IMS – Documentation

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1 Introduction

This work will focus on Mars logistics. With SpaceX's ambitions to build a colony on Mars, we take a look at how long it would take to transport the materials and supplies to Mars's surface, from where the surface colony could be established. We will also look at the optimal number of rockets that could be utilized for this purpose to complete the task within a reasonable time horizon. As carrying out these experiments in the real world is not viable in this field, the only acceptable solution is to employ the principles of modeling and simulation.

2 Analysis

The company SpaceX plans to deliver materials to the surface of Mars in order to build an inhabitable base on it. With Mars being 225 million kilometers (on average) away from Earth, this is not a trivial task. Starship, the rocket that is planned to carry out this delivery, has a payload of around 100 tons of material that it can take to Mars on a single shot[6]. It is a two-stage super heavy-lift spacecraft. It is intended to be fully reusable, which means both stages will be recovered after a mission and used again.

The first stage, called Super Heavy Booster[5][6], is a 71-meter-tall rocket booster with 33 Raptor engines. Its fuel capacity is 3400 tons of methane and liquid oxygen. The burn phase lasts for approximately 240 seconds while burning around 14 tons of fuel every second.

The second stage, nicknamed Starship[5][6], is only 50 meters tall and weighs up to 1320 tons with fuel and maximum payload. The engine compartment comprises of 6 Raptor engines, which are used to propel the spacecraft from Earth's orbit to Mars. The fuel capacity is 1200 tons of methane and liquid oxygen.

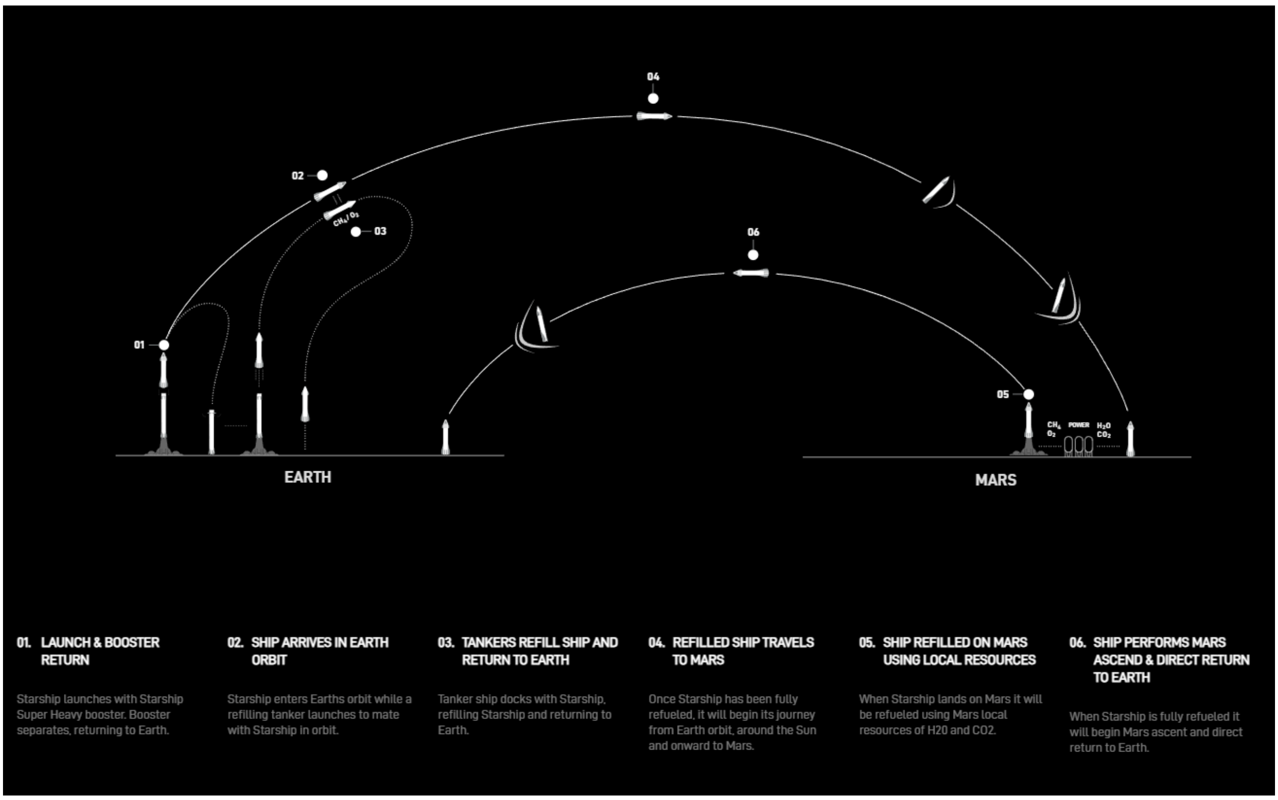

Figure 1: SpaceX plan for the Mars mission [4]

As both stages are manufactured separately, they need to be assembled together afterward. The process of joining the two stages and preparing the payload takes 2 months exponentially. Before the rocket can be launched, it needs to be granted permission to launch by the FAA, which takes 3 weeks exponentially.

The minimum-energy launch windows for a Martian expedition occur at intervals of approximately two years and two months (specifically 780 days, the planet's synodic period with respect to Earth). [8]

With the permission to launch granted, the rocket needs to be transferred to a launch pad and filled with fuel, which takes 2 days on average. After launch, it takes around 10 minutes for the rocket to reach the Earth's orbit [9]. This is where the first stage separates from the second stage and returns to Earth to be used again. The first stage has to wait for tankers to refill its fuel tanks. Tankers are a special type of spacecraft with the sole purpose of delivering fuel to the Starship. They also contain two stages, with the first stage being a Super Heavy Booster as well. Transferring fuel from a single tanker to the Starship takes approximately 4 hours and to fill the fuel tank completely, it needs to receive refueling from 4 to 8 tankers, which we averaged to 6. Tankers are also designed to be reusable, so after completing their mission, they return back to Earth. [4]

With the fuel ready, the Starship waits for the Mars transit window. When Mars gets close enough, all of the fueled orbiting Starships depart towards Mars. Reaching Martian orbit takes 80-150 days, depending on the launch date. Afterward, the unloading of the payload, synthesizing the fuel from methane on the surface, and refueling take five days exponentially. Then, the Starship can begin its trip back to Earth, which again takes somewhere from 80 to 150 days.

2.1 Used Technologies

We implemented the model using the modeling and simulation library SIMLIB[3], which is written in C++. This framework offers a wide range of simulation algorithms with simple usage and, therefore, is suitable for our experiment. For the compilation of our model, we used C++ standard C++17 [1] and GNU Make[2].

3 Conceptual Modelling

In this section, we discuss the design of the conceptual(abstract) model of our system, which, in its essence, can be considered a queuing system. As we focus on the logistics of the materials and goods to Mars, we only model the act of transportation and not the manufacturing process of the rockets. The model is simplified by omitting the chance of catastrophic failures in every stage of the flight.

3.1 Conceptual Model Description

Our model (see below) consists of 5 main parts. These include preparing the rocket, obtaining permission to launch, launching the rocket into orbit, refueling it with tankers, and finally, getting to Mars.

[1] https://en.cppreference.com/w/cpp/17
[2] https://www.gnu.org/software/make

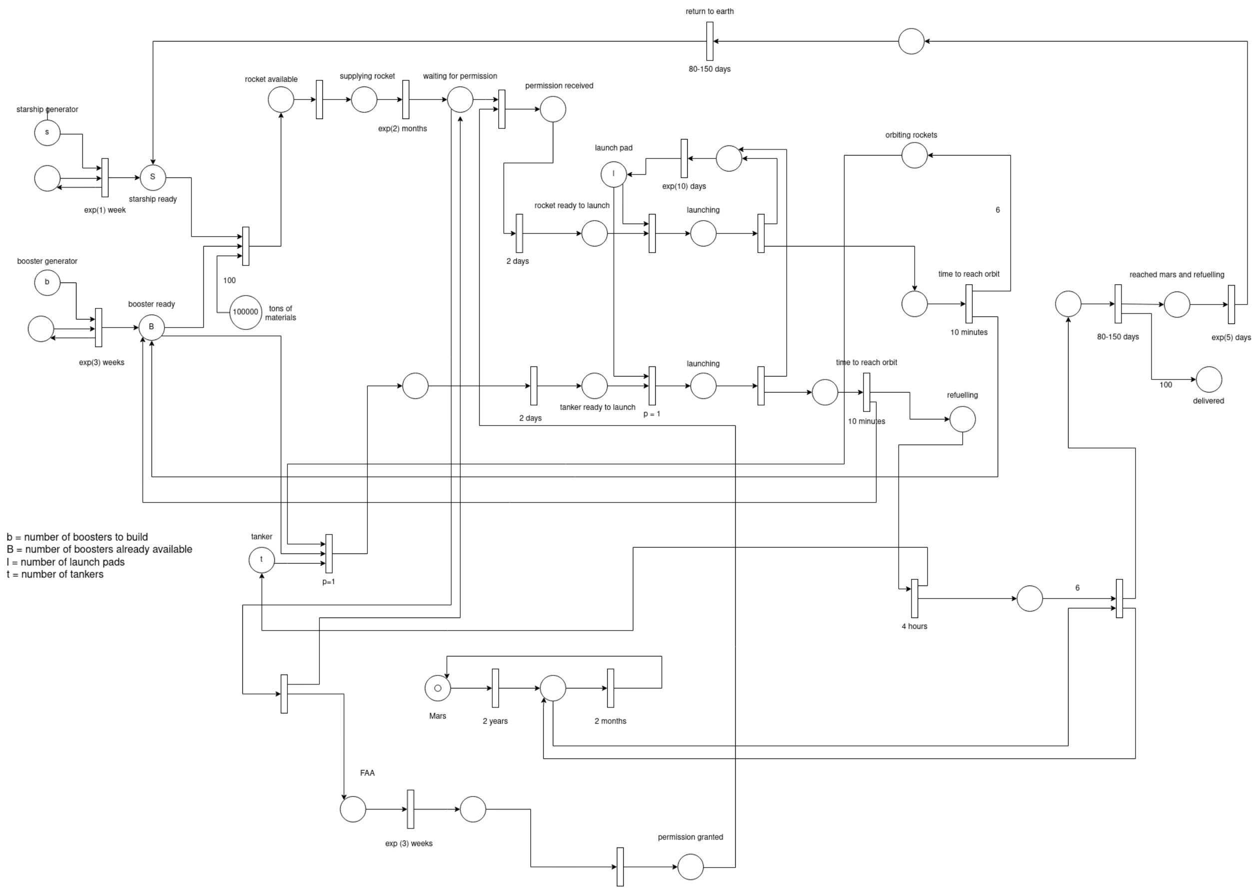

Figure 2: Petri network of our model

4 Simulation

Algorithm 1 Rocket preparation

wait for an available Starship;
wait for an available booster;
assemble booster and Starship;
fill the rocket with supplies;
request permission to launch;

Algorithm 2 Launch permission

wait for FAA to grant permission to launch;
grant permission;

Algorithm 3 Launch

wait for permission;
move the rocket to a launchpad depot;
wait for an available launchpad;
launch the rocket;
reach Earth's orbit;
return the booster back to Earth;

Algorithm 4 Refueling

wait for a rocket on the orbit;
wait for tanker;
wait for a booster;
move to a launchpad depot;
wait for a launchpad;
launch the rocket;
reach orbit;
return the booster;
refuel the Starship;
return Tanker back to Earth;
repeat from step 2 six times;

Algorithm 5 Journey to Mars and back

wait for Mars transit window;
reach Mars;
descent to Martian surface;
refuel the rocket;
return back to Earth;

4.1 Mapping of Conceptual Model to Simulation Model

As described in part 3.1, the preparation of the rocket is modeled as a process, `RocketProcess`, that starts as soon as a booster and a Starship are available. This process requests permission from another process, `FAAProcess`. After the permission is granted, the `RocketProcess` waits for `LaunchPad` store to be available and then proceeds with the launch. When the orbit is reached, a new `BoosterProcess` with tanker begins. After the refuelings are done, the `RocketProcess` waits for Mars transit window and then departs for Mars, where refueling commences and returns back to Earth.

Other processes include:

- `StarshipProcess` - serving to assemble the Starship and a booster into a rocket
- `BoosterProcess` - serving to assemble the Starship and a booster into a rocket or launch a tanker
- `LaunchPadProcess` - managing the availability of a launchpad
- `MarsProcess` - periodically enables Starships to depart for Mars

4.2 Running the Simulation Model

To use the program, it is necessary to run the command `make` to compile the source files. To run the program, use `make run`. By default, the program runs with implicitly set configuration values. These include: the number of launch pads (default 1), number of tankers (default 1), number of boosters (default 10), number of starships (default 80), and payload size in tons (default 10 000). It is possible to set these configuration values when running the program with a command of the following structure:

```
make run [ARGS="[-s <number of starships to build>] [-b <number of boosters to build>]
[-l <number of launchpads>] [-t <number of tankers>] [-p <payload size>] [-S <initial
number of starships>"] [-B <initial number of boosters>]
```

For example, running the experiment no. 1. can be done with the following command:

```
make run ARGS="-s 20 -b 10 -l 1 -t 1 -p 1000"
```

5 Experiments

In each experiment, we included a short description of the problem the experiment revolves around and the output of its simulation. Duration in all experiments is measured in hours. Every time an experiment is run, Mars is in its low-energy window.

5.1 Experiment 1

The first experiment is a simple run with an approximate status of what SpaceX would be capable of with its current facility. As a goal, we set to deliver 1000 tons of goods to Mars, which is around 2.4 times more than what ISS weighs[1].

Experiment 1						
Payload	Starship count	Booster count	Launch Pad count	Tanker count	Launches	Duration
1000	20	10	1	1	70	21115.7

This experiment shows that it would take about 2.4 years to deliver 1000 tons of payload to Mars. The biggest bottlenecks are the initial production of rockets and the short window for Mars transit.

5.2 Experiment 2

The second experiment is to use up to 3 launch pads. Currently, SpaceX only plans to use 3, which is why we chose this number.

Experiment 2						
Payload	Starship count	Booster count	Launch Pad count	Tanker count	Launches	Duration
1000	20	10	1	1	70	21115.7
1000	20	10	2	1	70	20895.5
1000	20	10	3	1	70	20865.4
1000	20	10	5	1	70	20895.5

In this experiment, we show that with the same number of boosters and Starships, the higher numbers of launch pads have no statistical benefit. The problem is caused by the fact that the extra launch pads are not being utilized, as not enough rockets are being launched.

5.3 Experiment 3

The third experiment is to show the influence of more tankers being used with the single launch pad.

Experiment 3						
Payload	Starship count	Booster count	Launch Pad count	Tanker count	Launches	Duration
1000	20	10	1	1	70	21115.7
1000	20	10	1	2	70	20795.3
1000	20	10	1	3	70	20795.3
10000	50	20	1	2	700	195856
10000	50	20	1	5	700	178779
10000	50	20	1	10	700	178728

This experiment shows that increasing the number of tankers enables SpaceX to refuel Starships on orbit more quickly, which leads to a decrease in the time required to complete the overall operation. The benefits, however, come with diminishing returns as more and more tankers do not speed up the refueling process with only a single launch pad available.

5.4 Experiment 4

The fourth experiment shows the influence of a combination of different numbers of launchpads and tankers.

Experiment 4						
Payload	Starship count	Booster count	Launch Pad count	Tanker count	Launches	Duration
10000	50	20	1	1	700	178217
10000	50	20	2	2	700	91128.3
10000	50	20	2	3	700	90986.7
10000	50	20	2	6	700	91128.3
10000	50	20	3	2	700	73659.4
10000	50	20	3	3	700	73480.3
10000	50	20	3	6	700	73496.9

In this experiment, we elaborate further on the knowledge gained from experiment no. 3. We prove that increasing the number of launchpads with the number of tankers yields a considerable benefit to the mission duration and the fact that increasing either of those values without the other one yields only partial results.

5.5 Experiment 5

The fifth experiment is to find an ideal ratio between the count of boosters and starships to reach as high as possible throughput to Mars within launch windows. We also use the number of launch pads and tankers that yielded the best results in the previous experiment.

Experiment 5						
Payload	Starship count	Booster count	Launch Pad count	Tanker count	Launches	Duration
10000	10	10	3	3	700	178697
10000	20	10	3	3	700	92186
10000	30	10	3	3	700	73576.8
10000	50	10	3	3	700	73466.7
10000	20	20	3	3	700	91099.6
10000	20	30	3	3	700	91122.7
10000	20	50	3	3	700	91159.7

In this experiment, we show that increasing the number of Starships has considerable benefits to mission duration. However, increasing the number of boosters does not have an observably positive effect as most of them stay on the ground, unused.

5.6 Experiment 6

In the last experiment, we model the mission with an initial set of boosters and Starships, that are ready to use, and do not wait for them to be manufactured one by one during the simulation run.

Experiment 6 Manfactured						
Payload	Starship count	Booster count	Launch Pad count	Tanker count	Launches	Duration
10000	10	10	1	1	700	248404
10000	50	20	3	3	700	73480.3
10000	50	20	5	5	700	55976.9
10000	50	20	10	10	700	38581.8
10000	100	30	20	20	700	21266

Experiment 6 Premade						
Payload	Starship count	Booster count	Launch Pad count	Tanker count	Launches	Duration
10000	10	10	1	1	700	248756
10000	50	20	3	3	700	73579.6
10000	50	20	5	5	700	56036.2
10000	50	20	10	10	700	38615.4
10000	100	30	20	20	700	21103.1

The results show that using the premade rockets does not offer much benefit as the majority of time is being spent on waiting for Mars. The duration of the manufacturing process of starships and boosters does not affect this result much.

6 Conclusion

This study shows that the mission to deliver 10000 tons of goods to Mars will take at least 2.4 years. The duration of at least 2 years is due to the fact that we are not capable of refueling all the starships required to transfer the goods during the initial Mars transit window. It also analyses the role other parameters can play in executing this mission faster. This duration counts with no rapid unscheduled disassemblies, also called RUDs [7] and other delays. Additionally, the cost of this mission can be estimated at about 7 billion USD [2], not counting the loss of goods and the cost of fuel.

6.1 Validation

The validity of the model will be tested when SpaceX succeeds at its mission to reach and deliver the first wave of goods to Mars. At the time of the study, SpaceX had not reached Earth's orbit with Starship. We based as much of the data as we could on the real-world facts, which are known of this mission and the rockets being used in it.

References

[1] Brian Dunbar and Alison Hall. *Station Facts*. online. 2023. URL: https://www.nasa.gov/international-space-station/space-station-facts-and-figures/.

[2] Greg Heilam. *How much money does Elon Musk's SpaceX Starship program cost?* online. 2023. URL: https://en.as.com/latest_news/how-much-money-does-elon-musks-spacex-starship-program-cost-n/.

[3] Petr Peringer, David Leska, and David Martinek. *SIMLIB/C++ (SIMulation LIBrary for C++)*. online. Sept. 2023. URL: http://www.fit.vutbr.cz/~peringer/SIMLIB.

[4] SpaceX. *MARS BEYOND THE ROAD TO MAKING HUMANITY MULTIPLANETARY*. online. 2023. URL: https://www.spacex.com/humanspaceflight/mars/.

[5] SpaceX. *Starship - Service to Earth Orbit, Moon, Mars and Beyond*. online. 2023. URL: https://www.spacex.com/vehicles/starship/.

[6] SpaceX. *Starship user guide*. 2020. URL: https://www.spacex.com/media/starship_users_guide_v1.pdf.

[7] SpaceX. *X statement by SpaceX*. online. 2023. URL: https://x.com/SpaceX/status/1725880148271190388?s=20.

[8] Wikipedia contributors. *Exploration of Mars — Wikipedia, The Free Encyclopedia*. [Online; accessed 7-December-2023]. 2023. URL: https://en.wikipedia.org/w/index.php?title=Exploration_of_Mars&oldid=1186568632.

[9] Jenny Winder. *How long does it take to get to space?* online. 2023. URL: https://www.skyatnightmagazine.com/space-science/how-long-does-take-get-space.