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Operations in Space: Exploring a New Industry

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ABSTRACT

This article sets the stage for examining operations management research opportunities in the emerging industry that involves operations in outer space. Currently, space exploration is moving in new and exciting directions, thanks to private investment and a more collaborative, commercial industry structure. While we do not yet know if space will be the next big industry, we make the case that the potential is certainly there. In this article, we outline the challenges presented within the "space industry" and highlight opportunities for operations management researchers in three categories—manufacturing operations, supply chain management, and sustainable operations. We also outline important questions related to stakeholder decisions and needs. [Submitted: November 28, 2017. Revised: March 17, 2018. Accepted: March 19, 2018.]

Subject Areas: Operations Management, Research, Space Industry, and Supply Chain.

INTRODUCTION

On October 11, 2017, a rocket sitting on launch platform LC-39A at (National Aeronautics and Space Administration) NASA's Kennedy Space Center in Florida fired up its engines. Over 400,000 kg of kerosene and subcooled liquid oxygen began producing the 7,607 kN of force needed by the first of its two engine stages to escape the Earth's gravity (for comparison, an F-15 fighter jet produces only 130 kN)[i]. Thirty-six minutes later, the 5.7-ton EchoStar 105/SES-11 satellite it was carrying deployed into orbit, where it will maintain an altitude of nearly 35,800 km above the equator and provide video and data services for the Americas. Everything worked perfectly.

Several things are notable about this "space" story. First, it was hardly noted on Earth. Most people could not have told you that a rocket went to space; the news barely covered it. A host of technological improvements since the early days

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[i] Note: 1 kN = 1,000 kg × m/s^2 = 102 kg × 9.81 m/s^2.

of spacecraft rendered this spectacular event of choreographed engineering and execution commonplace.[ii] Second, the group responsible for this launch was not NASA (or some other government agency) but SpaceX: a private company headed by the well-known Elon Musk. SpaceX serves as the poster child for a new and robust private spaceflight industry that is changing the way humanity accesses outer space. "Private, commercial spaceflight. Even lunar exploration, mining, and colonization – it's suddenly all on the table, making the race for space today more vital than it has felt in years," notes Roberson (2016). Together, these noteworthy aspects hint that space exploration may be charting a new course for the "space industry"—one that offers many possibilities for operations researchers.

The space industry has historically been defined through the lens of producing things that go into outer space, such as satellites and rockets. As the types of space activities have proliferated, a broader definition has emerged that includes all products and services that arise in the course of exploring and utilizing outer space. There are many parallels between the emerging space industry and the early years of the automobile industry. After the invention of the internal combustion engine, it was big news any time a new car or design was produced. Soon such advances were commonplace (the same as in our EchoStar satellite example). Also, the number of auto firms grew significantly early on, with more than 200 manufacturers in each of Britain, France, and the U.S. in the early 1900s (Scaruffi, 2013). Later on, car manufacturers moved from being largely vertically integrated to more decentralized (Langlois & Robertson, 1989). This involved many more entities than before. The number and complexity of automotive supply chain challenges grew quickly as a result of this shift. However, in the beginning of the automobile era, there was no organized supply chain research community, and thus, industry led the way in major innovations (e.g., mass production, interchangeable parts, just-in-time (JIT), lean production, and total quality management (TQM)). If operations management (OM) researchers want to be considered as thought leaders, we need to be more proactive in our research of operations solutions for the next big emerging industry. While we do not yet know whether outer space will be as big or transformative as the auto industry, it certainly seems as if the potential is there. Our goal in this article is to examine potential OM research opportunities in this new space industry, highlighting those that pose difficult and uncertain tradeoffs for decision makers.

Recently, a number of scholars have advocated for proactively expanding the scope and reach of a variety of disciplines, including practice-based OM (Roth, Singhal, Singhal, & Tang, 2016), supply chain management (SCM) (New, 1997; Singhal & Singhal, 2012), and behavioral operations (Gino & Pisano, 2008; Croson, Schultz, Siemsen, & Yeo, 2013). In the quest of expanding the scope of OM research, we examine potential research opportunities arising in the emerging space industry. We do so in a similar vein to OM research in operations and logistics arising from emerging geographic markets (Iyer, Lee, & Roth, 2013), global OM (Narasimhan, 2014), health care operations (Smith-Daniels, Schweikhart, & Smith-Daniels, 1988; Roth et al., 2016), innovation management processes

[ii] In fact, just 2 days before (on October 9th), three other unmanned spaceships recorded successful missions. Two weeks prior, another five launches occurred. On average, a blastoff currently occurs every 4.2 days, and for the most part, the media simply treats it as business as usual.

(Carrillo, Druehl, & Hsuan, 2015), interdisciplinary work with SCM (Sanders, Zacharia, & Fugate, 2013), socially responsible operations (Lee & Tang, 2017), and sustainable SCM (Sarkis, 2003; Brandenburg, Govindan, Sarkis, & Seuring, 2014). Singhal, Sodhi, and Tang (2014) summarize the thrust of such research thusly: "To make research still more meaningful for practice and more vibrant, the OM community needs to take proactive steps to ensure our research is driven by practice so that our research can also influence practice." There are examples where focused, rigorous academic research has led the way and changed how markets operated—such as the economic order quantity formula for inventory management—even if adoption has lagged the discovery in some cases (Erlenkotter, 2014). There are also numerous examples where industry has led the way and academia has had to catch up—"fast fashion" retailing with short production and distribution cycle times (Ghemawat, Nueno, & Dailey, 2003; Caro & Gallien, 2010; Cachon & Swinney, 2011) and the Toyota production system, whose procedures contradicted the best analytical models at the time (Roth, 2007), are two such cases. Instead of focusing on research areas that seek to explain what has happened in practice or why a certain industry (or company) launched a particular initiative, we would like to explore potentially new ideas that may motivate researchers from our field to start thinking about operations problems in space, perhaps even before these problems are completely identified.

In this article, we explore two questions: (i) Why is research on operations arising from the space industry intellectually valuable? (ii) What opportunities does the current space industry present for novel research? Over the next sections, we discuss how the underlying problems for operating in the space industry are fundamentally different from traditional OM research that has focused on Earth, map a number of existing research topics to these problems, and present some potential opportunities for future research.

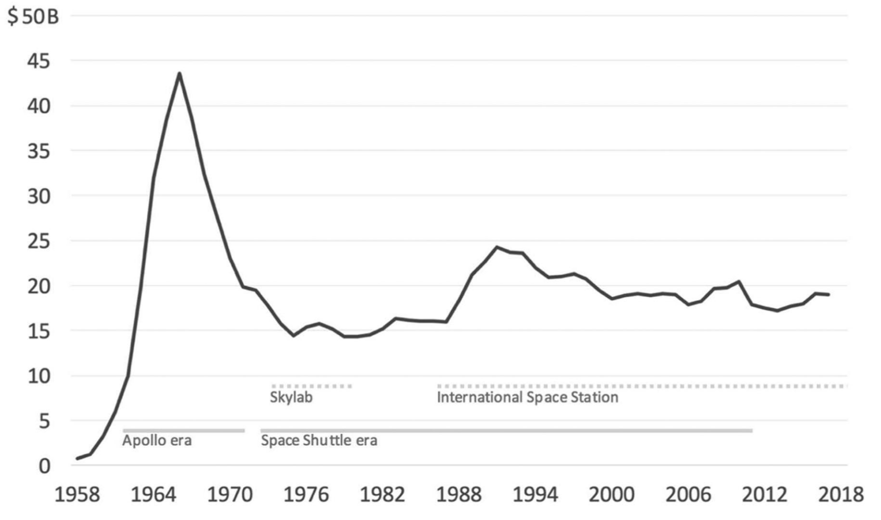
THE NEW SPACE INDUSTRY

In order to understand the current state of the space industry, let us briefly review the past history by arranging the progress of space exploration according to three successive phases: *competition*, *collaboration*, and *openness*.

Competition

In late 1957, the space race began when the Sputnik program put a satellite and then a dog (Laika) into orbit, inspiring competition between countries—most notably the Soviet Union and United States. President John F. Kennedy fueled that rivalry when, in a surprise move on May 25, 1961, he announced that the U.S. would go to the moon by decade's end. The back-and-forth between the two Cold War superpowers left a string of "firsts" in the record books, culminating in Apollo 11's historic delivery of Neil Armstrong and Buzz Aldrin to the moon, but also required massive investment (Figure 1). The early 1970s saw the last phases of this intensely competitive period in the form of space station launches (e.g., Soviet Salyut and U.S. Skylab) as political relations began to thaw. On top of that, the Vietnam war had changed the political focus and depleted resources in the U.S.,

Figure 1: NASA annual budget.



Note: Budgets shown in 2014 dollars ($B); Data from NASA.

leading to a deep reduction in NASA's budget that prevented sustained rivalry and redirected efforts (Bilstein, 1989).

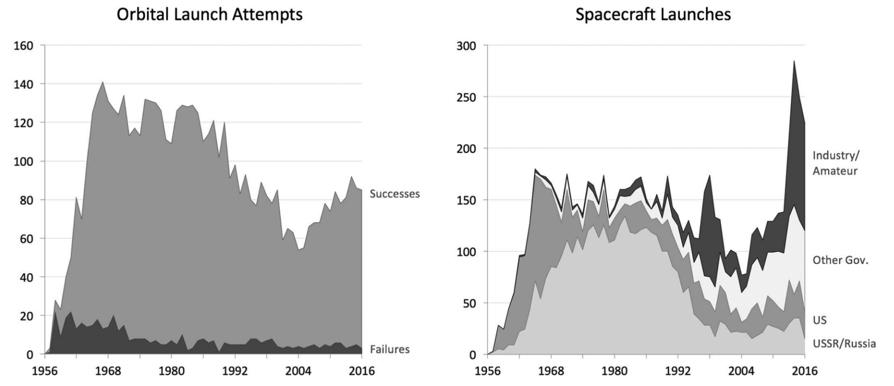
Collaboration

By 1975, the first joint space mission was underway, as the U.S. and Russia teamed up on an astronaut/cosmonaut safety project to develop a docking and rescue system compatible with both countries' spacecraft, and an unprecedented cooperation between the superpowers followed (Bilstein, 1989). NASA was also collaborating more on the ground, and the early 1970s marked a shift toward the agency sending up more satellites for other governments and companies than it did for itself (Bilstein, 1989). These changes were deliberate and conspicuous, ushering in an area of collaboration best illustrated by the International Space Station, which required 16 countries and over 40 missions to assemble.

Openness

By the time the U.S. space shuttle program was retired in 2011, the transition to a space industry that included private, commercial companies instead of national governments was already underway. Developmental programs paved the way for private firms to resupply the International Space Station with cargo and—eventually—people. According to Roberson (2016), "today, space exploration is undergoing a radical shift, the first major change since the Space Age began in the late 1950s, thanks to all of those new businesses focused on doing what NASA had been solely responsible for." Firms like SpaceX, Blue Origin, Virgin Galactic, Sierra Nevada, and Rocket Lab now develop different spacecraft. Firms like Made In Space, Planetary Resources, and Deep Space Industries now develop manufacturing and resource capabilities for space. Companies such as

Figure 2: Worldwide launches into space.



Note: Orbital launches include manned and unmanned spaceships launched into orbital flight from Earth. Spacecraft launches include all vehicles (e.g., spaceships, satellites, probes) launched from Earth or space. Data from Space Launch Report (Kyle, 2017), Spacecraft Encyclopedia (Lafleur, 2017).

NanoRacks and Astrobotic are positioned as logistics facilitators for payloads and launches. A whole ecosystem has emerged that is based on private investment (not just public). Part of this transformation began as early as 2004, when the Ansari XPRIZE awarded \$10M for the first private sector suborbital spaceflight. Just 3 years later, the Lunar XPRIZE attracted entrants from twice as many countries and helped inspire a decade of private investment in low-cost, robotic space exploration around the globe. The results of the shift can be seen in worldwide launch statistics (Figure 2). The uptick in *orbital launches* (i.e., rockets or shuttles launched from Earth) in the last 10 years coincides with the more open space industry—along with a surprisingly stable rate of success (~95%). Part of this is driven by a significant increase in *spacecraft launches* (i.e., vehicles launched from Earth or space) from non-U.S. and non-Russian governments, industry (e.g., telecommunications companies), and amateur groups (e.g., education projects, wealthy hobbyists) during that time. While the early history of space exploration was dominated by two countries, today's industry is global. Nine national space budgets exceed \$1B (including the U.S., China, Russia, India, Japan, France, Germany, Italy, and the rest of Europe, collectively, through the European Space Agency)—with another 40 nations allocating smaller budgets for their space agencies (Bryce Space and Technology, 2017). For example, in 2003, China became the third nation to launch a manned spaceship into orbit and has fueled additional growth with plans for its own permanent space station. In some ways, space is becoming another place to do business, where technology can be put to new and varied uses to further firm (or government) interests on the ground.

THE MOTIVATION

The case for further space exploration is generally based on three arguments: (i) *the appeal of the unknown*, (ii) *scientific advances*, or (iii) *supply and demand.*

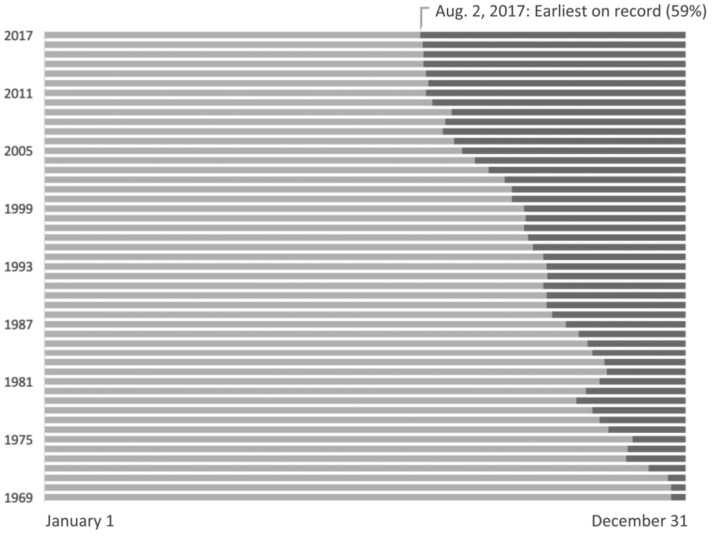
First, as long as there have been new things to explore, humans have been drawn to the challenge of the unknown. As famed English mountaineer George Mallory replied when asked why he wanted to climb Mount Everest, "Because it's there" (Mallory, 1923). This simple ethos of curiosity captures much of our fascination with space, even if the other two reasons seem more rational.

The second force behind further space exploration is the cultivation of knowledge. Conquering the technical challenges of space exploration has, historically, led to advancements in a wide array of fields. Just looking at innovations directly attributable to NASA that now impact consumers, one can count light-emitting diode (LED) tumor therapies and advances in artificial limbs (in medicine), memory foam and real-time Global Positioning System (GPS) improvement systems (in consumer products), and open source cloud computing platforms and single-crystal solar cells (in technology)—to name but a few (NASA, 2008). NASA has also propelled innovation through its various centers and partners (e.g., the Jet Propulsion Laboratory) and initiatives (e.g., the Small Business Innovation Research program), demonstrating how an entire network can benefit. Basic science research in outer space also contributes to our understanding across disciplines, from biology to physics. Currently, scientists are hoping to learn more about Mars and its history as a planet (which once had an atmosphere thick enough to sustain water on the planet surface but is now dusty and inhospitable) in order to help predict the future of Earth. In sum, space exploration generates benefits from tangible innovation and new product development as well as advances in general science and technology knowledge.

Finally, the third motivation arises from basic supply and demand. Scientists have postulated—from early predictions by Konstantin Tsiolkovsky (pioneer of astronautics) to recent predictions by Stephen Hawking—that humanity's long-term existence requires *not* remaining tethered to a single planet. Currently, the demand on Earth exceeds supply. In 2017, the globe's resource use outstripped its capacity for production on August 2nd, the equivalent of a "resource overdraft" of 41% (Figure 3). The demand for Earth's resources is expected to continue to grow due to population growth, longevity resulting from better health care, and increasing consumption caused by economic development in developing countries (Gerland et al., 2014). In parallel, the Earth's supply faces challenges, with reduced access to arable land (which has shrunk by a third since 1975), water (whose usage has grown twice as fast as the population in the last century), and fossil fuels (which models predict could be used up in 30–100 years, depending on the type) (Tilman et al., 2001; Shafiee & Topal, 2009; Cameron, Osborne, Horton, & Sinclair, 2015). On top of that, climate change brings the possibility of disruptions and devastation. If demand is clearly increasing and the Earth's supplies are shrinking and/or constrained, then the solutions needed to avoid disequilibrium involve reducing demand (through population or consumption controls) or increasing supply (through improvements to efficiency, increased sustainability, or alternative supply sources).

One of the economic arguments for space exploration lies in the opportunity to help rebalance the Earth's supply and demand equation. Space colonies could (over time) shift demand away from our home planet. Additionally, space is rich in several notable categories—capacity (volume), resources (elements),

Figure 3: Global biocapacity shortfall—Earth's ecosystem overshoot in calendar days.



Note: Biocapacity shown as Earth Overshoot Day, the date each year the Earth's annual natural resource production is used up by demand. Data from Global Footprint Network, Bullard (2015).

and energy (including dark energy and solar)—that could ease the reliance on Earth's finite supply. The extra *space* in space could provide for habitation, plant and food production, or waste solutions. Resources like phosphorous, zinc, platinum, cobalt, and gold could be extracted from asteroids or planets to replace scarce quantities on Earth. Figuring out alternate energy sources also opens up new possibilities—for instance, breakthroughs in plasma propulsion engine technology, which uses radio waves along with propellant, have brought interplanetary travel closer to reality. Instead of merely sounding like snippets from 2015's blockbuster movie *The Martian*, there is a thriving space industry working to make the successes of Matt Damon's character on Mars a possibility for all of us. (Japan, for example, is funneling investment and research in this direction after seeing little growth in the automobile and home appliance industries; Mitsubishi, Subaru (Fuji), and Kawasaki are each involved in the new space industry). The next question is whether those opportunities offer meaningful chances for operations research.

To make the case that research in the space industry is intellectually valuable, we contend that the question or cause must be relevant in practice. In a rich article on the topic, Toffel (2016) addresses a number of approaches to evaluating practical relevance, one of which requires answers to the following questions all be *yes*: Will the research address a new question or relationship? Will decision makers care (could it lead to catastrophic consequences)? Can the question be answered rigorously? In the case of space operations, we believe there are a host of research topics that meet these criteria. Certainly, the fact that space is a dangerous realm in which to operate raises the stakes on what might be routine elsewhere. Operators are also tackling new endeavors where the answers and approaches are not known in advance. In many ways, the space industry has been directed by technology-driven questions, but the need for decisions and structures to be analyzed through a business lens is often seen after crises. Take one of the most well-known failures, the space shuttle *Challenger* disintegration in 1986, which led to extensive inquiries into the organizational structure and managerial decision-making processes at NASA (Bilstein, 1989). Just as there were valuable internal questions to assess then, the expansion of the private space industry presents a whole new set of questions related to development, operations, and coordination for current practitioners. By way of Toffel's (2016) frameworks, the practical relevance of research in the new space industry offers the ability for researchers to directly impact outcomes that (at a minimum) are relevant and important in an exciting, new field and (at most) help determine the fate of humanity.

CHALLENGES OF SPACE OPERATIONS

One approach to addressing questions that arise in the context of *space operations* relies on our existing theories and frameworks and forces the questions to conform to our existing worldview. An illustrative example would be taking sourcing models from the global SCM literature and simply treating Earth as a single, distant supplier. That might be a good starting point but undersells the complexity of operating in space (and may omit factors that take on increased importance in outer space). As access to space has expanded and serious discussions of Mars missions and other such endeavors have emerged, many of the challenges of space have also risen to the forefront (Leckie et al., 2016). We identify four types of challenges: (i) *distance*, (ii) *gravity*, (iii) *inhospitable environments*, and (iv) *information*.

Distance

Things that humans might be interested in visiting in space (e.g., the moon, Mars, asteroids) are almost inconceivably far away. Consider that of the several hundred people who have been to space, all but 24 have remained in low Earth orbit (LEO)—within 2,000 km of the Earth's surface (the International Space Station is about 400 km away at any given point). The remaining 24 were part of the Apollo moon missions and entered lunar orbit—some as far away as 400,171 km. Mars is (at its closest) about 55,000,000 km away from Earth. This raises the challenge of how to cover such great distances and exist so far from home.

Gravity

Before you can cover extraordinarily large distances, however, there is the challenge of leaving Earth (or whatever massive object you are leaving from). Getting away from Earth's gravity requires speeds in excess of 40,000 km per hour, which in turn requires significant money (Leckie et al., 2016). For SpaceX's Falcon 9 rocket and capsule (at the frontier of affordability) that amounts to: $37M in rocket fixed costs (less than half that, if reused) and $250K in fuel, plus $850M in initial research and development (R&D) (Shotwell, 2014; de Selding, 2016).

Inhospitable environments

Just being in space comes with challenges that must be overcome with technology or ingenuity. Air, water, and food are three of the basic human needs. In space, those are nonexistent; on other celestial bodies, they are generally sparse or inaccessible. The next human need, protection from the elements, is equally daunting. Both the extreme radiation levels of space and the lack of gravity cause broad health problems.

Information

Our ability to collect, transmit, and use information in space is growing but limited. For instance, navigation is in its infancy and currently relies on Earth-bound equipment. There is also the problem of space debris—all the junk that orbits the planet—traveling at speeds up to 28,000 km per hour. More than 500,000 pieces are tracked (more than 20,000 of which are larger than a softball), and navigating these deadly threats is a regular activity of the International Space station (Scudder, 2016). Communicating across the vast reaches of space and figuring out ways to collect information that is standard on Earth (like medical diagnostic data in space) also fall into this bucket.

Together, these four challenges highlight how different the backdrop of the business environment appears when compared to existing terrestrial settings. Next, we make these general claims more concrete by looking at three promising research areas that our research communities are equipped to answer.

AREAS OF RESEARCH OPPORTUNITY

As part of a recent special issue on operations issues in emerging markets, Iyer et al. (2013) argue that as a result of new resources in developing nations, the global economy has experienced unique structural change that demands attention from operators and managers. The exact same arguments apply to today's space industry. Amidst the growth of capital, firms, and knowledge, both researchers and practitioners must figure out how different entities should manage their daily operations, organize their network, and develop sustainable operations in space. By considering those four aforementioned challenges (i.e., *distance*, *gravity*, *inhospitable environments*, and *information*), we now explore a number of promising avenues in the space industry for OM researchers. Specifically, we group these resulting opportunities in three categories—*manufacturing operations*, *supply chain management*, and *sustainable operations* (Table 1). While there are other topics not explored in this article, we focus on a set of core questions that offer immediate opportunities. We then address, in a subsequent section, how the needs of the various stakeholders—those individuals, firms, and governments engaging with the new space industry—are met and how their decisions relate to the above opportunities.

Table 1: Overview of challenges and research opportunities in space operations.

	Resulting Research Opportunities		
Challenges	Manufacturing Operations	Supply Chain Management	Sustainable Operations
Distance *Things are far away*	- Distributed production - Utilization of limited capacity - Need for flexibility	- Long lead times - Long cycle times and lack of flexibility	- Need for shortened supply chains to deal with disasters
Gravity *Earth's pull is strong*	- Inability to launch large/ fragile structures	- High cost of resupply	- Dealing with orbital debris
Inhospitable environ. *Many hurdles exist*	- Parts failure - Expanded production possibilities (zero-gravity)	- Poor inventory management - Limited access to abundant space resources	- Environmental impacts of production, operation, etc. - Need for reuse, recapture, and recycling
Information *Limited data & comm.*	- Planning	- Coordination among growing number of entities - New collaboration methods	

Manufacturing Operations

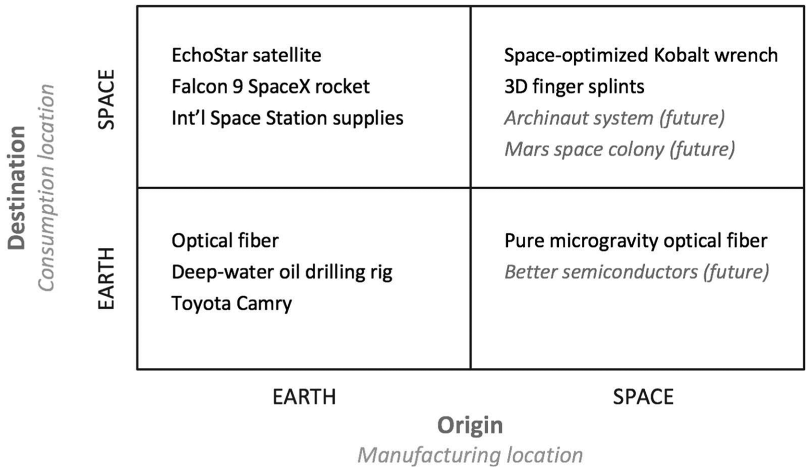
To highlight the relevance of manufacturing questions, we start with an example to provide some context. Currently, several companies and countries have ongoing missions (in early stages) for human travel to Mars. While most peg that accomplishment as being 15 years away, milestones are already being pursued and checked off. These represent audacious goals at the frontier of technology and exploration. Any hope of attempting space exploration beyond the near confines of Earth requires contending with the *distance* and *inhospitable environments* challenges because it is virtually impossible to take everything one would need on a long voyage—whether food, water, or supplies.

To overcome this fundamental challenge is to "build things in space." For example, Made In Space (https://madeinspace.us/) took the first step by installing a three-dimensional (3D) printer on the International Space Station in 2014 and then furthered that technology leap with a bigger, permanent additive manufacturing facility. As the first commercial manufacturing service in space, Made In Space now manufactures tools, devices, and parts for the crew while in orbit. The next step, whose funding has been awarded by NASA, is to autonomously manufacture and assemble large-scale structures (like structural booms, satellites, and even space stations) directly in space. This greatly reduces the limitations on operations in space because items are not limited to fitting inside a rocket (size) or withstanding blastoff (stability).

There is also the fabrication of Earth-based products that can be manufactured *better* in space—current testing is underway on superior optical fiber, which is not subject to the flaws of fiber optics made on Earth. This setup—while still in space—represents a potentially different set of manufacturing challenges: now production (the origin) is in space but consumption (the destination) is not. We differentiate these contexts by way of a two-by-two Earth-space operations framework (Figure 4) in which the origin *and* destination can be either Earth or space. Our two-by-two framework applies to both settings that deal with manufacturing operations and supply chain management: the Earth-Earth quadrant represents the traditional set of operations, while the other three quadrants include a space interface. The Made In Space examples above show up in both the space-space (e.g., wrench, splints) and space-Earth (e.g., pure microgravity optical fiber) quadrants. The novel idea of producing things that involve space as the origin represents the most disruptive change to the current landscape, and this idea leads to a number of interesting manufacturing operations questions:

(1) *Where and when should space production capacity be built? In space or on Earth? How can production be scaled up (speed and capabilities) and what role does uncertainty play?*
Gaimon and Burgess (2003) present an analytical model for capacity expansion that explicitly includes lead times to operationalize extra capacity as well as learning costs. Building on such models (that expand on the assumptions) may capture the unique differences of space and generate insight about how to manage production capacity in space. There may also be some qualitative lessons that can be taken from other extreme environments, including deep-water oil and gas production

Figure 4: A framework of earth-space operations.



facilities or research operations in Antarctica. Answering the question of how to expand production as we move farther away from Earth is an important step in human exploration.

(2) *How can capacity best be utilized? How should decision makers think about flexibility, adaptability, and efficiency in space manufacturing? How is production optimized in the space domain (and what factors become more influential in the decisions)?*
Given the current (or envisioned) production capacity, a more tangible question is around the best use for that capacity. There are many fruitful investigations to be had under this umbrella, from traditional scheduling problems to incorporation of new technologies into production. A first step may involve building on the single machine literature and incorporating additional constraints due to high space holding costs *or* building on the flexible manufacturing systems literature to assess the benefit of JIT flexibility and lead time reduction. Another step is to examine how new technologies enable manufacturing in space. For example, NASA is exploring automated construction on Mars in advance of human occupation through the use of intelligent robotics—the Valkyrie humanoid robot (Radford et al., 2015) and Made In Space Archinaut project extend the current notion of what is possible with automation. Despite these production technologies in space, there is no model to examine how to utilize these capabilities more efficiently or how these new capabilities change the economics of production.

There is also the whole other side of manufacturing (that of producing on Earth *for* space). This is represented by the upper left quadrant in Figure 4. Currently, a much bigger segment, questions around quality management and planning frame some of the major topics. Consider quality management. In 1994, the U.S.

Department of Defense began to move away from military standard (MIL-SPEC) and build-to-specification parts and allow for commercial parts. The goal was to increase access to state-of-the-art technology, lower costs, and quicken delivery; however, in the last 10 years, NASA has incurred $1.3 billion in losses as a result of parts not meeting performance standards (NASA, 2017b). Thanks to the unforgiving environment, small defects can result in major catastrophes. One example is the 2015 SpaceX resupply launch, where a single strut certified to handle 44.5 kN of force failed at only 8.9 kN, destroying over 2,400 km of equipment and supplies in the resulting explosion (NASA, 2017b). The recommendations accompanying these audit details from the NASA Office of Inspector General include structural, informational, and risk assessment improvements. Some aspects of production readiness have been examined in the literature, like the technology readiness level scale that NASA has used since the 1970s to assess complex system development and the challenges therein (Olechowski, Eppinger, & Joglekar, 2015).

(3) *What is the impact of quality on space operations? What are the underlying risks?*
It is not clear whether the risk of defective products can be mitigated in a cost-effective way. It may be that learning and expertise developed in the natural course of manufacturing is the most efficient. Or that redundancy and fail-safes offer a better option. There is a research opportunity to analyze failure rates, process costs, and risk in the new space economy to gain a deeper understanding of how quality affects operations. An interesting direction for empirical research could be in partnering with a firm (e.g., SpaceX) and gathering data on these elements to understand the ways that quality—and quality management practices—impacts decisions and outcomes.

Overall, the field of operations has advanced the study of manufacturing with research into inventory, efficiency, planning, just-in-time, and more while focused on cost reduction. The challenges of space require stepping through some of the same issues with an eye on quality, customer benefits, information processes, and strategic flexibility.

Supply Chain Management

It stands to reason that organizing all of the entities along a supply chain that interfaces with outer space is a big endeavor. The products are typically complex, technology-driven, and expensive. In addition, most missions are unmanned, increasing the dependence on systems. Relying on our Earth-space operations framework (Figure 4) helps illustrate how many of the initial issues will be similar regardless of context, since mankind currently has no instance where the supply chain does not touch Earth in some way. Three instructive examples from the International Space Station include astronaut supplies conveyed from Earth (upper left quadrant: Earth-space), custom-printed 3D finger splints for astronauts from the onboard Made In Space facility (upper right: space-space), and microgravity optical fiber production (lower right: space-Earth). In each case, the raw materials, supplier, transportation, and coordinating entity originate from Earth. While an entire supply chain may eventually be located in space, the challenge of interfacing and coordinating with Earth are the focus of this section.

Two of the operations elements that change the most in the context of space are supply chain lead times and the cost of resupply. These directly result from our first two challenges of space—distance and gravity. Basically, it is no small task to get things off Earth. It takes a typical rocket less than 3 minutes to reach space (past the common demarcation 100 km up known as the Karman line) and less than 10 minutes to reach LEO, yet it requires hours or days to dock with the International Space Station. A traditional docking involved 34 orbital laps of the Earth with a series of Hohmann transfers to match the exact orbit of the space station, but with precise timing, today's missions can dock in under 6 hours (Jaggard, 2013). That, however, does not include the time needed to ready a spacecraft for launch on the ground. As for cost, common estimates peg the cost of getting 0.5 km into orbit at $10,000 (Kramer & Mosher, 2016). As space exploration ventures farther away (e.g., the moon, Mars), these issues intensify. Topics of particular importance include:

(1) *How to manage the tradeoffs between infrequent and costly resupply opportunities and the high cost of inventory?*
One of the complicating factors of the space supply chain can be low volumes of sophisticated (expensive) parts. The current supply chain is seldom focused on mass production. Understanding how the system could be optimized for specialized products might involve designing a supply chain to minimize cost of resupply, taking into account risk and uncertainty.

(2) *How to reduce lead time?*
Long lead times result in supply chains that are not particularly responsive or flexible. To our knowledge, no one has looked at ways to improve the responsiveness of supply chain operations conducted in space or determine the optimal level of flexibility (how to balance increased cost with risk). Tang and Tomlin (2008) match three types of supply chain risks with flexible strategies, and Tomlin (2006) sets up a research framework that can be used to assess, for example, how environmental uncertainty impacts purchasing and the buyer-supplier dyad. Evaluating the supply chain in these contexts could look a lot like a build-to-order SCM strategy, which uses outsourcing and technology to deliver custom solutions (Gunasekaran & Ngai, 2005). Prior studies also address how supply chain buffers can be configured based on when demand is known (Toktay & Wein, 2001). Many of the same characteristics that lead markets to build-to-order—short planning cycles, compressed lead times, and quick distribution—might be possible if space supply chains adopted a similar approach in the new, more commercialized market.

Another track of interesting questions in SCM centers around supply chain design and coordination. As mentioned before, the expanding space industry features new firms and governments contributing to the space economy. Take, for instance, India's space program (ISRO), formed in 1969. They have recorded a series of international achievements recently, including being the first nation to launch a successful Mars orbiter on its initial attempt (in 2013) and setting the record for most satellites in a single payload (104, in 2017). Some of this success can be attributed to the SCM approach ISRO has taken, with an open model of innovation that features partnerships spanning numerous large *and small* private companies. Recently, it opened up even more of its lenient sourcing strategy and transferred all heavy-duty satellite fabrication and navigation to the private sector. The similarities to the shifting U.S. market are striking, with more private companies and less in-house control by the government agency. In NASA's case, the agency has moved away from handling cargo and crew deliveries, instead contracting with SpaceX, Orbital ATK, Boeing, and Sierra Nevada to conduct transport to the International Space Station. The shift raises additional coordination questions at the system and partner level:

(3) *How should coordination be handled across the SCM network?*
Some early work in this area in the aerospace engineering domain has looked at such questions as: how to coordinate deliveries of multiple cargo spacecraft (to the upcoming 2019 Chinese space station) to maximize utilization (Lin, Luo, & Tang, 2014) and how to model multiple missions with discrete event simulation to capture the feasibility of complex space station operations (Lin, Wang, Hong, Yang, & Zhou, 2017)? More broadly, determining the optimal setup, integration, and information flows is a chance for the operations community to influence coordination in this area. A taxonomy of available coordination mechanisms frames the benefits available (Fugate, Sahin, & Mentzer, 2006). One approach might be to model the incentives of the space supply chain and how risk shifts with various coordinated contracts; Cachon (2003) offers a detailed approach to newsvendor and base-stock models in retail settings, which could serve as a foundation. New insights may be obtained when cost and uncertainty parameters are modified for space SCM. Finally, contending with the *information* challenge far from Earth presents opportunities to develop new procedures and mechanisms. The limitations of current methods of communication over long distances (e.g., between Earth and Mars) will necessitate new ways of collaborating on operational issues.

Even if the SCM concerns above were negligible, logistics management issues would still cause operational headaches. Shull, Gralla, Silver, and De Weck (2006) document how tracking and storing equipment, predicting spare parts requirements, and shipping appropriate levels of crew provisions have all been issues aboard the International Space Station. Historically, 3% of U.S. items—tagged with labor intensive bar codes—have not been able to be located on board the space station (things can literally float away), resulting in costly replacement options for mission critical items (Shull et al., 2006). A recent RFID logistics management program, which started with handheld scanners and now uses fixed readers, is one example of trying to improve inventory logistics in zero gravity. Recent assessments highlight numerous inventory issues, including improper accounting of flight inventory, limited use of implemented systems, and inefficient spare parts disposal decisions (NASA, 2017a). How to address these issues in the contest of space, where complications with physical inventory involve costly and time intensive consequences, may provide a rich direction of future research:

(4) *What options are available for improving inventory management in space? Can the cost of stock-outs, obsolescence, and shrinkage be quantified?*
Herein lies another opportunity for including the extra constraints and costs of operating in space and diagnosing the impact. While we discussed Made In Space in earlier sections, the possibility of build-on-demand also has significant supply chain consequences for a system with lots of constraints, both in terms of sourcing, inventory, and managing variety. For example, build-on-demand production in space permits stocking raw material (e.g., thermoplastics that can be used to create any number of items) instead of duplicates of individual inventory items. Such a shift affects many of the management decisions in the supply chain, since greater flexibility reduces the amount of safety stock needed, higher material density results in easier transport and storage, and onsite production reduces time lags. Additionally, many of the above represent topics that are currently undergoing changes in terms of recent technology (e.g., radio frequency identification (RFID)), opening up even more areas of research.

One of the most captivating ideas of this new space industry is the ability to use the universe to source materials instead of relying on Earth. We are now approaching the technical prowess to harvest asteroids and other celestial bodies for resources—including metals (for construction and technology applications), water (for rocket fuel), and every known element (like the rare-on-Earth Helium-3, which the moon is replete with and could eliminate our dependence on fossil fuels) (Jakhu & Buzdugan, 2008). Plus, this applies both ways. Not only would sourcing in space improve the supply chain options for space missions, but it could completely change the economics of key industries on the ground (with resource values in nearby space measured in astronomical trillions and quadrillions of dollars). Already, companies like Planetary Resources, Deep Space Industries, Moon Express, Shackleton Energy, and Asterank are spooling up businesses to tackle these opportunities, along with serious investment from countries like Luxembourg, the U.S., and Russia. Topics of particular interest might include:

(5) *How sourcing in space can change the economics of SCM?*
As it stands now, the expense involved with space exploration is one of the most limiting hurdles. Research that investigates the breakeven point that changes the demand side of that equation *and* figures out how the system might redistribute that concentrated wealth to across the supply chain would help clear that hurdle. How can SCM figure into unlocking the wealth that extraterrestrial resources offer? What is the most efficient way to pursue those resources? The fact that spaceships returning from space are mostly empty means that available backloading capacity already exists and can be utilized in the future, once opportunities materialize.

In sum, the space supply chain delivers information, people, and supplies across the largest supply chain in the world—to remote (and inhospitable) locations, in low volume transports, with high variable costs, amid uncertainty, and with mixed production models and long lead times (Fayez et al., 2006). In many cases, the constraints faced by the supply chain are unique to the space environment and necessitate renewed examination, especially as the scope becomes not just LEO but includes the further reaches of space, including the moon, Mars, and farther.

Sustainable Operations

In the 2013 film *Gravity* (another recent blockbuster about space—which itself is a signal of the changing space industry), the action kicks off when Russia decommissions one of its satellites by blowing it up, scattering thousands of debris fragments and destroying a space shuttle, the Hubble telescope, and part of the International Space Station in the process. This chain reaction resulting from space debris, while not perfectly plausible as written, is a very real phenomenon known as the Kessler effect (Kessler & Cour-Palais, 1978).

As real-life parallels, in 2013, a Russian satellite was destroyed by the remnants of a previously-exploded Chinese satellite, and in 2009, a retired Russian Strela satellite collided with a U.S. satellite from Iridium Communications, adding further debris to the more than 500,000 pieces there. These cases illustrate one aspect of designing a sustainable space operation—that of product reuse, recapture, or recycling to avoid waste. Since waste cannot sit in a space landfill (yet) but orbits for decades or centuries, treating orbital access as a scarce commodity is a requirement of any sustainability platform. Already, this aspect of sustainability has been identified in public policy circles. Weeden and Chow (2012) specify the need for boundaries and tackle policy approaches to avoid the tragedy of the commons in space. Brachet (2012) specifically examines an initiative from the United Nations that deals with space debris and its mitigation. To date, most work in sustainable operations has centered on Earth. As operations move away from our planet, defining what it means to be sustainable in another environment and how to achieve goals related to that will need to be addressed.

While it is tempting to think product designers might be focused on this issue of sustainability, we argue that most efforts that could be interpreted as sustainable design are unintentional. For example, the Apollo moon missions settled on a specialized lunar landing module and a lunar-orbit rendezvous (LOR) plan (instead of the clear frontrunners going in—direct ascent to the lunar surface by rocket and Earth-orbit rendezvous). In retrospect, the LOR plan seems clear, with less fuel required, simpler technology, and only a small portion of the lander jettisoned as waste (and even that could be used for seismic experiments on the moon) (Hansen, 1995). Or consider the ingenious water recapture system on board the International Space Station that recycles water from all available sources, including the humid vapors from exhaled breath (both from the crew and lab rodents). Finally, consider the recent technical achievement by SpaceX that allows it to land the majority of its Falcon orbital-class rocket shortly after takeoff and reuse it (a first). Reuse in this case (as in the space station's) was motivated by cost efficiency; in the Apollo design, technical feasibility drove the waste reduction.

The severe constraints of space naturally direct attention toward these types of solutions, but further benefits—especially in the context of the public policy debate over the Kessler effect—seem inevitable. The sustainable operations community can add to this area by addressing:

(1) *What is the environmental impact of products and supply chains in the context of space? Can the effect be quantified in terms that highlight the cost of such decisions?*
One of the first tasks involves showing the magnitude of the impact to make the case that these decisions include long-term consequences. Life cycle analysis—looking at designing for sustainability, sourcing decisions, avoiding waste, and process redesign—offers one option to approach this. Souza (2013) presents a thorough overview of the strategic (e.g., network design, feasibility), tactical (e.g., how to reacquire, choice of disposition), and operational (e.g., sequencing, priority) supply chain issues that would need to be answered for a closed loop supply chain analysis in this manner. The more tactical portions might be addressed via a stochastic optimization model, similar to Ferguson, Fleischmann, and Souza (2011), which investigates optimal disposition decisions and how to think about dismantling for spare parts. In the setting of space, there are additional constraints on the system, which likely influence the model assumptions (such as higher penalty costs *and* a system that must reprocess all products instead of only the most valuable). After quantifying the impact, determining how risk and responsibility should be shared across the various supply chain entities also become important.

(2) *What are the benefits and costs of debris recovery?*
Remediating the current space waste and avoiding future additions will require study. Novel reverse logistics programs and closed loop supply chains will be needed as a result of the difficult recovery options and challenges of space. One intriguing line of research involves looking directly at the Kessler effect and using simulations to study the effectiveness of different mitigation programs. The European Space Agency's DELTA (Debris Environment Long-Term Analysis) tool might offer a path toward answering this type of question.

Another pertinent sustainability topic highlighted by the Kessler effect is that of disaster preparedness in space. Predictions currently exist for the frequency and severity of catastrophic collisions from space debris. Other calamities, like the famous Apollo 13 mission, result from component failure. Cases like these change the variables of interest from dollar amounts to survival rates or damage mitigation. In these contexts, operations researchers again have an important voice:

(3) *How should disaster preparedness be planned for and operationalized in space?*
Answering questions around operational planning in disaster scenarios, creating shortened supply chains for rapid response, and understanding the forecast and impact of such space dilemmas helps plan for operational contingencies in the highly uncertain realm of space exploration.

> Previously, operations researchers have looked at similar questions for Earth-based catastrophes. Apte, Khawam, Regnier, and Simon (2016) highlight the financial and operational benefits of setting up disaster response supply chains in advance and being prepared for complexity. Models in that spirit (i.e., supply network optimization) represent a good starting point, although new parameters or modifications might be needed to account for unique aspects of supply chains in space.

DISCUSSION

In the last section, we focused on opportunities in *manufacturing operations*, *supply chain management*, and *sustainable operations* (Table 1) primarily from the perspective of manufacturers and suppliers. However, with the emergence of the private sector in the space industry, there continues to be a shift from public funding to private funding, requiring firms in the space industry to engage different stakeholders. A number of higher-level questions emerge from this expanded set of interactions (around needs, decision-making, and how those relate to the three opportunities in the last section). By taking the stakeholder resource-based view of a firm (Sodhi, 2015), we now extend our discussion to include "external" stakeholders; namely, *investors*, *customers*, *competitors*, and the *government*.

Investors

The space industry has been publicly funded by governments until recently. As more private companies venture into this industry, how should investors evaluate different projects with extreme uncertainties regarding the underlying product and technology development? For instance, founded in 2002, SpaceX established the goal of reducing space transportation costs and enabling the colonization of Mars. To achieve that goal, SpaceX needs to develop mechanisms for delivering heavy payloads into outer space (they have recently succeeded in testing their Falcon Heavy rocket). An intermediate milestone was to develop the Falcon launch vehicle and the Dragon spacecraft for delivering payloads into Earth orbit. However, the development of the Falcon and Dragon encountered setbacks. SpaceX continued development at significant cost, even though the payoff and development path was uncertain. Companies need early adopters in order to support the business, move down the learning curve, reduce costs, and ultimately get closer to meeting long-term goals. Despite these risky projects, SpaceX received launch contracts from public and private sectors with a valuation of $21 billion in 2017. How should investors evaluate space technology projects with extreme uncertainties? This question deserves exploration as more companies are entering the space industry.

Customers

Figuring out how to commercialize space will be an important step for private companies. How should these companies monetize their services? There are two classes of customers for their consideration. The first class is government and/or business, while the second class is consumer. For instance, in addition to the ongoing launch contracts for delivering cargo and supplies to the International

Space Station with NASA, SpaceX uses its fleet of Falcon rockets to launch telecommunications satellites for communications satellite owners/operators (e.g., SES of Luxembourg). Goods and services for the second class are in the early stages. Space tourism plays an important role for the space industry to tap into the consumer market. Thus far, the handful of individuals who have paid to go into space (at estimated costs of $20 million or more) have done so via Russian Soyuz spaceships. However, numerous private companies are prepping for such tourism services, including Virgin Galactic (which hopes to launch suborbital passenger flights by the end of 2018), Blue Origin, and SpaceX (which plans to send two passengers around the moon with its recently tested Falcon Heavy rocket). When serving these two classes of customers, many questions arise. For the commercial sectors, how should one design a "contingent" contract when the outcome is highly uncertain? For the consumer sector, consumer safety can also be an issue. If insurance firms want to enter this market, how should they set the premiums for insuring commercial or consumer contracts when the outcome is highly uncertain?

Competitors

As more governments are now sourcing their launch services to private firms and as more consumers are curious about space travel, more private companies are entering the space industry. How should various companies compete in this industry? For instance, SpaceX, Orbital ATK, and United Launch Alliance focus on the development of different rockets for delivering heavy payloads, but each launch is very costly. To reduce the launch cost of satellites, companies such as Rocket Lab of New Zealand and Japan Space Agency are developing small rockets to carry small payloads. Besides cost, these companies may need to compete on capabilities, reliability, and reusability (e.g., multiuse rocket stages and launch pad infrastructure). How should these companies compete in the future as more firms enter? For instance, should these companies compete on "space sustainability" by designing new systems using materials that are "space degradable"? Would investors and customers care about space sustainability?

Governments

When more companies are developing different technologies for different services in space, how should governments around the globe regulate outer space? For instance, to ensure "sustainability in space" as discussed in the last section, private companies may not have economic incentives to reduce debris in space. As such, who is responsible for "space sustainability"? Should government develop regulations for these companies to reduce space debris? In addition to regulatory decisions, governments also face financial decisions. For example, would governments see better outcomes from funding a large space initiative *or* advanced research on Earth instead (e.g., renewable energy or cancer cures)? Also, how will the dynamics of free-riding impact the space industry and will some governments benefit from others' investment in moving down the learning curve? The OM field has developed many frameworks that apply to problems involving uncertainty and risk management. Even newsvendor models might apply to such tradeoffs questions. If a government spends too much (overage), it has wasted resources; if it spends too little (underage), then the technologies do not advance or demand does not materialize—and it has again wasted resources.

In summary, as more private firms enter the space industry, there is a need to understand the interactions between a larger group of stakeholders. Specifically, these stakeholders need to ensure that firms take environmental sustainability, social responsibility, and financial responsibility into consideration when they develop new products and services.

CONCLUSIONS

The operations community has flourished in the past few decades, with breakthrough impact thanks to practical contributions in revenue management, supply chain coordination, risk management, and—more recently—sustainable operations and behavioral operations. In addition to these topics, the field has also expanded its footprint by taking the best in the operations field and applying it to specific domains, such as healthcare, retailing, and emerging markets. By proactively addressing questions in a field early on, which represents the early phase in a new knowledge creation S-curve, operations researchers have delivered early research that often results in high yield value (Roth et al., 2016). One could argue that the way to stay relevant as a discipline lies in constantly taking the field's tools and knowledge and applying them to the most current business issues and markets. In this article, we have advocated for focusing on a new emerging industry, space. The examples and illustrations provided signal some of the early opportunities available. In the next decade, many of these questions will have been addressed by industry participants. Our hope is that researchers will take these up and make practical contributions in a field that offers a fresh context and exciting growth.

There is also the purely practical point about how to know what is relevant and important. As pointed out by Toffel (2016), there is an important difference between conducting research that *could* be relevant and that which *is* relevant—and getting as close as possible to the realities that exist in the workplace should be the goal. While it is not likely that any of us will make it onto the International Space Station as an initial research step, creating opportunities to learn and ask questions of those who are in the space industry is invaluable. In fact, some of the seeds for this article originated with the interplanetary track at the White House Frontiers Conference, which prominently featured the obstacles being worked through as NASA plans for its mission to Mars. Similar encounters can be achieved through field interviews, consuming news and popular press on the field, and industry reports (e.g., the NASA audits referenced herein). We think this research community is well-positioned to answer the tough, ambiguous questions that decision makers in this new space industry face and look forward to our journey.

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