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Assignment – 2

Sustainability of Rocket technology by Reusability

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Abstract:

The report specifies the evolution of rocket technology with the time. The current trends of rockets and future implementation of rockets to make them more sustainable and reusable. The analysis is provided with the examples of latest technology of reusable rocket technology implemented by the famous rocket agency SpaceX. Two rockets Falcon 9 and Falcon Heavy are taken as examples, explaining their payload capacity, size, rocket integration techniques and cost comparison between the two variants between the reusable and expendable variant. Discussion on the sustainability of space travel and space mining with the concept of reusable rockets and the future developments in the rockets by SpaceX like Starlink, Starship and Dragon space capsule are also made. The main aim of the report is to present various ideas in the implementation of rockets to make it usable more than once and make the space launch more affordable and sustainable.

Evolution of Rockets: Around 400 BC, Archytas (Greek Philosopher) wanted to amuse people by sending a wooden shaped pigeon into the sky. For this he made a wooden shaped pigeon tied to a steam propelled sphere which made the bird to push into the sky. Later in the first century A.D, the Chinese have simplified form of gunpowder [1]. They used this to create explosions during religious festivals, the bamboo tubes are filled with a mixture and tossed them into fires. They began experimenting with the gun powder and discovered that these tubes could launch themselves just by the power produced from the escaping gas. The true rocket was born.

In 1898, a Russian schoolteacher, Konstantin Tsiolkovsky proposed the idea of space exploration by rocket by suggesting the use of liquid propellants for rockets in order to achieve greater range. For his ideas, careful research, and great vision, Tsiolkovsky has been called the father of modern astronautics. In Germany, a space society is formed with name the Verein fur Raumschiffahrt (Society for Space Travel), which led to the development of the V-2 rocket. Their main idea was to use this rocket in the world war 2 against the London city and allies. Unfortunately, even before the rocket was fully made the Germans were defeated in the war [1]. The V-2 rocket is very small in comparison to the present rockets but works in the similar way to the current rockets which used liquid oxygen and alcohol as a fuel. The world superpowers United States and the Soviet Union realized the potential of rocketry as a military weapon and began a variety of experimental programs.

On October 4, 1957, the first modern world rocket was launched by the Soviet Union. The rocket was intended to launch and artificial satellite called sputnik I. The launch was a huge success opening the doors space administration. In less than a month, Soviet Union launched another rocket to send a dog named Laika in to the space [1]. A few months later, the United States launched its own satellite into space named Explorer I by the US Army. Later in the year, the formation of one the great space agency National Aeronautics and Space Administration (NASA) took place with an idea of exploring the space for the benefit of mankind.

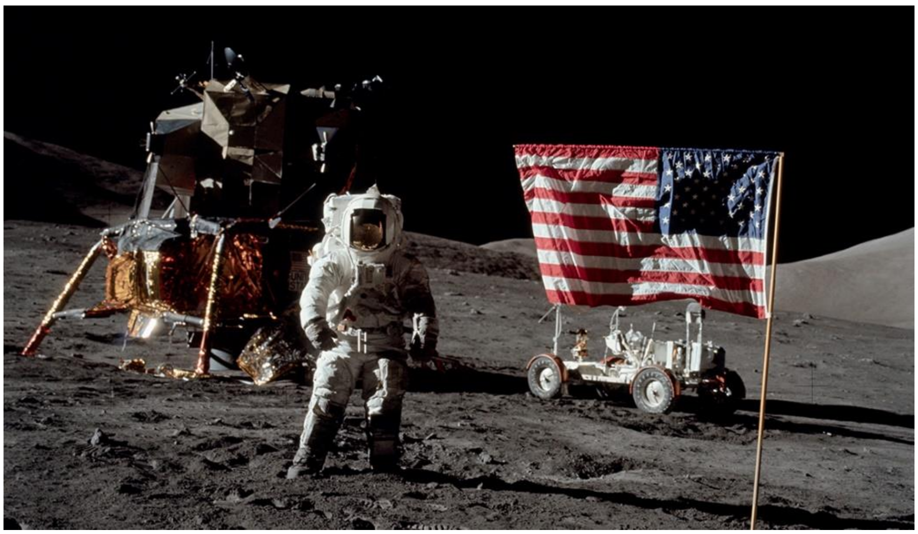

Figure 1: First land on moon by NASA

As the time passed by many new advancements are made in the rockets. Astronauts were able to orbit the earth and land on the moon. Rovers (robots) were able to land on the different planets. Space is completely open for both scientific and commercial exploration. From the data received by the satellites, scientists were able to forecast the weather and communication across the world is made possible within seconds [1]. As the demand for more payload and powerful rockets increased, a new range class of rockets were designed and manufactured.

Concept of reusability:

As we are racing towards the commercial race in the space and rocket industry, the need to develop a long lasting and sustainable rockets which are able heavy weights is increasing. The concept of commercial space travel is becoming more and the space agencies are striving to make it more affordable [2]. The rockets might first use fuel and water to go to the space and land on other planets but they can bring back valuable metals which are not available on earth or present in a smaller scale. Mining these materials on such planets will be more economically favorable and reduce the impact on the earth's environment [2]. Since the resources on the earth are depleting people also need a new planet to make human civilization sustainable and an alternative to earth like mars. Development of human habitats on mars and colonizing it requires a lot of infrastructure to be send to mars [2]. We also need heavy lifting rockets for this purpose which requires to reusable.

To make the commercial space travel more affordable and to reduce the cost of the payload deployment in space a reusable launch vehicle is necessary. The concept of reusable launch system is to recover some or all the parts of the rockets for later use [2]. Currently there are mostly Expendable launch systems in which the no parts of the recovered. The rocket parts after are launch fell into the sea and get buried.

The initial idea of reusable launch systems was proposed by Silbervogel project in the first half of twentieth century. This idea came into a big picture when the first human landings on the moon were made in 1969 [7]. The first large scale reusable rocket was launched by NASA through STS space shuttle program which is first reusable spacecraft to be operational. As of now these shuttles were not used due to technical and commercial reasons for not delivering the required goal.

SpaceX and Reusable Rockets:

The company Space exploration technologies (SpaceX) was found in 2002 with main goal of increasing reliability and cost reduction of space launches. As of now, SpaceX is the only company which manufactures a full scale reusable rockets. Their initial rocket is falcon1 launch vehicle which is tested on an air force base in California [3]. The vehicle is designed from a blank sheet with all major mechanisms including the hardware and software entirely in house which is completely different from an ongoing practice of aerospace industry. The overall philosophy of SpaceX is to minimizing the external dependency both to reduce costs and reduce the rocket development time. The well renowned space agency NASA is now the major customer of the SpaceX. The final goal of SpaceX is not about launching the rockets or cargo delivery to the space but human space travel and make humans multi-planetary. The NASA space shuttle to deliver a 27,500 kg payload to the LEO costs about USD 1.5 billion which is $54,500/kg while the SpaceX on the other hand with the reusable rocket launch system offers 22,800 kg payload at a cost of $62 million which is $2,720/kg [4]. There is fivefold decrease in the launch cost per kg and moreover the rocket being completely reusable makes no production cost in the next rocket production and less environment impact. SpaceX has more than 9500 employees with annual growth rate of 50 percent.

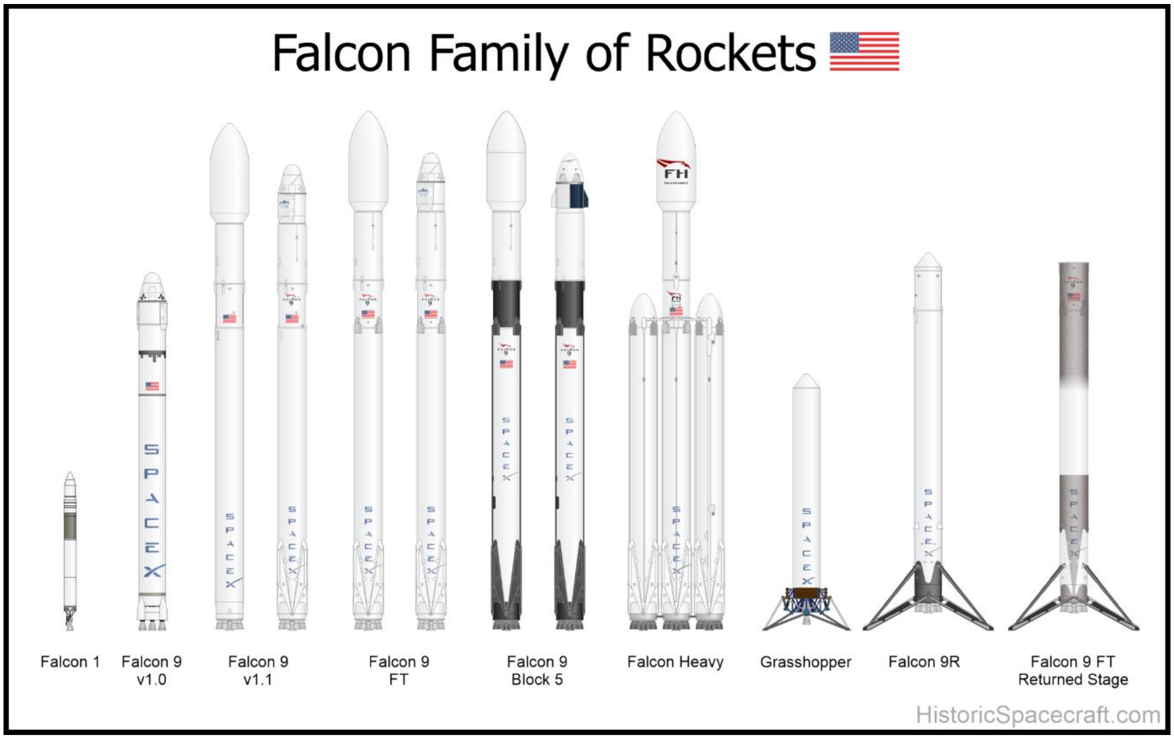

Figure 2: Rocket Family of SpaceX

The rocket Falcon 9 designed and manufactured by SpaceX has been the most successful commercial space launch rocket with 46 launches between 2010 -2017 with 98 percent reliability. Falcon 9 booster rocket with EEL v-class booster is able to lift around 12,500 kg to the low earth orbit and 4640 kg to the geosynchronous transfer orbit. It is a two stage launch vehicle with RP-1 and LOX propellants [4]. Falcon Heavy is an upgraded version of falcon 9, with a total of three Falcon 9, one as a main booster and the other two as side boosters. This has a total payload capacity of 29,600 kg to the low earth orbit and 15,600 kg to the geosynchronous transfer orbit. SpaceX also developed a reusable spacecraft named Dragon with the sponsorship of NASA. It is developed to send 2.5 metric tons of cargo to the ISS (International space station). The spacecraft can be used for crewed and unscrewed missions to space and can be effectively recovered and reusable.

Falcon 9 Launch Vehicle:

Falcon 9 is a very large Evolved Expanded Launch Vehicle booster launch vehicle. It has two stages which uses RP-1 and LOX propellants. The initial stage consists of nine merlin engines, who can produce a thrust of 4.9 MN at the lift-off stage. In the next stage a single merlin-vacuum engine is used has a larger nozzle to optimize the performance required from the operation of the vacuum. Falcon 9 is around 55 m tall with a 5.2 m payload [4]. Falcon 9 was launched from the SpaceX launch complex SLC-40 on the cape Canaveral which also support Falcon Heavy variant.

Figure 3: Falcon 9 on the Launch pad

Falcon 9 is main designed as a human rated vehicle. It exceeds the rating of NASA human rating requirements, like structural Factors-of-Safety of 1.4. It is also capable of carrying crew when docked with dragon space capsule. During the launch, the rocket is held down in the launch pad for three seconds after the stage one ignition to enable the pressure changes in engine and stabilize before coming to the flight. There is also an onboard flight computer which detects the key parameters during the launch, any deviation in the parameters immediately aborts the launch in T-0.5 seconds. The launch control personal can the analyses the data from the computer and make necessary changes to the rocket [4]. This feature greatly enhances the reliability of the system by making sure that all the crucial systems working normally at the time of lift-off.

- **Production and Assembly:**

The production of Falcon 9 is completely different from the production of current rockets. SpaceX operates on a vertical integration unlike other space agencies. Most of the components are developed in the same area where the rocket is assembled which in turn makes the cost and time required to assemble to decrease. Falcon 9 rockets are manufactured in the California and sent to Florida for launch [5]. Not relying on other companies and educing dependencies SpaceX streamlined the process of rocket assembly. The rocket mainly consists of 9 merlin engines each which are able to produce 340kN of thrust. All these engines and other parts are assembled in a single go.

Figure 4: Used Falcon 9 brought to Factory for refurbishment

- **Reusability:**

From the initial stages of establishing the company, SpaceX through that reusability in the rockets should be achieved. The rocket after deploying the satellite in the orbit should make its way back to the earth making it ready for next launch. To achieve this rocket should be able to re-enter back to each surface without getting burnt. At the first parachutes were equipped to the rocket but failed to survive the aerodynamic stress and heat during the reentry phase [2]. In the late 2011, SpaceX has changed the approach of reentry, eliminating the concept of parachutes and using a propulsive powered descent approach. In the design phase, SpaceX used a prototype named grasshopper rocket to check the possibility of the new concept for re-entry. They made several tests on the prototype and finally it ended up successfully. They learnt how to do it in right in every test they conducted.

The same concept is applied to the Falcon 9. The SpaceX has announce that their first reusable rocket is ready to fly. On September 2013, the Falcon 9 was ready to launch, after the phase one separation, the test plan made a first burn reentry to reduce the velocity then again a second burn before it is near to the water [5]. The first stage crash landed on the ship in the ocean which is a failure. The SpaceX team tried to learn from their mistakes and after three failures in a row they made a final attempt, which is a complete success the first stage of the rocket reentry successfully back to the earth surface.

Figure 5: Falcon 9 Booster landing

After the separation of the first stage which is to be recovered, cold thrusters are triggered which make the first stage to fall into the earth. The booster is programmed to a flight back to earth. It must autonomously perform the control manure when entering to the earth atmosphere to follow the path and land vertically. There are three flight control parts Cold gas thruster, grid fins and Re-Ignitable engines [5]. The Falcon 9 is equipped with 8 cold gas thrusters that are equipped on the top of the first stage which are used to control the orientation of the booster. These are mainly used for the flip action to be performed after the first stage. There are total of 4 grid fins which are used for precise control of the rocket position prior to landing. They are alone responsible for incredible 10-meter accuracy. The re-ignitable engines control the speed of the rocket which is necessary to reduce the speed of the rocket re-entry. Inertial navigation system and Global position system are used to preprogram the flight path and derivation in the flight path will be assisted by them to correct the path. The falcon 9 is deployed with 4 landing legs which are made of titanium and carbon fiber and contains an impact attenuator for hard landings.

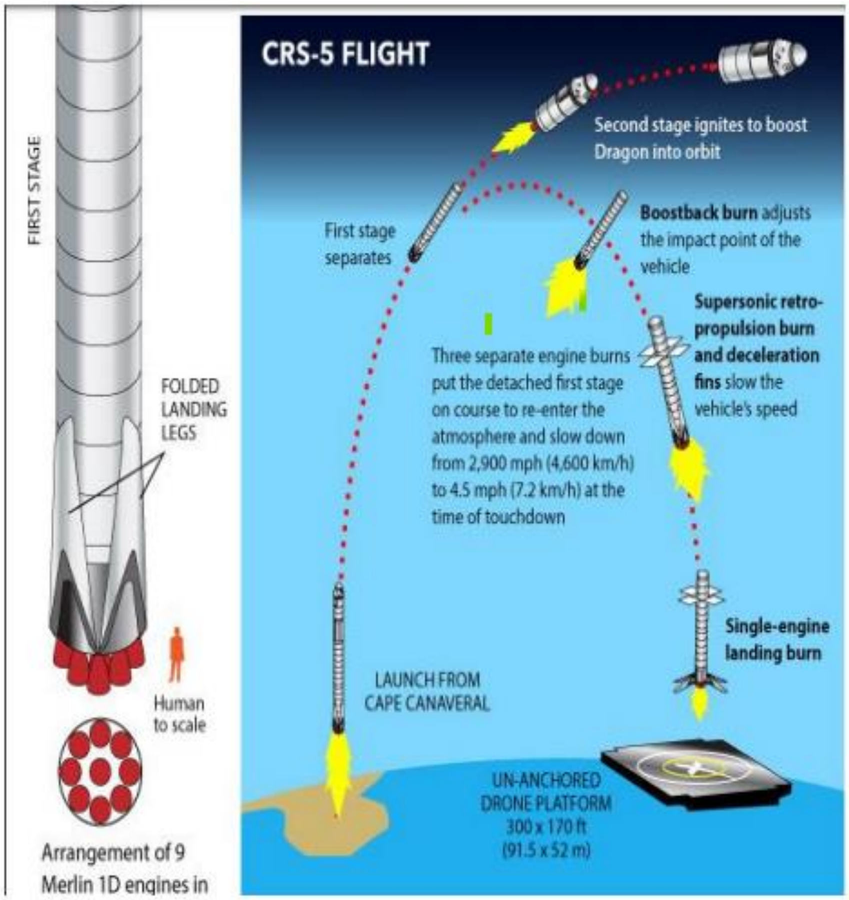

Figure 6: Falcon 9 Re-entry explanation

Falcon Heavy Launch Vehicle:

Falcon Heavy is a partly reusable heavy launch vehicle which is derived from falcon 9. It consists of a strengthened Falcon 9 as the middle core with two additional Falcon 9 boosters on either side of the main booster [2]. It has a heavy payload capacity and is the third largest rocket ever built by mankind. SpaceX conducted the first launch of Falcon Heavy on February 2018 with tesla roadster as a payload. All the three booster rockets were able to return to earth successfully. The rocket is mainly designed to exceed the current requirements of human.

Figure 7: Falcon Heavy on the Launch pad

Reusability: The reusability concept in the falcon 9 is applied to the Falcon Heavy as well. Since the three boosters are falcon 9 which are also previous launched and reentered successfully made a clear way for Falcon Heavy reusability of boosters [6]. Due to heaviness and high payload capacity all the boosters cannot be landed at a single place, the two side booster were able to land back on the earth surface and the main booster made a re-entry on the ship in the sea.

Figure 8: Falcon Heavy Boosters and Central Core Rentry

Economic point of view:

Falcon 9 rocket is used to carry payload from the earth surface to the outer space. Reusable launch vehicle is designed to be recovered and launched again. SpaceX Falcon 9 has two stages; the first stage is powered by rocket engines utilizing liquid propellants which is recovered while the second stage is an expendable one [7]. SpaceX launches Falcon in two different variants one is reusable and the other is expendable. In reusable variant to break the forward thrust some amount of fuel needs to store in the first stage which is utilized during the downward decent of the first stage [7]. The cost of rocket launch is divided into various categories like design and manufacture costs, testing and inspection costs, delivery cost, start ramp and live broadcast cost, landing and preparation for reuse.

Price category:	*Cost component:*
Cost of carrier rocket:	Cost of First stage
	Cost of second stage
	Cost of aerodynamic fairing
Launch expenses:	Fuel
	Control centre services
	Launchpad services
	Transport services
	Testing
Costs for a reusable system:	Amortisation of reuse
	Refurbishment costs
	Operational costs for landing (Launchpad /ASDS)
	Transport service
	Testing

Figure 9: Various Factors that affect the rocket launch cost

The following table specifies the cost comparison between the two variants of Falcon 9 and Falcon Heavy [7]. There is a significant reduction in the cost when reuse variant is used instead of expendable one. All the values are in millions.

	Falcon 9	F9 reuse
Cost of first stage (A —— R)	30	10
Cost of second stage (B)	8	8
Aerodynamic fairing cost (C)	6	6
Total cost of rocket (F)	44	24
Cost of launch operations (S)	4	4
Fuel costs (K)	0,2	0,2
Total cost of launch (N)=(F+S+K)	48,2	28,2
Margin (P–N)	13,8	33,8
Margin in %	22%	55%
Selling price of Launch F9 [6] (P)	62	62

	Falcon Heavy	FH reuse
Cost of first stage (3 x A —— 3 x R)	90	30
Cost of second stage (B)	8	8
Aerodynamic fairing cost (C)	6	6
Total cost of rocket (F)	104	44
Cost of launch operations (S)	4	4
Fuel costs (K)=(∼3xK)	0,6	0,6
Total cost of launch (N)=(F+S+K)	108,6	48,6
Margin (P–N)	-18,6	41,4
Margin in %	-21%	46%
Selling price of Launch FH [6] (P)	90	90

Figure 10 : Tables showing Savings when Falcon 9 and Falcon Heavy are used in Re-use State

Conclusion and Future Scope:

Advantages of the reusable rocket launches will be a great beneficial to the space exploration. With an ability in increasing the launch frequency more launches can be done within the limited time. This progress results in the sustainability one in the form of evolution of rockets and the other in the form of knowledge gained continuous space travel and exploration of deep space. Due to this amount of satellites that orbit the earth increases which in turn improves the standard of people down the earth like providing access to everyone (for example Starlink) and improved weather forecasts. Increase in the satellites that revolve the earth could also lead to new technologies that weren't possible prior.

Another crucial use of reusable rockets is obtaining materials on other celestial bodies which are rare to find on earth. For instance, Helium 3 which is highly found on moon is useful for nuclear fusion research. By making use of these materials long term and high energy efficient power resources become more realistic which paves the way for more environmentally safe and sustainable power sources.

In the future, Using the concept of reusability SpaceX is planning to make a mass transport rocket called BFR that could carry around 240 passengers. The vehicle is capable to travelling at ultrasonic speeds making the travel time between the major cities very less at about 30 minutes around the earth. Moreover, SpaceX is currently developing the starship through travel to the mars and other plants is possible at a very low cost. This idea results in great achievement in overall sustainable economic, social and environment qualities.

Stephen Hawking world renowned physicist claimed that the earth could no longer sustain the increasing human race. The humans need an another planet to evolve and make human race multi-planetary otherwise the human race will extinct one day. To make all these things possible reusable rocket launch system plays a crucial role in the sustainability of mankind.

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Reusable Launch Space Systems

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Abstract

The paper focuses on reusable launch space systems. It aims to describe the current state of reusability in space systems and to analyze the launch cost of current Falcon carrier rockets.

The first chapter is dedicated to general information about reusable launch space systems. This includes definition of reusable and expendable launch systems or history of reusable launch systems. The second part is focused on the era after STS and new the concept of RLV. The following parts of this paper aim to analyze the launch price of current Falcon carrier rockets.

Keywords

Reusable launch system; Reusable launch vehicle; Spacecraft; Spaceplane; Launch vehicle; Spaceflight; Commercial spaceflight; Space industry

1. Introduction

A reusable launch system is a launch system intended to allow for recovery of part or all of its components for later reuse. An expendable launch system id designed to be used only once, and its components are not recovered.

The development of reusable launch space systems began in the first half of the twentieth century (between 1935 and 1945) by the Silbervogel project[1]. In the following of the post-war epoch cosmonautics was experiencing a rapid development that resulted in a piloted space flight and a landing on the Moon in 1969. Reusable launch systems became a major subject of development in the early 1970s. This epoch also gave rise to the largest project in the field of reusable space vehicles. It was the STS Space Shuttle program, which was the first reusable space vehicle to be operational. At present these space shuttles have already been retired from service for technical and economic reasons. Some economic and operational objectives of the project have not been fulfilled. It was intended to greatly reduce the cost of access to low Earth orbit, but it was criticized for failing to deliver on this goal.

2. Epoch after STS

At present it is possible to talk about the epoch after STS shuttles, which is characterized by the transition from state agencies to private projects. Especially in the case of the development of space transport systems and transport to Earth's orbit. Private projects often offer lower costs for the research and the space transportation than state-run organizations. State organizations however still play an irreplaceable role, notably in shifting the current astronautics boundaries.

2.1 SpaceX and Blue Origin reintroduced the concept of RLV

SpaceX since its foundation in 2002 aimed to develop a reusable carrier rocket system that would allow a reduction launch prices and kick-start the space economy. At present it is the most important company in the field of re-use of space transport systems. SpaceX has developed a reusable rocket launching system to successfully re-use the first stage of Falcon 9 and Falcon Heavy. First successful recovery was in 2015 and first successful relaunch in March 2017.

In the future the significant competition for SpaceX in the field of reusable systems could represent Blue Origin company, which is also involved in the development of RLV.[2] In 2015 Blue Origin successfully landed with a sub-orbital New Shephard carrier rocket.

2.2 High development cost

he biggest issue for a reusable space system is high development costs and the low flight rate. This situation results in that other companies of the carrier rocket industry are still very conservative and cautious about reusability. An example of this may be United Launch Alliance (ULA), a joint venture of Boeing and Lockheed Martin, which operates Atlas V, Delta II and Delta IV carrier rockets. According to published information about future rocket Vulcan, ULA is considering only the reusability of rocket engines [11]. Re-usability in this form could be introduced by 2025 at the earliest. Airbus (Ariane) works similarly.

If we move from carrier rockets to space shuttles, there are several interesting projects currently running. For example the Boeing X-37 and Dream Chaser space shuttles.

3. Rocket reusability from an economic point of view

This chapter focuses on analyzing launch price of current Falcon 9 and Falcon HT rockets.

The Falcon 9 carrier rocket is a rocket used to carry a payload from Earth's surface into outer space. Reusable launch carrier rockets are designed to be recovered and launched again. The SpaceX Falcon 9 is the world's first partially-reusable launch system powered by rocket engines utilizing liquid propellants. This carrier rocket has a reusable first stage and an expendable second stage.

Falcon launches have two basic modes available. Reusable and expendable. In reusable mode, there is a fuel cost to brake the forward thrust, slow down for reentry through the atmosphere, and then finally for landing. Some amount of fuel must be reserved for stage recovery and cannot be used for thrust to orbit and therefore the functional payload is reduced.

Cost of carrier rocket launch can be mainly categorized in two parts:

1. Direct Cost
2. Indirect Cost

3.1 Analysis of the cost of launch Falcon carrier rocket

The launch price consists of cost of the carrier rocket and costs related to the start and landing, which are represented in particular by fuel costs, rocket transport, testing and others. In case of repeated use of the carrier, there is the cost of re-using and reducing the value of the rocket through wear, rebuilding and testing of the rocket for reuse as well as the cost of running the ASDS. The cost analysis of launching rockets with cargo under the aerodynamic cover is shown in Table 1.

Table 1. Analysis of the rocket launch cost

Price category:	*Cost component:*
Cost of carrier rocket:	Cost of First stage
	Cost of second stage
	Cost of aerodynamic fairing
Launch expenses:	Fuel
	Control centre services
	Launchpad services
	Transport services
	Testing
Costs for a reusable system:	Amortisation of reuse
	Refurbishment costs
	Operational costs for landing (Launchpad /ASDS)
	Transport service
	Testing

Table 2. Costs start at F9

	Assumed prize:
First stage as % of total direct costs (A)	(70%)
Second stage as % of total direct costs (B)	(15 – 20%)
Aerodynamic fairing cost (C)	(6*)
Cost of Merlin engine 1D+ (rough estimate)	∼1.5 (x 9)*
Cost of Merlin engine 1D vakuum (rough estimate)	∼1.6*
Selling price of Launch [6] (P)	62*

3.1.1 Cost of the Falcon carrier rocket

The price of the Falcon carrier rocket consists of first stage, second stage and aerodynamic fairing cost.

The price of the first stage consists of Merlin (9x), first stage fuselage, control, navigation and landing system, and tanks. The price of the Merlin rocket engine has not been published but it is estimated at $ 1,500,000 per piece. SpaceX manufacture most parts in-house, including engines, control and navigation systems.

The price of the second stage consists of the Merlin engine (1x), the second stage fuselage , the control system and the tank. The costs are described in Table 2 and Table 3. Cost savings when it is reused the first stage is shown in Table 4.

3.1.2 Costs to start, landing and preparation costs for reuse

Start costs consist of fuel costs, delivery, inspection, testing, flight control, start ramp and live start broadcast costs. Landing costs and preparation for re-use consist of the costs of the stage refurbishment as well as the cost of the service landing ramp or ASDS and freight costs. A separate item of the cost of the start is insurance. Fuel and oxidiser are typically less than 0.3% of the launch price of the F9 carrier rocket.

Table 4 illustrates a model case of cost savings when it is reused the first stage. The model is just a demonstration of savings. Because of the complexity of the problem it can not display accurate values. Most of the values are based on the statements and materials released by SpaceX. Values are

Table 3. Costs start at F9

	Assumed prize:
Cost of first stage total (A)	30 – 40 (30)
Cost of second stage total (B)	7,5 – 12 (8)
Total cost of rocket (A+B+C)	44
Fuel costs	0,2 – 0,3 (0,2)
Rescue and Prepare Costs for Start (R)	8 - 15 (10)
Cost of launch operations (S)	4

Table 4. Savings model when reusing the first Falcon 9, the values are in millions of USD

	Falcon 9	F9 reuse
Cost of first stage (A —— R)	30	10
Cost of second stage (B)	8	8
Aerodynamic fairing cost (C)	6	6
Total cost of rocket (F)	44	24
Cost of launch operations (S)	4	4
Fuel costs (K)	0,2	0,2
Total cost of launch (N)=(F+S+K)	48,2	28,2
Margin (P–N)	13,8	33,8
Margin in %	22%	55%
Selling price of Launch F9 [6] (P)	62	62

excluding possible discounts. The actual values will be very individual in real cases depending on the specific conditions of the start. The model emphasizes direct costs and only necessarily essentials indirect costs are taken into account. Other indirect costs, such as insurance, make a separate chapter for each start.

3.1.3 Rescue and Prepare Costs for Start (R)

According to the company representatives SpaceX, in the case of the firsts re-use of the stages, re-use costs accounted less than half of the cost of production new stage[3]. The following versions of F9 have improved reuse capabilities. The incoming F9 Block 5 option is supposed to be capable of up to 10 starts without replacing parts. For the model, the price (R) is set at 1/3 of the price of the new stage (A). It can be expected that there will be an expansion of reusability and optimizations related processes that will represent a further cost reduction.[4]

Table 5 shows the profit growth of around 30%, which corresponds to the values that were mentioned in this context representatives of SpaceX. Values also correspond to some published discounts from the start price.

In the case of the heavy Falcon Heavy carrier rocket, even more significant savings can be expected, as shown in Table 6. FH rocket builds on the standard Falcon 9 rocket, complemented by two auxiliary rocket stages. The auxiliary stages are also basically modified the first stages of the Falcon 9. From the point of view of re-use, there are basically three first stages of the F9 rocket, which start together and then land independently.[5]

Table 5. Falcon Heavy reuse model, values in millions USD

	Falcon Heavy	FH reuse
Cost of first stage (3 x A —— 3 x R)	90	30
Cost of second stage (B)	8	8
Aerodynamic fairing cost (C)	6	6
Total cost of rocket (F)	104	44
Cost of launch operations (S)	4	4
Fuel costs (K)=(∼3xK)	0,6	0,6
Total cost of launch (N)=(F+S+K)	108,6	48,6
Margin (P–N)	-18,6	41,4
Margin in %	-21%	46%
Selling price of Launch FH [6] (P)	90	90

For heavy Falcon Heavy rocket launchers, table 6 shows a rise in re-usability importance. There is a clear difference in start-up costs for the expendable variant versus the reusable variant. This is not surprising, as there is a 3 stage rescue, compared to one at F9. A expendable option has costs clearly exceeding the table price for the start. In this configuration, the start would be a loss. In reality, the difference would probably be even greater because the model calculates with lower prices for individual items. SpaceX is now fully reliant on FH for reusability.[6] Considering an impressive load of 63 800 kg to LEO, this step is understandable. It can also be expected that in the case of demanding start run without rescue, the starting price will probably be above the table price. The purpose of this analysis was to demonstrate the importance of reusability for the Falcon Heavy carrier rocket.

4. Conclusion

The long-term vision and goal of the space industry is to create a launch vehicle that is capable of delivering fast, safe, reliable and relatively inexpensive launch to the space. Reusability is a response to these requirements. I believe that reusability will have a significant impact on cosmonautics over the next few decades, and it will become a matter of course within a few decades. In my opinion, re-usable means are now the phenomenon of the time in cosmonautics. Just recovering only the first stage of a Falcon 9 for reuse on multiple flights would allow SpaceX to significantly lower the price of launches for satellites and supply or crewed spacecraft.

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Space Sustainability Engineering: Quantitative Tools and Methods for Space Applications

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Abstract—**This research explores the use of sustainability tools for space activities through a case study comparing the cost and environmental impacts of the SpaceX Falcon 9 and Falcon Heavy systems. The Falcon 9 and Falcon Heavy are similar in design; however, the Falcon Heavy was the first rocket launch system to successfully utilize a reusable first-stage booster system. The methodology employed was an attributional hybrid-Life Cycle Assessment (LCA). Upstream and downstream inputs and impacts were accounted for via economic input-output and process-based methodologies. A cradle-to-use-scoped system boundary for the two SpaceX Falcon systems were evaluated on a per-kilogram-delivered-to-geosynchronous-orbit basis. Producer cost data was integrated into the LCA framework to provide a cursory Life Cycle Costing (LCC) producer cost impact category to compare with the LCA environmental impact potentials. Findings showed the combined economic and environmental benefits achieved by SpaceX through developing the Falcon Heavy reusable booster system significantly reduced all evaluated environmental and cost impacts when compared to the Falcon 9. By applying the simple principal of reuse, SpaceX was able to reduce the cost of launch to high orbit by over $6,000 per kilogram while reducing environmental impact potential averages by >40% below the Falcon 9 system. This case study demonstrates the benefit of quantitative sustainability tools to guide economically and environmentally beneficial design for space activities.**

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1. INTRODUCTION

As we are amid a commercial space race, verging towards a space resource bonanza, we can use the lessons learned from the impacts of our industrialized society and apply them to space activities. Such lessons have manifested the relatively new yet well vetted field of sustainability engineering. The sustainability engineering toolbox holds a variety of quantitative methodologies to help ensure indefinitely sustained social, economic, and environmental wellbeing to all. Sustainability research regularly provides findings and recommendations that improve overall system performance while reducing negative impacts, foreseeing unanticipated consequences, and managing harmful tradeoffs. Life cycle assessment (LCA) is one such sustainable engineering methodology used to quantify and characterize environmental and other impacts to improve the studied engineered system's cradle-to-grave performance. LCA can be integrated with life cycle costing (LCC) methodologies to also evaluate cost impacts and savings of improved environmental performance.

The field of sustainability engineering has evolved in recent years to include a host of quantitative tools; engineers use these tools to measure the sustainability of a product, process, or system and ultimately improve designs. Sustainability encompasses the intersection of three overlapping pillars: economy, environment, and society. The sustainability engineering toolbox holds a diverse set of quantitative methodologies to help ensure indefinitely sustained social, economic, and environmental wellbeing, summarized in Figure 1. Improvements to systems made via sustainability assessments correlate well with cost savings and overall system performance improvements. The tools include Life Cycle Assessment (LCA), Social LCA (S-LCA), Techno-Economic Analysis (TEA), and Life Cycle Costing (LCC).

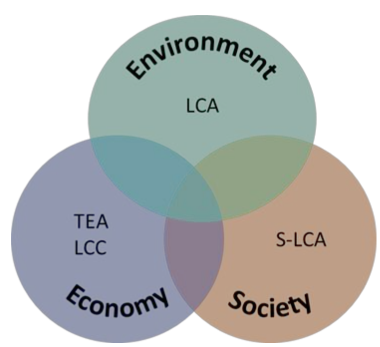

Figure 1. Three pillars of sustainability and sustainability tools for space activities.
The tools are mapped to the pillar that they inform. LCA = Life Cycle Assessment, S-LCA = Social LCA, TEA = Techno-Economic Analysis, LCC = Life Cycle Costing.

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Space resources will likely first be used in space (e.g. water mined for fuel) and eventually valuable metals will be returned for use on earth (*1*). As Earth's high grade scarce and rare earth metals resources becoming increasingly scarce, mining these materials in space, such as from planetary bodies and asteroids, may soon become economically favorable (*2*). Mining resources from space may result in fewer environmental impacts on Earth, simply from the halt of Earth mining (*3*). In effect, utilizing space resources may allow for offsetting a variety of environmental impacts off the surface of Earth, minimizing social impact potential, and while still gaining the vast economic benefits of a new untapped space resource base.

Businesses like Made In Space have determined the existing cost-per-kilogram to low earth orbit (LEO) is worth the expense in order to gain access to the microgravity manufacturing conditions that allow for production of high-quality 3D printed fiberoptic materials. Other companies, like Deep Space Industries and Planetary Resources are developing technologies for asteroid mining. Today, the biggest barrier to space exploration and mining is the cost of escaping Earth's atmosphere; shipping heavy equipment and cargo requires a lot of fuel, which is costly both from an economic and environmental standpoint.

Sustainability of space activities can be quantified using several tools available in the sustainability engineer's toolbox. This paper explores the use of two sustainability tools -LCC and LCA- for space activities through a case study comparing the cost and environmental impacts of the SpaceX Falcon 9 and Falcon Heavy systems. We discuss other sustainability tools that can be used to further inform sustainability of space activities, including Social LCA and TEA.

2. SUSTAINABILITY ENGINEERING TOOLBOX

Life Cycle Costing (LCC) is a tool to determine the most cost-effective option among different competing alternatives. The steps to conducting an LCC are similar to an LCA, and include construction, maintenance, and operations costs. While often confused with LCA, LCC exclusively tracks costs, and while it can include downstream costs such as maintenance and disposal, upstream costs beyond the primary supply chain are typically not included. All the costs are usually discounted and total to a present-day value, or net present value (NPV). LCC is most commonly used in the building industry and in asset management; standards are set forth by ISO 15686-5:2017. In this analysis, we use basic LCC methods to estimate the cost of the Falcon Heavy and Falcon 9; details of which are presented in the subsequent section.

Life cycle assessment (LCA) is used to quantify and characterize environmental impacts to improve a given engineered system's cradle-to-grave performance. LCA methodological standards have been developed and vetted and are widely used today. The International Organization for Standardization (ISO) have published a series of pertinent reports on LCA standards: ISO 14040:2006 and ISO 14044:2006 (*4, 5*). ISO 14040 details four steps of and LCA:

1. Goal and Scope Definition,
2. Life Cycle Inventory (LCI) Collection and Analysis,
3. Life Cycle Impact Assessment (LCIA), and
4. Interpretation of Results.

Each step requires multiple iterations of previous stages, often requiring updates and improvements as more information and analysis is completed.

Important features of the goal and scope step are the system boundary and functional unit definition. The system boundary defines what lies within (and without) the scope of the study. The functional unit is a standard quantitative reference that best represents the various functions of a defined unit of good or service to which impacts can be assigned. The inventory phase (LCI) consists of collecting quantitative data on flows for each process or step required in producing one unit of product. LCIA is the portion of an LCA which calculates and compares environmental impacts utilizing established impact categories and characterization methods (e.g. US EPA TRACI). Impact categories include global warming potential, resource depletion, ecotoxicity, acidification, eutrophication, and human health effects. Interpretation includes a completeness check (ensuring relevant information and data are available and complete), a sensitivity check (assessing reliability by determining how results are affected by uncertainties in data, assumptions, and methodologies), scenario analysis, and uncertainty analyses.

LCA study scopes/system boundaries are regularly defined through several life-cycle categories. These include:

- Cradle-to-gate: a life-cycle boundary including all upstream activities until a designated upstream point in time before end-of-life, often ending at the output "gate" of the product's factory floor.
- Cradle-to-use: a life-cycle boundary encompassing cradle-to-gate that includes the use-phase of the product or system but excludes any end-of-life impacts.
- Cradle-to-grave: a life-cycle boundary which includes all upstream and downstream activities from materials extraction through end-of-life.
- Cradle-to-cradle: a life-cycle boundary encompassing cradle-to-grave that includes recycling, reuse, coproduct management, and other ideas related to industrial ecology and circular economies.

There are two primary methods for performing LCAs: process-LCA and economic input-output LCA (EIO-LCA), with a third approach, hybrid-LCA, which uses a combination of these methods. Process LCAs are attributional in nature, and quantify and assess environmental impacts from each activity, product, or method (i.e. unit and system processes) included in the system boundary through careful study of system process details. Process-LCAs utilize and tally large datasets including emissions, flows, and resource usage for each process in the system. The more specific the data to the processes modeled, the more precise and accurate the results. However, when such specific and extensive datasets are not available for new and emerging technologies, EIO-LCA can be used to provide more generalized results.

EIO-LCA was first developed by researchers at Carnegie Mellon University and is available for use at “eiolca.net”. EIO-LCA estimates environmental emissions resulting from economic activities (i.e. purchases) in the major sectors of the economy using input-output tables derived from the bureau of labor statistics (Matthews and Small 2000). EIO-LCA results are often not representative of a specific product since they rely on sector-level averages.

A hybrid LCA combines elements of process-LCA and EIO-LCA methods. Hybrid LCAs utilize both methods in various combinations; often a process LCA model is built first and missing process data is supplemented with EIO-LCA data or verified by EIO-LCA sector results.

3. Case Study: Falcon 9 vs. Heavy

The Falcon 9 manufactured by SpaceX has been the most successful commercial space launch venture, with a total of 46 launches between 2010-2017 with 98% reliability (*6*). SpaceX has also been in the final stages of certifying its groundbreaking Falcon Heavy rocket launch vehicle design that was designed to considerably reduce the cost of orbital transportation by reusing two of its first-stage booster rockets (SpaceX.com). Falcon 9 and Heavy rocket engines use liquid oxygen and rocket grade kerosene (LOX/RP1) as the rocket propellants. An attributional, hybrid LCA methodology was employed in this study because of the lack of process-LCA data on the orbital transportation industry.

Hybrid LCA methodologies were employed to utilize EIO-LCA data for the NAICS code 336414 “guided missile and space vehicle manufacturing.” The unit processes and LCI databases used to construct LCA were used and referenced from our previous research (*7, 8*). Producer cost were estimated from published consumer price at the basic assumption of 40% profit markup for producer cost estimates and adjusted to the EIO-LCA dataset’s $USD2002 input unit. The system boundary scope was cradle-to-use (including spacecraft/rocket and fuel production, and launch/fuel combustion) with a functional unit of transporting one kilogram of payload to geosynchronous earth orbit (GEO). The EPA TRACI 2.1 impact categories were used. LCI inventory data and sources used are provided in Table 1.

Table 1. Life Cycle Inventory Primary Input Data

Inventory (Source)	Value and Unit
Falcon 9 Consumer Cost (Spacex.com)	6.2E+07 ($USD18/Launch)
Falcon Heavy Consumer Cost (Spacex.com)	9.00E+07 ($USD18/Launch)
Falcon 9 Total Payload to GEO* (Spacex.com)	4.02E+03 (kg/Launch)
Falcon Heavy Total Payload to GEO* (Spacex.com)	1.68E+04 (kg/Launch)
Falcon 9 Total Launch Mass (Spacex.com)	5.49E+05 (kg/Launch)
Falcon Heavy Total Launch Mass (Spacex.com)	1.42E+06 (kg/Launch)
Falcon 9 Empty Vehicle Mass** (SpaceLaunchReport.com)	3.27E+04 (kg/Launch)
Falcon Heavy Empty Vehicle Mass** (SpaceLaunchReport.com)	5.55E+04 (kg/Launch)
Oxidizer: Kerosene Mixture Ratio (LOX:RP-1) (Astronautix.com)	2.56 LOX:RP-1 (by mass)

*SpaceX advertises prices for rocket launch payload delivery for both the Falcon 9 and Heavy either to GTO or to Mars, not GEO. The “Payload to Mars” advertised values were used as a substitute for GEO delivery comparisons.

**Empty vehicle mass is also referred to as burnout mass.

4. Results and Discussion

Results showed substantial reduction in all quantified impact categories in this study between the Falcon 9 & Heavy systems when compared using LCA and LCC on a per kg delivered to GEO basis (Figure 2). When averaging the percentage impact reduction across all impact categories, the reusable design of the Falcon Heavy system reduced impacts by 58%, all while reducing producer cost by over $6,000/kg to GEO. The fossil fuel resource depletion impact category showed the least improvement (37%) between systems, while the non-carcinogenics, ozone depletion, and producer cost impacts showed equally large improvement (>65%).

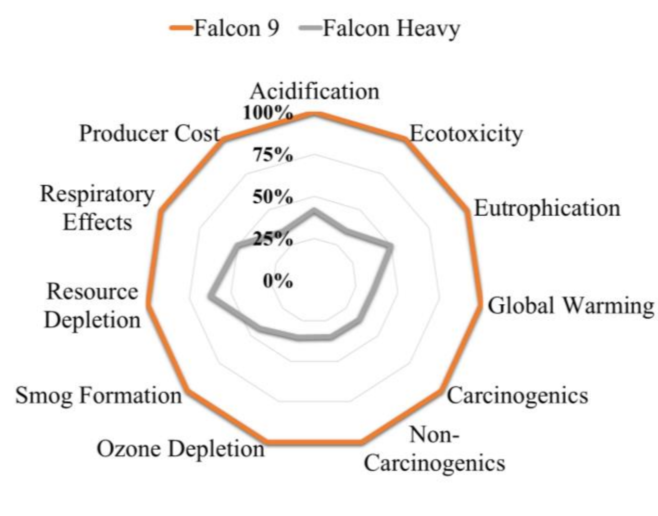

Figure 2. Falcon 9 & Heavy Life Cycle Impact Assessment Results Radar Plot Comparison. Normalized to Falcon 9 impacts ==100%.

More resolution in LCIA results findings for global warming potential (GWP), resource depletion, and producer cost impacts come from various modeled system process with attributed impact potentials (Figure 3). For GWP, measured in units of kg of carbon dioxide equivalent (kg CO_2 eq.), in both Falcon 9 & Heavy systems the most significant portion of impact potential results from the production of the spacecraft/rocket launch equipment and infrastructure. Because space vehicle production was evaluated via an EIO-LCA process, only average sector contributions can be evaluated, providing the top three contributors as power generation (44%), iron and steel production (9%), and oil and gas production (4%). Most of the resource depletion impacts (86%) for both systems resulted from the RP-1 (kerosene) fuel production. Rocket launch systems use a combination of propellants, such as RP1/LOX for both Falcon systems. Other rocket launch systems, such as the ULA Delta IV and retired Space Shuttle, use LH_2/LOX fuel mix, producing atmospheric H_2O emissions and less resource depletion.

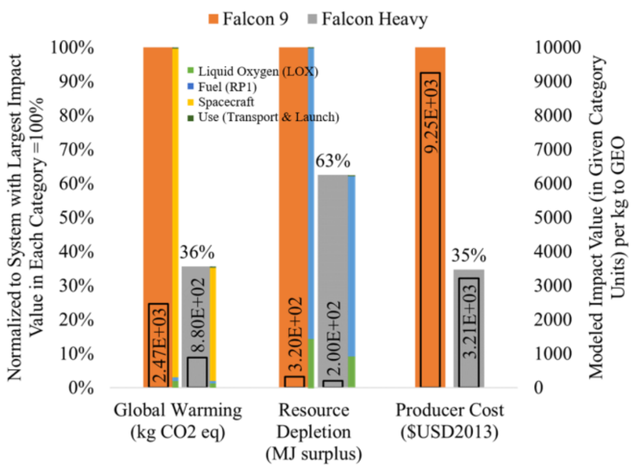

Figure 3. Cradle-to-use select environmental and producer cost impacts of orbital transportation systems by mass delivered to orbit. Colored bars normalized to Falcon 9 impacts ==100% on left axis. Black outlined bars correspond to given category units in parenthesis and right axis values.

These results illustrate both the economic and environmental benefits of applying sustainability principals, like the Falcon Heavy reusing rocket infrastructure, and how such benefits can be quantified and further improved. Such findings and analysis only scratch the surface of what sustainability engineering could bring to the orbital transportation and rocket launch industries and systems.

A potential downside to the Falcon Heavy system is its substantially large payload, being a super heavy-lift launch vehicle capable of delivering over 50,000 kg to LEO, and not yet being certified to deliver humans to orbit. Smaller and human payloads to LEO or below may be more efficient using smaller payload vehicles. The Falcon 9 Full Thrust (evaluated herein) is considered a medium-lift vehicle and is being evaluated for human space flight via the Dragon space vehicle. Examples of other rocket launch technologies and services demanding similar sustainability comparison include both large rocket launch systems, such as the Soyuz or Long March 9, as well as smaller or nontraditional systems, such as Pegasus, Blue Origin, and Virgin Galactic.

5. Other Sustainability Tools

In addition to LCA and LCC, TEA is an ideal tool to evaluate new technologies related to space resources. TEA quantifies the economic viability of a product or process (*9*) and is typically used by companies to evaluate the potential of new endeavors. Results can provide direction to research, development, investment, and policy making. It integrates well with the stage gate analysis process many private industry and R&D centers use for project development. TEA uses a mixture of methods including cost assessment, risk assessment, and performance assessment to guide decision making. While the Department of Energy has published a handful of spreadsheet-based TEAs for specific products (e.g. distributed generation renewable energy technologies), there is no software available for conducting TEA (*10*). The most value of TEA is in the Financial Analysis step, where scenario analysis is typically conducted. Scenario analysis enables evaluation of alternate supply chain choices, process configurations, and price points that would make the endeavor profitable. The main steps of a TEA include:

1. Goal & Scope Definition
2. Process Model
3. Energy & Mass Balance
4. Cost Engineering
5. Financial Analysis
6. Refine Model, Identify Improvements, and Iterate

Social LCA (S-LCA) is a method that aims to assess the sociological and social effects associated with a particular product's production activities. The society of Environmental Toxicology and Chemistry (SETAC) and the United Nation Environment Programme (UNEP) worked together to develop the methodology of S-LCA. The method follows the same ISO 14040 framework that LCAs follow, but some aspects of each stage differs (*11*). Five main stakeholder groups are considered in S-LCA: [i] worker, [ii] consumer, [iii] local community, [iv] society and [v] value chain actors. One of those stages that differs most involves the LCI and LCIA stages, where impact categories can include health & safety, working conditions, cultural heritage, human rights, governance, and socio-economic consequences. The main limitation of the approach is the struggle to maintain consistency between studies since much of the data is of qualitative nature and social indicators can vary based on the study's system (*12*).

6. The Future of Space Sustainability

To improve quantitative sustainability assessments for activities that occur in space, both LCA and S-LCA would need to be updated. With respect to LCA, third step (LCIA) would need new methods for activities in space. LCIA converts the LCI data into meaningful environmental impacts, such as global warming potential, resource consumption, water quality, air quality, and land use. All the existing LCIA tools available to an LCA practitioner are based on impacts to earth (not even all of earth's impacts are yet covered by LCIA tools; most were developed for the US and Europe and exclude unique environmental impacts in other countries). LCIA categories must be developed for conditions in space. E.g. to evaluate potential vacuum pollution on lunar and asteroid mining operations, to account for resource depletion (lunar ice mined as rocket fuel), solid waste management (mining refuse, with synergistic or future material value), and human health impacts (prolonged exposure to solar radiation and microgravity), et cetera, standardized LCIA impact categories and characterization methodologies must be developed and implemented.

Social LCA can more easily be adapted for space activities. The five main stakeholder groups considered in S-LCA would remain the same, but likely represent a very specific set of people. In addition, the [ii] consumer, [iii] local community, and [iv] society may have less direct impacts than [i] worker and [v] value chain actors. The LCIA step of S-LCA would also have to be adapted to match activities in space; for example impact categories might include health & safety (which would already be included in regular LCAs), working conditions, exogeoconservation (*13*), governance (*14*), and socio-economic consequences.

Sustainability engineering attempts to optimize the benefits and tradeoffs that occur within the economic, social, and environmental systems impacted by human designed systems. Terrestrial sustainability engineering came about as a response to the rapid accumulation of harmful impacts external to the economic market system (such as ecotoxicity) in the later parts of the twentieth century. As we continue to develop and design technologies and systems in space, it is critical that we concurrently evaluate the sustainability of these plans and endeavors. Quantitative sustainability engineering can help engineers, stakeholders, investors, and policy makers foresee unintended consequence that would be detrimental to long-term activities, whether on earth or in space. This research, having applied sustainability principles and quantitative engineering methodologies to space activities, is only a small example of the research required to prevent unintended consequences from occurring in space, thus compromising the potential utilization of space resources. In addition, integrating sustainability into design often results in economic savings; as example the re-use of the Falcon Heavy boosters with both a 65% reduction in cost and 64% reduction in GWP.

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BIOGRAPHY

Tyler M. Harris *is a former US Marine and current sustainability "engineering artist" working at PNNL. He received his B.S. in Environmental Science and Astronomy from Columbia University in 2007, his M.S.E. in Sustainability Engineering from Arizona State University in 2015, and most recently earned his Ph.D. in Civil and Environmental Engineering from Colorado School of Mines in August 2018. His thesis,* Quantitative Sustainability Modeling and Assessment of US Transportation Systems Including Biofuel and Orbital Transportation Systems Case Studies*, was completed under the supervision of Dr. Amy Landis. He began his space sustainability research with his senior thesis at Columbia. He was also lead mechanical technician on*

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***Amy E. Landis** is Professor of Civil and Environmental Engineering and the first Presidential Faculty Fellow for Access, Attainment and Diversity at the Colorado School of Mines. She was a full professor at Clemson University from 2015 to 2017 as the Thomas F. Hash '69 Endowed Chair in Sustainable Development. She served as director of Clemson's Institute for Sustainability and was an associate professor at Arizona State University's School of Sustainable Engineering in the Built Environment from 2012 to 2015. During her tenure at ASU she served as director of research for the Center for Earth Systems Engineering and Management, senior sustainability scientist for the Global Institute of Sustainability, Lincoln Fellow of Sustainable Development and Ethics for the Lincoln Center for Applied Ethics and Tooker Professor of STEM Education for the Ira A. Fulton Schools of Engineering. She began her career as an assistant professor at the University of Pittsburgh after earning her PhD in 2007 from the University of Illinois at Chicago under the supervision of Thomas L. Theis. Her research ranges from design of systems based on industrial ecology and byproduct synergies, life cycle and sustainability assessments of biopolymers and biofuels and design and analysis of sustainable solutions for health care, and now space sustainability. She is also dedicated to sustainability engineering education and outreach, and diversity in STEM. She has established networking and mentorship programs at three different universities to advance diversity and STEM. She also works with local high schools, after-school programs, local nonprofit organizations, extensions and museums to integrate sustainability and engineering into K-12 and undergraduate curricula.*