must come from the feedstock. However, this term does allow for the possibility of capturing the effect of inefficiencies in the fabrication process where feedstock mass is wasted, which means it was unable to be converted into the high-value product and becomes scrap.

We can then form the nondimensionalized form of the above equation as:

\[
\frac{C_{\text{facility, allowable}}}{m_{\text{produced}}(C_{\text{launch}} + C_{\text{matl}})} \leq \left[ \frac{C_{\text{revenue}}}{C_{\text{launch}} + C_{\text{matl}}} - \frac{C_{\text{reentry}}}{C_{\text{launch}} + C_{\text{matl}}} - \frac{m_{\text{feedstock}}}{m_{\text{produced}}} \right]
\]

Which can be expressed more compactly as:

\[
\hat{C}_{\text{facility, allowable}} \leq \hat{C}_{\text{revenue}} - \hat{C}_{\text{reentry}} - \mu
\]

Where

\[
\begin{align*}
\hat{C}_{\text{facility, allowable}} &= \frac{C_{\text{facility, allowable}}}{m_{\text{produced}}(C_{\text{launch}} + C_{\text{matl}})} \\
\hat{C}_{\text{revenue}} &= \frac{C_{\text{revenue}}}{C_{\text{launch}} + C_{\text{matl}}} \\
\hat{C}_{\text{reentry}} &= \frac{C_{\text{reentry}}}{C_{\text{launch}} + C_{\text{matl}}} \\
\mu &= \frac{m_{\text{feedstock}}}{m_{\text{produced}}}
\end{align*}
\]

At this point, it should be noted that these same nondimensional parameters would arise as key metrics regardless of the functional form of the cost and revenue models as long as the same variables are involved in the model. However, the curves plotted in Figure 6-2 are for the linear cost and revenue models as shown in Equation 6.12.

Now, we establish the idea of a feasibility limit for an Earth-return ISM application, where we enforce that the allowable facility cost must be a positive quantity. To ensure that \( C_{\text{facility, allowable}} \geq 0 \) as required, the ISM application must satisfy the following inequality:
Figure 6-2: This notional plot shows the increase in $\hat{C}_{\text{facility,allowable}}$ with increasing $\hat{c}_{\text{revenue}}$ and/or decreasing $\hat{c}_{\text{reentry}}$. This trend indicates that proposed Earth-return ISM concepts become more feasible as the sale price per unit mass of product increases, as the cost of reentry per unit mass decreases, and as the cost of launch per unit mass decreases. This nondimensional plot can be used to compare commercial viability of proposed ISM applications with the same total mass production. However, if two concepts have the same $\hat{C}_{\text{facility,allowable}}$ but one produces more mass of product, then that concept will be preferred. Note that while the plot shown used a fixed value of $\mu = 1$, the same trend would be shown if we set $\hat{c}_{\text{reentry}} = 1$ and vary $\mu$ instead (with the exception that $\mu \geq 1$).
\[ c_{\text{revenue}} \geq c_{\text{reentry}} + \frac{m_{\text{feedstock}}}{m_{\text{produced}}} (c_{\text{launch}} + c_{\text{mat}}) \] (6.13)

If a particular application does not satisfy this inequality, then ISM of that product will not be commercially viable regardless of the quantity produced or potentially low realized cost of the required ISM facility. One caveat to the above statement, is that if a government agency subsidizes recurring operations costs, then it may be possible to eventually achieve a commercially viable ISM operation even with a negative allowable facility cost.

### 6.3 Application of Cost Analysis

The framework established above will now be used to evaluate proposed ISM concepts. This same process could be repeated to evaluate newly proposed concepts as they arise. For now, the ISM of ZBLAN optical fiber, silicon carbide wafers, and epitaxial thin films will be considered.

#### 6.3.1 ZBLAN Optical Fiber

The production of ZBLAN optical fiber in microgravity is a promising application of ISM. Testing conducted on parabolic flights has shown that the production of ZBLAN in a microgravity environment will reduce crystallization flaws in the fiber (see Figure 6-3), which will reduce transmission losses (see Figure 6-4) [63, 62, 70]. This improved performance of ZBLAN over existing optical fiber enables a high selling price [11]. However, parabolic flights do not provide sufficient microgravity duration for the production of the kilometer lengths needed by the fiber optics industry [17]. Back in December 2017, Made In Space launched its Optical Fiber Production in Microgravity Experiment to the ISS to demonstrate commercial production of ZBLAN fiber in space.
Figure 6-3: Crystallization in ZBLAN fiber is seen to be significantly reduced in fibers pulled in microgravity (left) compared to those pulled in a 1-g environment (right) [11].

Figure 6-4: ZBLAN fiber can reduce attenuation from about 1 dB/km in silica fiber down to about 0.01 dB/km for infrared transmissions [11].
6.3.2 Silicon Carbide Wafers

Silicon carbide (SiC) wafers are desirable in the power electronics industry for their favorable properties over existing silicon wafers, such as their higher allowable operating temperature, higher radiation resistance, higher maximum current density, and greater durability. However, defects naturally form during SiC wafer production on Earth. These defects, in turn, reduce the electrical conductivity of the device, which increases the power loss. ACME Advanced Materials has shown through parabolic flights and sounding rocket launches that the lowest quality SiC wafers can be processed, or healed, to remove defects in microgravity yielding higher quality wafers than the best Earth-based wafers, as shown in Figure 6-5. This healing process involves varying pressure and temperature of the wafers in microgravity [1, 17].

ACME is considering investigation of long-duration healing of wafers to higher quality in the persistent microgravity environment of the ISS. However, they have indicated that existing approaches with parabolic flights provide a good business case for them. If even higher quality wafers can be made on ISS, ACME may choose to pursue orbital operations as well [2].

6.3.3 Epitaxial Thin Film Growth

The fabrication of high-purity thin film materials, such as semiconducting materials for advanced electronics, via molecular beam epitaxy requires a strong vacuum environment. The best Earth-based vacuum technologies have limited pumping speed, small chamber volumes, and can only achieve pressures of $10^{-10}$ Torr, which is not low enough to prevent contamination when thin film growth is conducted. In LEO, the vacuum environment is $10^{-7}$ Torr, which is worse than can be achieved on Earth. However, it is known that in the orbital wake of a spacecraft pressures as low as $10^{-14}$ Torr can be achieved (see Figure 6-6). This ultra-vacuum environment can be exploited for its low pressure, high purity, large volume, and nearly infinite pumping speed. This can result in higher quality, larger area semiconductors and enable throughput to be increased to commercial quantities. From 1994 to 1996, the Wake
Figure 6-5: Microgravity processing of silicon carbide wafers can transform low-quality wafers into nearly defect-free wafers with reduced power dissipation [17].

Shield Facility flew on three Space Shuttle flights to demonstrate the epitaxial growth of thin film materials in the orbital wake vacuum for use in electronic devices on Earth [24, 19, 58].

6.3.4 Results

In order to compute the allowable facility cost for various different concepts, numeric values must be assigned to each of the parameters in the cost and revenue models. For all concepts considered, we will use $c_{\text{launch}} = \$10,000/\text{kg}^\dagger$, $c_{\text{reentry}} = \$23,000/\text{kg}^\ddagger$, and $t_{\text{life}} = 5$ years. These quantities are taken to be constant across all ISM concepts.

The rest of the parameter values are dependent on the particular ISM concept,

\dagger\text{Launch cost to LEO is used because as long as LEO can provide the required space environment, then it is more cost-effective to launch into and return from this low orbit instead of from MEO or GEO.}

\ddagger\text{Reentry cost is based on a cost of $\$133M$ for NASA CRS missions. The 6,000 kg of upmass can be valued at $\$10,000/\text{kg}$ launch cost. Then, the remaining cost for the CRS mission is distributed over the 3,000 kg of return mass to give $\$24,333/\text{kg}$.}
Figure 6-6: This schematic shows the formation of the orital wake vacuum behind the Wake Shield Facility [58].

and are reported in Table 6.1. The computed values for $C_{facility, allowable}$ shown are based on the average selling price of the product and the given $m_{produced}$. However, Figure 6-7 uses the high and low values for potential selling price and treats $m_{produced}$ as an independent variable to show the resulting range in $C_{facility, allowable}$.

The analysis above assumed a fixed launch and reentry cost. However, with the launch services industry rapidly changing with the recent emergence of new commercial launch providers, it is important to consider the sensitivity of allowable facility cost to these launch and reentry costs. Figure 6-8 shows this sensitivity as a function of percentage of the nominal assumed launch and reentry costs in this analysis.
Table 6.1: Parameter Values for Selected Earth-return ISM Concepts

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ZBLAN Optical Fiber</th>
<th>Silicon Carbide Wafers</th>
<th>Epitaxial Thin Film Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{produced}$</td>
<td>25 kg/yr *</td>
<td>360 kg/yr †</td>
<td>250 kg/yr †</td>
</tr>
<tr>
<td>$C_{revenue}$</td>
<td>$900,000/kg$ to $21,000,000/kg$ §</td>
<td>$125,000/kg$ to $250,000/kg$ ‡</td>
<td>$110,000/kg$ to $220,000/kg$ [24]</td>
</tr>
<tr>
<td>$\mu = \frac{m_{feedstock}}{m_{produced}}$</td>
<td>1 [11]</td>
<td>1.01 [1]</td>
<td>1 [24]</td>
</tr>
<tr>
<td>$C_{matl}$</td>
<td>$100,000/kg$</td>
<td>$41,666/kg$ ‡</td>
<td>$5,500/kg$ [24]</td>
</tr>
<tr>
<td>$m_{produced}$ [Eqn 6.3]</td>
<td>125 kg</td>
<td>1,800 kg</td>
<td>1,250 kg</td>
</tr>
<tr>
<td>$C_{facility,allowable}$ [Eqn 6.10]</td>
<td>$1,352M$</td>
<td>$200M$</td>
<td>$156M$</td>
</tr>
</tbody>
</table>

*Earth-based ZBLAN production is currently ~100 kg/yr, but ~1,000 kg/yr could be needed if the potential of ZBLAN to capture a large portion of the existing exotic glass and silica optical fiber market is realized [55].

†Based on 5,000 wafers/month with each 4-inch wafer having a mass of 6 g [1].

‡Based on the Mark II Wake Shield Facility producing 7,000 wafers/yr for a total of 40 million devices/yr [24].

§Based on a sale price of $300/m to $3,000/m and 1 kg of fiber preform producing 3 to 7 km of optical fiber [11].

¶Based on $750/wafer to $1,500/wafer with each 4-inch wafer having a mass of 6 g [1].

*Based on $250/wafer with each 4-inch wafer having a mass of 6 g [1].
Figure 6-7: Dimensional allowable facility cost vs. mass of product for various Earth-return ISM applications. Point designs for ZBLAN, SiC wafers, and thin film epitaxy as reported in Table 6.1 are shown as data points. The point design for ZBLAN dominates both the SiC wafer and thin film epitaxy concepts because it has a higher $C_{facility, allowable}$ and a lower $m_{produced}$. Despite being distinct processes, ISM for SiC wafers and thin film epitaxy exhibit similar commercial viability. This is because both concepts exhibit a quantity $c_{revenue} - \mu c_{matl} \approx $150,000/kg. The minimum value allowable for commercial viability (meaning that $C_{facility, allowable} \geq 0$) is $c_{revenue} - \mu c_{matl} \approx $33,000/kg. The shaded regions show the uncertainty resulting from the range in potential selling price, $c_{revenue}$, as reported in literature. The solid lines represent how $C_{facility, allowable}$ would change for each concept if $m_{produced}$ were varied, either because of changes in demand, production rate, or ISM facility operational life.
As launch and reentry costs fall from their current values, all Earth-return system ISM concepts become more favorable. However, the rate at which allowable facility cost increases with decreasing launch and reentry costs depends on the total mass of product fabricated in a given ISM concept. With fixed launch costs, a concept can be equally commercially viable if it produces a large quantity of a low value product or a small quantity of a high value product. As launch vehicle costs fall, concepts that produce a large quantity of product become increasingly preferred.\(^1\)

\(^1\)The curves for ISM of SiC wafers and thin film epitaxy actually intersect at about 350% of current launch and reentry costs. For launch vehicle costs above this point thin film epitaxy is preferred, whereas for costs below this point SiC wafers are preferred. With launch showing a trend of reducing costs, it’s unlikely this crossover point will be significant, but particular care should be paid to evaluating concepts that may have a crossover point below current launch costs.
Figure 6-9: Made In Space Optical Fiber Facility used for pulling ZBLAN fiber on ISS [67].

6.4 Hardware Specifications

Now that the allowable facility cost for each concept as a function of total mass of product has been determined, we can look at the specifications of the hardware required to accomplish the manufacturing of the products. Specifications for ISM of ZBLAN optical fiber, SiC wafers, and epitaxial thin films are reported in Table 6.2. It should be noted that the specifications for mass and volume reported are only for the manufacturing equipment itself, not for the feedstock. This data reinforces the strength of the ZBLAN optical fiber concept for ISM because the manufacturing equipment has a small volume and low mass while still delivering a high production rate capability to meet demand. The particular hardware for Made In Space Fiber Optics, which has been launched to ISS, is shown in Figure 6-9. The hardware used to perform epitaxial thin film growth using the Wake Shield Facility is shown in Figure 6-10.
Table 6.2: Hardware Specifications for Selected Earth-return ISM Concepts

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ZBLAN Optical Fiber</th>
<th>Silicon Carbide Wafers</th>
<th>Epitaxial Thin Film Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Rate Capability</td>
<td>48 kg/day [17, 11]</td>
<td>0.6 kg/day *</td>
<td>0.68 kg/day [24]</td>
</tr>
<tr>
<td>Mass</td>
<td>45 to 50 kg [17, 11]</td>
<td>&lt;725 kg †</td>
<td>Free-flier:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,900 kg [24, 38]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WSF Package:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3,670 kg [38]</td>
</tr>
<tr>
<td>Volume</td>
<td>0.064 m³, cylinder</td>
<td>&lt;11.9 m³ ‡</td>
<td>Free-flier:</td>
</tr>
<tr>
<td></td>
<td>with 28 cm diameter</td>
<td></td>
<td>3.7 m diameter disk</td>
</tr>
<tr>
<td></td>
<td>and 104 cm length</td>
<td></td>
<td>[24, 19]</td>
</tr>
<tr>
<td></td>
<td>[11]</td>
<td></td>
<td>WSF Package:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>75 m³ [38]</td>
</tr>
<tr>
<td>Power</td>
<td>Data unavailable</td>
<td>Data unavailable</td>
<td>1.2 kW ‡</td>
</tr>
</tbody>
</table>

*Based on the use of 60 kW-hr batteries for 50 hr of epitaxial thin film growth [38].

†Because ACME does not disclose the mass of its hardware, this is the upper limit given by the payload mass of the Cessna Citation 650 used by Sierra Industries, who was contracted by ACME to perform parabolic flight tests [3].

‡Because ACME does not disclose the volume of its hardware, this is the upper limit given by the cabin volume of the Cessna Citation 650 used by Sierra Industries, who was contracted by ACME to perform parabolic flight tests [3].

§Based on the use of 60 kW-hr batteries for 50 hr of epitaxial thin film growth [38].
Figure 6-10: The free-flying Wake Shield Facility is photographed by astronauts on STS-69. In this image, the orbital wake vacuum is present on the left side where molecular beam epitaxy will be performed [26].

6.4.1 Discussion

Analysis of the generalized class of Earth-return systems for ISM has revealed several key findings. Any commercially viable concept in this area requires identification of a product that, by utilizing some unique feature of the space environment, can be fabricated better in-space than on Earth. In general, an ideal ISM concept for Earth-return systems is one that can convert cheap raw material into a high-value product with a large potential market. In the implementation of the concept, it is important that the manufacturing equipment has a small SWaP footprint and can achieve high production rates with minimal scrap parts over a long operational life.\(^1\)

The analysis framework established lets one determine the allowable facility cost given various combinations of the driving parameters. The goal is to determine the ideal tradeoff between each of these parameters to maximize allowable facility cost. In this process, detailed analysis was performed for three specific ISM Earth-return products: ZBLAN fiber optics, SiC wafers, and epitaxial thin films. The ISM of

\(^1\)In all of the concepts investigated, nearly all of the feedstock mass is able to be converted into the value-adding product. Nevertheless, this is still an important consideration when evaluating new concepts.
ZBLAN fiber optic cable was determined to be the most promising application of those considered. However, this analysis process can be repeated for additional ISM concepts as they arise to identify even better concepts.
Chapter 7

Conclusion

In this thesis, the potential for commercial viability of ISM concepts has been explored with the goal of determining technology development targets to guide investment leading to commercially viable ISM. This involves answering the research question "What are the key system drivers and ISM facility properties for an ISM operation that surpasses current launch alternatives in cost or performance?" This endeavor proves challenging due to the wide variety of ISM concepts the have been proposed, both historically and at the present, with a wide range of associated products and manufacturing equipment.

7.1 Generalized Classes Identified

The first step in answering the research question required the identification of the key application areas in which ISM could prove valuable, as detailed in Chapter 3. Generalized classes of ISM application areas were identified by looking at the fundamental change in design constraints resulting from the use of ISM compared to the existing launch approach. This resulted in the following generalized classes: structurally optimized systems, larger-than-launchable systems, Earth-return systems, repairable systems, recycling orbital debris as feedstock, on-demand manufactured systems, accurately tested systems, and planetary surface systems. Each of these potential application areas take advantage of a unique ISM-relaxed design constraint to either reduce
the cost or improve the performance of fabricated systems over existing launched capabilities. These generalized classes are collectively exhaustive of all potential ISM concepts, but they are not mutually exclusive. The generalized classes guide the quantitative analysis of commercial viability of ISM concepts conducted throughout the rest of the thesis.

7.2 Allowable Facility Cost as an Evaluation Criterion

The analysis framework developed in this thesis can be applied to any of the generalized classes of ISM applications to determine commercial viability. In particular, the definition of allowable facility cost in relation to actual realized facility cost, as discussed in Chapter 4, is critical to enabling the evaluation of diverse concepts in the generalized classes without over constraining the creativity and ingenuity of commercial industry in developing and proposing ISM concepts. The computation of allowable facility cost for various concepts captures the potential upside of proposed ISM activities while identifying the key sensitivities that drive allowable facility cost. For a company to develop an ISM capability, it is necessary that the company's required investment be less than the allowable facility cost. Because this thesis does not seek to estimate what actual realized ISM facility costs will be, it allows instead for the determination of what ISM facility costs will need to be for commercial viability. Formulating the problem in this way allows for flexibility in the interpretation of allowable facility cost with regards to varying levels of government investment in ISM RDTE, as well as varying degrees of mass production of ISM facilities.

From the perspective of a government agency, like NASA, seeking to promote ISM by funding technology development, such as through Tipping Point solicitations or SBIRs, the results presented in this thesis can be used to evaluate industry proposals based on their reported key performance metrics and predicted costs. These results can also aid NASA in specifying performance requirements for ISM systems such
that commercial viability can be achieved within the allocated R&D budget. From the perspective of industry representatives, such as companies like Made In Space and Tethers Unlimited, these results can aid in planning future concepts based on anticipated funding support as well as future developments, such as falling launch costs.

### 7.3 Case Studies Conducted

For the purposes of this thesis, an in-depth study was conducted for the generalized classes of structurally optimized systems and of Earth-return systems, which both represent promising ISM application areas with significant commercial interest.

#### 7.3.1 Key Findings for Structurally Optimized Systems

For development of ISM concepts in the class of structurally optimized systems, important considerations must be made regarding both the component chosen for fabrication and the design of the manufacturing equipment itself. One important nondimensional parameter that was identified is the structural mass fraction, $\nu = \frac{\lambda_{SO.ISM}}{\lambda_{SO,LV}}$. This fraction is a measure of the amount of structural mass in the ISM component relative to what it was in the launched case. This fraction is driven by the difference between launch loads and on-orbit loads for the component selected for fabrication. The mass to be fabricated is also a critical driver of allowable facility cost, but requires a design tradeoff regarding the growing actual realized cost of a more capable ISM facility.

Targets for the design of the ISM facility can also be driven by the need to deliver improved performance in the fabricated component. For example, solar array performance in W/kg and kW/m$^3$ is driven by the structural mass fraction, $\nu$, as well as the mass fraction of the part of the system that can be structurally optimized to the part of the system that cannot (such as the solar cells themselves), $\lambda_{SO,LV}/\lambda_{NSO}$. Performance is also driven by the nondimensional facility mass, $\frac{m_{\text{facility}}}{x_{\lambda_{NSO}}}$, and the nondimensional facility volume, $V_{\text{facility}}/V_{SO.ISM}$. This dependence can be used to de-
termine the required facility mass and volume target for a desired performance gain in the fabricated system. Alternatively, the ISM facility can be designed as a free-flying platform which merely delivers the fabricated components, as opposed to an on-board facility. In this free-flying facility case, we effectively set $m_{\text{facility}} = V_{\text{facility}} = 0$, but rendezvous and proximity operations are now required to deliver the product to the customer satellite. When planning for future structural optimization ISM facilities, special care must be made to the recent trend in falling launch costs, which hurts the potential cost savings of these concepts. As launch costs fall, structural optimization will only become effective for performance benefit at higher cost, or for cost savings at destinations far from Earth, where launch costs are higher.

### 7.3.2 Key Findings for Earth-return Systems

For development of ISM concepts in the class of Earth-return systems, important considerations must be made regarding both the product chosen for fabrication and the design of the manufacturing equipment itself. Operations in this class requires the identification of an ISM product that has superior performance (which drives a higher selling price) than Earth-manufactured alternatives and can only be fabricated in the space environment where it takes advantage of some unique phenomena, such as long-duration microgravity or ultra vacuum. If for any reason the product can eventually be fabricated on Earth with equivalent performance to the space-based product, Earth-based operations will necessarily prove cheaper. This risk of moving manufacturing operations back to Earth is always present for any Earth-return system.

### 7.4 Future Work

The work presented in this thesis includes a mid-level analysis of two generalized classes of ISM applications based on available data for historical, existing, and proposed ISM concepts. Future work will develop the established analysis framework to improve the model fidelity, expand the breadth of concepts considered, and validate models through physical experimentation.
The analysis framework presented in this thesis sets the stage for future improvements to the cost and performance modeling effort for ISM systems. Model fidelity can be improved through more accurate computation of parameters identified as key system drivers for commercial viability of ISM. For example, finite element analysis can be used to better identify the potential structural mass savings under various loading conditions. Similarly, better economic modeling could capture the effects of market dynamics, game theory, and price elasticity of demand on the potential sale of Earth-return products. Alternatively, model fidelity can be improved by either including additional input parameters for cost and performance modeling, or by evaluating results with cost models having nonlinear functional forms. Improving model fidelity can also take the form of tracing key parameter values back to specific manufacturing technologies, such as different types of additive and subtractive manufacturing, instead of simply determining the parameter targets for those technologies. Sensitivity analysis could also be better informed using more accurate predictions for future values of key parameters.

Within the scope of this thesis, analysis was only conducted for the class of structurally optimized systems and Earth-return systems. This was intended to demonstrate the validity and usefulness of the analysis framework for setting technology development targets, while allowing for insights to be gained regarding ISM concepts in those application areas. However, for a complete picture of the design options for ISM, one would need to conduct analysis of all of the generalized classes, as well as potential hybrid classes, identified in this thesis. Thus, the breadth of ISM concepts considered can easily be expanded by simply applying the analysis framework to each of the identified generalized classes. Additionally, as new ISM concepts are proposed in the future, their prospect for commercial viability can be continually evaluated with respect to previous and other existing concepts.

This thesis work did not include an experimental component. Instead, available data for ISM concepts was used to determine parameter values and validate models. Future work should focus on physical experimentation to demonstrate and buy down the risk of ISM concepts. The goal of these experimental efforts can be informed by
the key system drivers identified in this thesis. The experiments would either be used to validate key parameter values used to assess commercial viability or show how various technologies stack up in terms of the key parameter values, such as structural optimization fraction, specific revenue of product, and ISM facility mass, volume, production rate, and cost. Interestingly, breakeven points for commercial viability oftentimes depend on the mass of the ISM facility as well as the production rate and total mass produced by the ISM facility. This means that Earth-based, sub-scale ISM demonstrators, which oftentimes necessarily begin as a proof-of-concept that has not been optimized for size, weight, and power, cannot be truly shown to be commercially viable until a more flight-like unit has been produced and tested.
Appendix A

Tables
Table A.1: Launch Vehicle Data (taken from [10])

<table>
<thead>
<tr>
<th>Launch Vehicle</th>
<th>Payload to LEO (kg)</th>
<th>Fairing Diameter (m)</th>
<th>Fairing Length (m)</th>
<th>Price per Launch ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antares</td>
<td>6,200 to 6,600</td>
<td>3.9</td>
<td>9.9</td>
<td>80 to 85</td>
</tr>
<tr>
<td>Ariane 5 ECA</td>
<td>20,000</td>
<td>5.4</td>
<td>17</td>
<td>178</td>
</tr>
<tr>
<td>Atlas V</td>
<td>8,123 to 18,814</td>
<td>4 or 5</td>
<td>12 to 26.5</td>
<td>109 to 179</td>
</tr>
<tr>
<td>Delta II</td>
<td>2,036 to 3,755</td>
<td>2.9 or 3</td>
<td>8.5 to 9.3</td>
<td>137.3</td>
</tr>
<tr>
<td>Delta IV</td>
<td>9,420 to 28,790</td>
<td>4 or 5</td>
<td>11.7 to 19.8</td>
<td>164 to 400</td>
</tr>
<tr>
<td>Electron</td>
<td>225</td>
<td>1.2</td>
<td>2</td>
<td>4.9</td>
</tr>
<tr>
<td>Dnepr</td>
<td>3,200</td>
<td>3</td>
<td>5.3 or 6.1</td>
<td>29</td>
</tr>
<tr>
<td>Falcon 9</td>
<td>22,800</td>
<td>5.2</td>
<td>13.2</td>
<td>62 (new) or 49 (reused)</td>
</tr>
<tr>
<td>Falcon Heavy</td>
<td>63,800</td>
<td>5.2</td>
<td>13.2</td>
<td>90</td>
</tr>
<tr>
<td>GSLV</td>
<td>5,000</td>
<td>3.4</td>
<td>7.8</td>
<td>47</td>
</tr>
<tr>
<td>H-IIA/B</td>
<td>10,000 to 16,500</td>
<td>4.07</td>
<td>12</td>
<td>90 to 112.5</td>
</tr>
<tr>
<td>Launcher One</td>
<td>500</td>
<td>1.4</td>
<td>3.6</td>
<td>12</td>
</tr>
<tr>
<td>Minotaur IV</td>
<td>1,600</td>
<td>2.1</td>
<td>4.11</td>
<td>46</td>
</tr>
<tr>
<td>New Glenn</td>
<td>45,000</td>
<td>7</td>
<td>Undisclosed</td>
<td>Undisclosed</td>
</tr>
<tr>
<td>NGL</td>
<td>Undisclosed</td>
<td>5</td>
<td>15 or 20</td>
<td>Undisclosed</td>
</tr>
<tr>
<td>Pegasus XL</td>
<td>450</td>
<td>1.2</td>
<td>2.1</td>
<td>40</td>
</tr>
<tr>
<td>Proton M</td>
<td>23,000</td>
<td>4.4 or 5</td>
<td>13.3 to 16.3</td>
<td>65</td>
</tr>
<tr>
<td>Saturn V</td>
<td>140,000</td>
<td>6.6 (Skylab)</td>
<td>11.1 (Skylab)</td>
<td>1,200</td>
</tr>
<tr>
<td>Soyuz FG</td>
<td>7,800</td>
<td>4.1</td>
<td>11.4</td>
<td>50 to 213</td>
</tr>
<tr>
<td>Fregat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space Launch System</td>
<td>70,000 to 130,000</td>
<td>8.4</td>
<td>12.5 or 25</td>
<td>2,000</td>
</tr>
<tr>
<td>Stratolaunch</td>
<td>1,350</td>
<td>1.2</td>
<td>2.1</td>
<td>Undisclosed</td>
</tr>
<tr>
<td>Vulcan</td>
<td>9,400 to 31,400</td>
<td>4 or 5.4</td>
<td>12 to 21.3</td>
<td>Undisclosed</td>
</tr>
</tbody>
</table>
Table A.2: Launch Vehicle Loading Environment

<table>
<thead>
<tr>
<th>Launch Vehicle</th>
<th>Max Axial Acceleration (g)</th>
<th>Max Lateral Acceleration (g)</th>
<th>Acoustic Environment (dB)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ariane 5 ECA [5]</td>
<td>4.55</td>
<td>0.25</td>
<td>139.5</td>
</tr>
<tr>
<td>Atlas V [64]</td>
<td>6</td>
<td>2</td>
<td>133.3 to 138.1</td>
</tr>
<tr>
<td>Delta IV [65]</td>
<td>6.5</td>
<td>2</td>
<td>140 to 142.7</td>
</tr>
<tr>
<td>Electron [51]</td>
<td>6.6</td>
<td>0.9</td>
<td>135 †</td>
</tr>
<tr>
<td>Falcon 9 [56]</td>
<td>6</td>
<td>2</td>
<td>131.4</td>
</tr>
<tr>
<td>Pegasus XL [42]</td>
<td>3.7</td>
<td>2.33</td>
<td>130.8</td>
</tr>
<tr>
<td>Space Launch System [37]</td>
<td>4.1</td>
<td>2</td>
<td>144.7</td>
</tr>
</tbody>
</table>

*Overall sound pressure level (OASPL) based on 60% fill factor and 95% probability with 50% confidence
†Overall sound pressure level (OASPL) based on 50% fill factor
Table A.3: SBIR/STTR Funding for ISM Projects in Generalized Classes

<table>
<thead>
<tr>
<th>Company</th>
<th>Project</th>
<th>Generalized Class</th>
<th>Year</th>
<th>Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Made In Space, Inc.</td>
<td>Industrial Crystallization Facility for Nonlinear Optical Materials</td>
<td>Earth-Return</td>
<td>2017</td>
<td>$124,653</td>
</tr>
<tr>
<td></td>
<td>The Vulcan Advanced Hybrid Manufacturing System</td>
<td>On-Demand, Repairable</td>
<td>2017</td>
<td>$124,865</td>
</tr>
<tr>
<td></td>
<td>MicroCast: Additive Manufacturing of Metal Plus Insulator Structures with Sub-mm Features</td>
<td>On-Demand, Repairable</td>
<td>2014</td>
<td>$119,934</td>
</tr>
<tr>
<td></td>
<td>ISS Additive Manufacturing Facility for On-Demand Fabrication in Space</td>
<td>On-Demand, Repairable</td>
<td>2011</td>
<td>$824,597</td>
</tr>
<tr>
<td>Techshot, Inc.</td>
<td>Sintered Inductive Metal Printer with Laser Exposure</td>
<td>On-Demand, Repairable</td>
<td>2017</td>
<td>$749,782</td>
</tr>
<tr>
<td></td>
<td>Software and Tools for Electronics Printing in Space (STEPS)</td>
<td>On-Demand, Repairable</td>
<td>2017</td>
<td>$124,762</td>
</tr>
<tr>
<td></td>
<td>Space Plastic Recycling System</td>
<td>Planetary Surface</td>
<td>2015</td>
<td>$124,832</td>
</tr>
<tr>
<td>ZeCoat Corporation</td>
<td>Battery-Powered Process for Coating Telescope Mirrors in Space</td>
<td>Earth-Return, Larger-than-Launchable</td>
<td>2017</td>
<td>$124,697</td>
</tr>
<tr>
<td>FOMS, Inc.</td>
<td>Space Facility for Orbital Remote Manufacturing (SPACEFORM)</td>
<td>Earth-Return</td>
<td>2017</td>
<td>$750,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2016</td>
<td>$122,800</td>
</tr>
<tr>
<td>Ultra Tech Machinery, Inc.</td>
<td>ISS Multi-Material Fabrication Laboratory using Ultrasonic Additive Manufacturing Technology</td>
<td>On-Demand, Repairable</td>
<td>2017</td>
<td>$125,000</td>
</tr>
<tr>
<td>Altius Space Machines, Inc.</td>
<td>ISP3: In-Situ Printing Plastic Production System for Space Additive Manufacturing</td>
<td>Planetary Surface</td>
<td>2016</td>
<td>$124,943</td>
</tr>
<tr>
<td>Nano EnerTex</td>
<td>Lunar In-Situ Fabrication: The Manufacturing of Thin Film Solar Cells on the Surface of the Moon</td>
<td>Planetary Surface, Larger-than-Launchable</td>
<td>2006</td>
<td>$68,198</td>
</tr>
<tr>
<td>Company</td>
<td>Project</td>
<td>Generalized Class</td>
<td>Year</td>
<td>Funding</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------------------------------------------------------------------------</td>
<td>----------------------------------------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>Optomec, Inc.</td>
<td>Adaptive Laser Sintering System for In-Space Printed Electronics</td>
<td>On-Demand, Repairable</td>
<td>2017</td>
<td>$124,760</td>
</tr>
<tr>
<td>Longhurst Engineering, PLC</td>
<td>In-Space Friction Stir Welding Machine</td>
<td>Larger-than-Launchable, Repairable</td>
<td>2013</td>
<td>$125,000</td>
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<tr>
<td>General Digital Industries</td>
<td>Wire-Based Welding Processes for In-Orbit Applications</td>
<td>Larger-than-Launchable, Repairable</td>
<td>1990</td>
<td>$499,959</td>
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<tr>
<td></td>
<td>Investigation of GMA Welding in Space</td>
<td>Larger-than-Launchable, Repairable</td>
<td>1990</td>
<td>$49,947</td>
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<tr>
<td>Makel Engineering</td>
<td>In Situ Manufacturing of Plastics and Composites to Support H&amp;R Exploration</td>
<td>Planetary Surface</td>
<td>2006</td>
<td>$50,000</td>
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<tr>
<td></td>
<td>High Efficiency, Integrated Manufacturing System for Mars Using Microchannel Component Technology</td>
<td>Planetary Surface</td>
<td>2006</td>
<td>$69,460</td>
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<tr>
<td>Luna Innovations, Inc.</td>
<td>In-Situ Generation of Polymer Concrete Construction</td>
<td>Planetary Surface, Larger-than-Launchable</td>
<td>2016</td>
<td>$125,000</td>
</tr>
<tr>
<td></td>
<td>Materials Characterization for Space Manufactured Components</td>
<td>All (enabling)</td>
<td>2007</td>
<td>$99,983</td>
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<tr>
<td>Physical Sciences, Inc.</td>
<td>Novel Technology for In-Space Manufacture of Thin Membranes for Solar Sails</td>
<td>Larger-than-Launchable</td>
<td>2000</td>
<td>$599,978</td>
</tr>
<tr>
<td></td>
<td>Production of oxygen and Other Products by Pyrolysis of Lunar Materials</td>
<td>Planetary Surface</td>
<td>1988</td>
<td>$441,530</td>
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<tr>
<td></td>
<td>Multicolor Imaging Pyrometer for Materials Processing in Space</td>
<td>Earth-Return, Planetary Surface</td>
<td>1985</td>
<td>$489,092</td>
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<td></td>
<td></td>
<td></td>
<td>1985</td>
<td>$49,995</td>
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<tr>
<td>Company</td>
<td>Project</td>
<td>Generalized Class</td>
<td>Year</td>
<td>Funding</td>
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<tr>
<td>------------------</td>
<td>-------------------------------------------------------------------------</td>
<td>------------------------------------------</td>
<td>------</td>
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<tr>
<td>Tethers Unlimited, Inc.</td>
<td>ERASMUS: Food Contact Safe Plastics Recycler and 3D Printer System</td>
<td>Planetary Surface, On-Demand</td>
<td>2017</td>
<td>$749,912</td>
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<td></td>
<td>2016</td>
<td>$124,867</td>
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<td></td>
<td>Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA) Process</td>
<td>On-Demand, Repairable, Planetary Surface</td>
<td>2017</td>
<td>$124,990</td>
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<tr>
<td></td>
<td>The Automated X-Link for Orbital Networking (AXON) Connector</td>
<td>Larger-than-Launchable, Repairable</td>
<td>2017</td>
<td>$124,989</td>
</tr>
<tr>
<td></td>
<td>MakerSat</td>
<td>Larger-than-Launchable, Structurally Optimized</td>
<td>2017</td>
<td>$124,846</td>
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<tr>
<td></td>
<td>OrbWeaver: System for Repurposing an ESPA Ring to Create a Large Phased Array SATCOM System</td>
<td>Larger-than-Launchable, Planetary Surface</td>
<td>2017</td>
<td>$1,499,265</td>
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<tr>
<td></td>
<td>The Constructable Platform: Modular Architecture for a Persistent Platform in GEO</td>
<td>Repairable, Larger-than-Launchable</td>
<td>2017</td>
<td>$1,499,404</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2016</td>
<td>$149,952</td>
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<td></td>
<td>CRISSP - Customizable Recyclable International Space Station Packaging</td>
<td>Planetary Surface</td>
<td>2016</td>
<td>$749,872</td>
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<td></td>
<td>2015</td>
<td>$124,976</td>
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<td></td>
<td>Positrusion Filament Recycling System for ISS</td>
<td>Planetary Surface</td>
<td>2015</td>
<td>$1,749,870</td>
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<td></td>
<td>2014</td>
<td>$124,984</td>
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<td></td>
<td></td>
<td></td>
<td>2013</td>
<td>$124,999</td>
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</table>
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