SSE Group Assignment

Systems Engineering for Asteroid Mining

SSE Group 36

Delft University of Technology

TU Delft

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by

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Name	Student Number
Burr, Zachary	4659821
Chin A Foeng, Luke	4609972
Petit dit de la Roche, Nicolaas	4556135
Welzel, Lukas	4551486

TUDelft Faculty of Aerospace Engineering

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Chapter 1

Market Analysis

The key competitors identified included a broad range of companies, not only the ones that would specifically move asteroids to a near-Earth or lunar orbit. This range of companies was included so as not to exclude any company that could have the potential capabilities to fulfill the need statement or mission statement defined for our company. Several potential competitors were found to have gone defunct over the past several years, a clear weakness. However, although these companies no longer exist, their strengths and weaknesses must still be accounted for, as there are benefits to taking these into account. Mainly, they can be compared against our own strengths and weaknesses so as not to miss any important aspects of a space mining company that could be important to our own. Note that Bradford Space acquired Deep Space Industries, so one can assume the capabilities of this company are now capabilities of Bradford Space.[2] Table 1.1 details the key competitors in the asteroid mining space, as well as some key capabilities of the asteroid mining systems of these companies.

This task was conducted by looking into all viable asteroid companies, where viability depended on how capable these companies would be at executing their main missions, as asteroid mining is an extremely expensive industry to take part in.

Table 1.1: This table displays several asteroid mining competitors and their system capabilities.

Space Resource Mining Company	Mission Name	System Capabilities	Sources
Deep Space Industries	Xplorer	Deep Space Injections Provides up to 5 km/s ΔV In-Situ Manufacturing	[8]
Asteroid Mining Corporation	AMP-1	Extract up to 20 tonnes of Material Material Refinement Material Return conducted with reusable capsules	[5]
OffWorld		Water Extraction Metal Extraction	[7]
Planetary Resources	Arkyd-6	Asteroid Mapping Deep-Scanning Sample and Return Missions	[3] [10]
Kleos		In-Situ Manufacturing Asteroid Mining	[4], [9]

Table 1.2 shows the key strengths and weaknesses of each of the companies' asteroid mining systems. Note that several companies include the ability to produce space structures or even complex space systems from some of the material mined. However, although these capabilities are possible in theory, they have yet to be proven in the real-world. These complex systems would encounter issues with the amount of small particulates that are created as a result of the mining operations. Ultimately, simplicity was considered a relatively important strength, as the less complex a space system is, the less likely it is to fail. This is especially important in deep space mining operations, as latency becomes a large issue, along with any complex processes such as in-situ processing or manufacturing.

As a recommendation, one could continue this market analysis with a SWOT analysis, followed by a Porter's Five Forces analysis. One could also go further by incorporating scientific missions into the market analysis, as they are examples of the correct execution of such a complex mission. One could find ways to either lower the costs of a scientific mission, or optimize a scientific mission solely for sample return.

Table 1.2: This table outlines the key strengths and risks associated with each company's asteroid system.

Space Mining Company	**Key Strengths**	**Key Risks**
Deep Space Industries	System contains a large amount of on-board ΔV, Company has developed a proprietary 3D printer design that converts raw asteroid material into potential space systems	The system has a small bus size, not large enough for profitable sample return The 5 km/s of ΔV is enough for a one-way trip.
Asteroid Mining Corporation	This company would refine the material in-situ, and would return a large quantity of it to Earth, leading to higher returns	Profitability only occurs when a large amount of material is returned. Since the system is designed to return 20 tonnes of refine material, high launch costs are expected due to the necessary propellant required, as well as the refining equipment on-board. This company has conducted no real world tests.
OffWorld	Parts are designed by a weight optimized AI algorithm. AI is also incorporated into the autonomous control of the vehicle, which becomes increasingly necessary the farther out the system must travel	Company mentions that no major redesign is necessary for the system to be used for asteroid mining, even though they incorporate wheels, which are a plus on large planets, but waste valuable weight budget when used on asteroids. This company has conducted no in-space testing of their system.
Planetary Resources	The system makes use of in-situ resource processing, leading to higher returns. The system has a small form factor, which can lead to multiple systems being launched at once. The company has also completed a successful on-orbit demonstration of several key systems, most notably the first commercial mid-wave infrared imager in space.	In-Situ resource processing requires expensive, complicated, heavy equipment, leading to increased launch costs.
Kleos	The in-space manufacturing system is currently undergoing extensive LEO testing, as it is incorporated onto every one of their geospatial satellites in their fleet	This system is in its early testing stages, and is quite complex, leading to potential delays in the long -term.

Chapter 2

Mission Statements

2.1 Need Statement

To facilitate the exploitation of space resources, an asteroid must be moved from a near-Earth orbit into an orbit about the Earth or Moon, where it is more easily accessible.

This statement lays out a clear and present need for the mission: if the asteroid or the resources present therein are to be accessed and utilized, this is a necessary first step. Since our mission is only to transport the asteroid, we focus on making the asteroid *available*, so that the company is a service provider. This service allows or rather facilitates the use of the asteroid, which is where real positive economic value is generated. The second part of the need statement constrains our mission, as we just focus on a single asteroid, in a specific kind of orbit (NEO) which needs to be moved into a different specific orbit. The last part of the need statement gives the rationale for the need: We need to move it to make using the asteroid possible or easier.

2.2 Mission Statement

Move the target asteroid into an orbit about the Earth or Moon.

Here the specific mission is clearly and concisely stated. The statement also leaves room for any possible solution: it only states *what* the mission is, not *how* to achieve it. This mission statement is very concise as we only include the ”what”.

Chapter 3

Stakeholders

It is important to identify the mission’s stakeholders and their needs in order to gain an understanding of those that influence the success of the mission. In this chapter the most critical stakeholders are identified and their primary requirements listed along with a short explanation.

3.1 Active Stakeholders

Our commercial company

- **AM-SH-PFM-1** The system shall be able to bring a specific C-type near-Earth asteroid up to 10 meters in size into an orbit around Earth.
- **AM-SH-PFM-2** The system shall be able to bring a specific C-type near-Earth asteroid up to 10 meters in size into an orbit around the Moon.
- **AM-SH-CST-1** The total cost of the system, including manufacturing, launching and operation shall be less than <TBD> Euros per retrieved asteroid.
- **AM-SH-CST-2** The initial cost of the system, including manufacturing, launching and operation until successful asteroid retrieval shall be less than <TBD> Euros.

Naturally our company is a stakeholder. The company will be the only entity directly interacting and managing the system while it is in use. Most important for the company is that the system is able to move specific asteroids into an orbit around the moon and that the total cost of doing this is less than whatever the company thinks it can sell this service for. Additionally, the initial cost must be lower than the initial capital available for the project.

3.2 Passive Stakeholders

Companies involved in the manufacturing of the system

- **AM-SH-PRD-1** Each individual to be manufactured part of the system shall have its dimensions fully specified.
- **AM-SH-PRD-2** The system can be fully assembled from its individual parts without the need for changes to be made to the individual parts.

Launch system companies providing delivery of the system into orbit

- **AM-SH-BDG-1** The total mass of the system shall not exceed <TBD> kilogram.
- **AM-SH-BDG-2** The system shall fit within the fairing of the <TBD> launch vehicle.

Governmental agencies

- **AM-SH-LEG-1** The system shall comply with international Space Law.
- **AM-SH-LEG-2** The system and its production shall comply with local laws.
- **AM-SH-LEG-3** At no point shall the to be retrieved asteroid be on a collision course with Earth.
- **AM-SH-LEG-4** The retrieved asteroid shall not interfere with any active space missions.
- **AM-SH-LEG-5** The system shall not interfere with any active space missions.

Not much is known yet about the manufacturing companies that our company will employ to make parts and assemble the system, as much depends on the design of the system and the eventual manufacturing companies employed. Of course in the end it must be possible for manufacturing companies to make individual parts of our system and assemble it.
Another important part of getting our system operational is getting it into space. For this launch system companies will be employed. Important is our system must be within the budgets of whatever launch vehicle we end up deciding to go with.
Naturally moving an asteroid closer to Earth will garner the attention of governmental agencies. They will require that at no point our system moves the asteroid on a collision course with Earth and that our system and asteroid will not interfere with any ongoing space missions. Also involvement of governmental agencies will be present to check whether our system complies with local laws and safety standards.

3.3 Customers

Space mining corporations (passive)

- **AM-SH-PFM-3** The final orbit of the retrieved asteroid shall be accessible for <TBD> space mining equipment.
- **AM-SH-PFM-4** The system shall maintain the integrity of the asteroid throughout the duration of the mission.
- **AM-SH-PFM-7** The asteroid shall be in its final orbit no later than <TBD> weeks after the order is placed.

Research Agencies (passive)

- **AM-SH-PFM-5** The final orbit of the retrieved asteroid shall be accessible for <TBD> science equipment
- **AM-SH-PFM-6** The asteroid shall arrive at its final orbit without being broken up.

We can foresee two main customers: space mining corporations that want to exploit the resources present on asteroids, and research agencies that want convenient access to asteroids in order to do science on them. These are both passive customers as they will not interact with our system but will only interact with the relocated asteroid after it is brought into its final orbit. Important for the customers is that the final orbit is within reach of their respective equipment. Additionally mining corporations would require a minimal amount of the asteroid resources to be lost during transportation and research agencies might require the asteroid to arrive mostly intact to preserve its original state.

Chapter 4

Acceptance Criteria

The acceptance criteria that will define the success or failure of the mission are given below. Failing any of these criteria means that the mission has to be considered unsuccessful.

AC1 **The project shall have a positive economic net present value.** This is a single value assessment of the financial aspects of the project. It takes into account:

- costs (negative cash flows) of the project
- financial benefits (positive cash flows) of the project
- discount rate (the time at which costs and benefits occur)

Using just net-profit would not be sufficient to evaluate a project a-priory, especially one which might be running for a long time (potentially more than 25 years) before the benefit for the customer is created. Using this value gives a better assessment of the quality of a project than most other single values, can be computed relatively easily and a priori. Its evolution can be tracked over time to assess the financial performance of the project. This acceptance criteria directly follows from **AM-SH-CST-1**, **AM-SH-CST-2** and **AM-SH-PFM-7**.

AC2 **The initial investment shall not exceed the company's capital.** This has to be an acceptance criteria since the project cannot be started without sufficient funds and hence will not be successful. This acceptance criteria directly follows from **AM-SH-CST-2**.

AC3 **The final orbit of the asteroid shall be be inside the customer defined target orbit envelope.** This has to be an acceptance criteria since it is the desired end-state and goal of the project. Since achieving the exact orbit desired by the customer might not always be possible or feasible some margin has to be allowable for mission success. This follows from **AM-SH-PFM-1** and **AM-SH-PFM-2** as well as **AM-SH-PFM-5**.

AC4 **The intermediate orbits of the asteroid shall not put it on a collision trajectory with any celestial bodies or space-craft.** This is a criteria that rules out creating a kinetic impactor on a trajectory with earth or human-made objects. This must be avoided at all costs to not endanger human lives and the company. This directly follows from **AM-SH-LEG-3** and **AM-SH-LEG-4**.

AC5 **The project shall not violate international laws.** If international laws are violated the company may not be able to capitalize on the profits and might face criminal persecution. This acceptance criterion follows from **AM-SH-LEG-1**. We do not include **AM-SH-LEG-2** as a success criterion since the mission might still be successful while not complying with **AM-SH-LEG-2** due to the nature and state of space-law.

Chapter 5

Concepts

5.1 Design Options Tree

To generate all possible concepts for relocating the asteroid, a design options tree was constructed. This is shown in Figure 5.1, with an enlarged version of this figure available in Appendix B. The concepts have been split into two main groups: on-site concepts—those which involve rendezvousing with the asteroid—and off-site—those which utilize a system that does not physically go to the asteroid. These are further broken down based on re-usability: whether the same system can be used to move multiple asteroids, or only one. The concepts are finally grouped by the method they use to move the asteroid. An additional separate category was added for human based concepts: involving astronauts being sent to the asteroid.

Performing a trade-off with all of these potential concepts would be extremely time-consuming, and likely a lot of the concepts would be immediately eliminated for being infeasible. Therefore, first a feasibility study was performed, whereby the concepts that are obviously infeasible or do not meet the requirements were eliminated. A number of infeasibility types were identified, which are all color-coded in the DOT. Obviously infeasible options

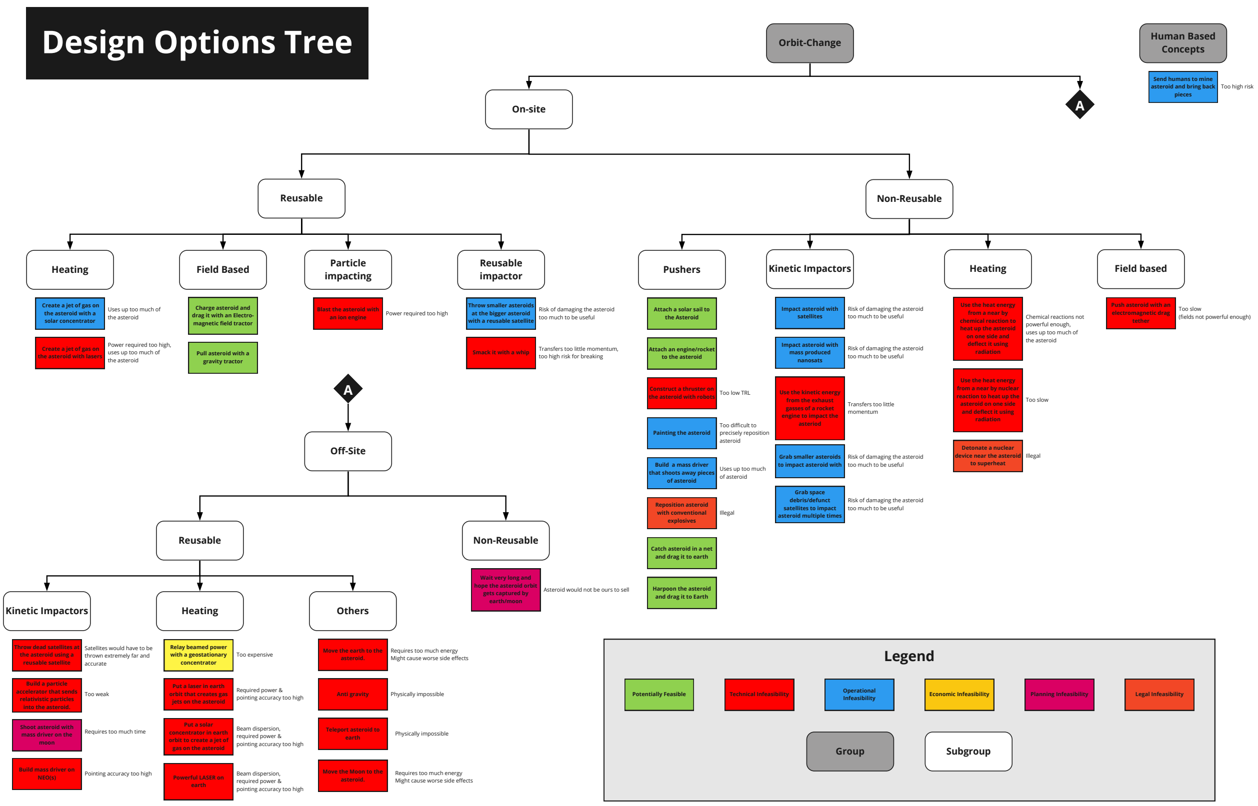


Figure 5.1: Design Option Tree [1]. An enlarged version of this figure can be found in Appendix B

were ruled out without a trade-off based on engineering judgment. The options that are not obviously infeasible are then entered into the trade-off to be compared.

This leaves six potential concepts which will enter the trade-off. The remaining options are:

- **Electromagnetic field tractor**: The asteroid is charged, then the spacecraft creates a strong EM field in the vicinity, which will accelerate the asteroid in the desired direction.
- **Gravity field tractor**: A large mass is stationed near the asteroid. The mass will pull on the asteroid, accelerating it in the desired direction.
- **Solar sail**: A solar sail will be attached directly to the asteroid itself, accelerating it and steering it with solar radiation pressure.
- **Direct engine/rocket attachment**: The spacecraft connects directly to the asteroid and pushes it with the rocket thrust.
- **Net**: The asteroid is grabbed with a net and dragged behind the spacecraft.
- **Harpoon**: The asteroid is grabbed with a harpoon and dragged behind the spacecraft.

5.2 Trade-off

The trade-off we will perform is techno-financial in nature since we are working for a commercial company. This means that both technical as well as financial aspects of the concepts need to be evaluated.

5.2.1 Selection Criteria

The following selection criteria were chosen:

- **Sustainability**: The sustainability of the project. This primarily hinges on whether the concept is reusable or not, i.e. if the same spacecraft can potentially be used to move multiple asteroids. If the same spacecraft can be reused this results in much lower emissions on Earth and lower cost as an new spacecraft does not need to be constructed and launched. Additionally, if the concept can be used to clean up space debris during the course of the normal mission, this makes the mission even more sustainable. Furthermore, some international laws require that defunct spacecraft need to be either de-orbited or put into graveyard orbits, relating this criterion to **AC5**. It is important to note, that while this is not directly related to requirements for a single mission, it is related to mission success via **AC1** as a reusable concept will much easier archive a positive economic net present value.

- **Risk**: The total risk associated with the project. Since the mission is the relocation of an asteroid the operational risk associated with different concepts can be very large (e.g. accidentally creating an impactor or otherwise harmful trajectory). Furthermore, in long missions financial and development risk can be come very large. We expect the total risk associated with different concepts to vary. This follows from **AC4** and **AC5** as well as several related requirements such as **AM-SH-PFM-4** and **AM-SH-PFM-6**. Risk is a large composite criterion including most importantly safety, financial, development, technical and schedule related risks.
- **Cost**: The total cost of the project. Since the asteroid is the same for all concepts this is a good selection criteria since it takes into account the entire project costs and will vary between different concepts. Cost is chosen as the financial aspect for this techno-financial trade-off since it is assumed that the asteroid recovered for each concept is the same (same profit) and the time of delivery (discount rate) is captured in a different criterion. Cost as a criterion reflects the acceptance criterion **AC1** and the related requirements.
- **Mission Duration**: How long it takes from the beginning of the project until the asteroid is in its final orbit. This is a good selection criteria since the time until the product is delivered is very important for the profitability of the project and will vary strongly between different concepts. Including this as a criterion that is not from a purely financial perspective allows us to use it also as a performance assessment for the different concepts. It also relates to **AM-SH-PFM-7**.

The criteria weights were determined using a analytic hierarchy process (AHP). For this AHP 12 experts were contacted and interviewed. Each expert opinion was assigned a weight between 1 (very little experience) and 10 (extensive practical experience) through self-assessment of their experience in the space industry and asteroid mining. The experts were then asked to input the AHP data in two steps. For each criterion pair they were asked which one they deem to be more important and then how much more important they assess the criterion to be. They could give relative importance scores from one to nine (see Table 5.1) for an explanation of the relative importance scores). Using an AHP process for the criteria weights makes it easier to obtain the weights for each category since it is built up out of direct importance comparisons, reducing the complexity of the decision.

The result of the AHP is that risk is the most important criterion by far, with cost and mission duration following, and sustainability being least important. This result is in line with previous work for asteroid redirection [1]. While risk has a large importance on the trade-off it is important to note that this is reasonable. Not only can the impact of a failed mission (see **AC4**) be very large, failures can also lead to anomalies from which the concept cannot recover since so much Delta V is involved. The roughly equal importance of cost and mission duration is also reasonable since both are parameters that strongly affect the profitability of the mission (**AC1**). The higher importance of cost can be explained with its impact on the economic net present value and the assumed long time for return-on-investment irrespective of concept mission duration. Sustainability is a small but still significant factor due to its impact on e.g. **AC5**.

Table 5.1: Explanation of the relative importance scoring system used in the AHP.

Score	Definition	Explanation
1	Same Importance	Both criteria are equally important for the mission.
3	Medium Importance Difference	Knowledge and experience favor one category for its importance for the mission.
5	Large Importance Difference	Knowledge and experience strongly favor one category for its importance for the mission.
7	Very Large Importance Difference	Knowledge, experience and tests or past missions demonstrate strong favor for one category in its importance for the mission.
9	Extreme Importance Difference	Past missions demonstrate extremely clearly the importance of one category over the other.

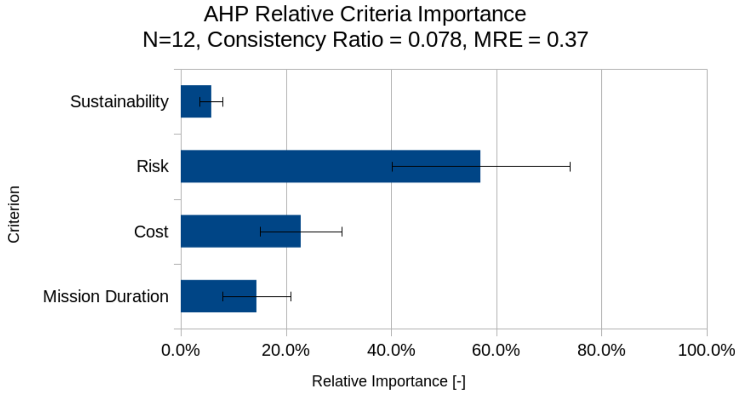


Figure 5.2: Criteria weights from AHP.

Table 5.2: Explanation of the scores given for each criterion. The score is linked to the expected performance of the design options regarding the (expected) requirements for each criterion.

Score	Definition	Explanation
1	Poor Performance	It is unclear if the design option will meet the requirements for this category.
3	Medium Performance	The design option will probably meet the requirements for this category
5	Good Performance	The design option will meet the requirements easily.
7	Very Good Performance	It has been demonstrated that the design option will meet the requirements easily.
9	Superior Performance	It has been demonstrated that the design option will meet the requirements easily and in past missions or tests the design option has clearly outperformed the other design options.

5.2.2 Final Selection

Now that the concepts are narrowed down, and the trade-off criteria have been chosen, a trade-off can be performed. First a graphical trade-off was done to quickly weigh the different options. The results of this are shown in Figure 5.3, with an enlarged version available in Appendix C. From this it can be seen that the net and harpoon concepts can be eliminated, as they perform the worst on risk, which is the most important category. Additionally, the solar sail and EM field tractor can be removed, as they perform the same or worse as the gravity tractor for all criteria. This leaves only the gravity tractor and rocket attachment. From the graphical trade-off there is no clear winner between these concepts. Therefore sophisticated trade-off methods are needed to compare these two.

Table 5.3: Pugh Matrix scoring system.

Score	Explanation
-1	Tends to under-fulfill requirements
0	Tends to fulfill requirements
1	Tends to over-fulfill requirements

One such trade-off method is the Pugh matrix, which is shown in Table 5.4. Two concepts were very close in the graphical trade-off, so we expect that the analysis via the Pugh matrix also will be relatively close. Since neither requirements nor the concept performance is fully defined we choose to focus on trends in expected requirement compliance for the scoring, shown in Table 5.3. This makes it easier to judge the scoring and increases the resolution of the trade-off method, helping to differentiate between two close concepts. Nevertheless, the difference between both concepts is still very close and the outcome could very well change upon discovering more requirements or with different weights and scoring.

This means that there is a need to 1) increase the quality and 2) assess the certainty of the result via a sensitivity analysis. In order to address the first point an AHP is chosen to increase certainty in the outcome. The process for an AHP that is described above is followed and only the gravity tractor and rocket attachment are

	Sustainability	Risk	Cost	Mission Duration
EM field tractor	Can be reused, performance degradation might limit life-span. Can clean up space debris during operation. green	Full thrust/drag vector control during the entire mission. Field can be switched off/on on demand. SC is not connected to asteroid. Low TRL. yellow	Expensive high-powered electronics. Expected large launch mass. Additional mass can be collected (free-of-charge/with additional profit) before earth departure/in-situ. red	Acceleration on asteroid is quite small, resulting in long duration yellow
Gravity tractor	Fully reusable, potentially requires refueling. Can clean up space debris during usage. blue	Full thrust/drag vector control during the entire mission. Field cannot be switched off/on on demand but SC can be stationed at larger distance from asteroid, reducing its influence by 1/r^2. SC is not connected to asteroid. Medium TRL. Requires a lot of mass which might be difficult to aquire. yellow	Large launch mass. Additional mass can be collected (free-of-charge/with additional profit) before earth departure/in-situ. yellow	Acceleration on asteroid is quite small, resulting in long duration yellow
Solar sail	Potentially reusable, likely has very limited lifespan yellow	Limited thrust/drag vector control during the non-shadowed mission periods. Thrust cannot be switched off/on on demand but could potentially be lowered. SC must be directly connected to asteroid. TRL depending on sail size, from low to medium. yellow	Requires large solar sails, development/production is probably costly. yellow	Acceleration on asteroid is quite small, resulting in long duration yellow
Rocket attachment	Not reusable red	Thrust/drag vector control only during burn times. Thrust can be switched off/on on demand but total burn timeis very limited. SC must be directly connected to asteroid. Medium TRL. yellow	Relatively cheap technology (COTS), connector might require considerable development effort depending on thrust. green	Different rocket types/thrust levels can be used to tailor to desired duration. Allows for shorter mission durations than with other concepts. blue
Net	Not reusable red	Thrust/drag vector control only during burn times. Thrust can be switched off/on on demand but is very limited. SC must be connected to asteroid via cable. Low TRL. red	COTS components with slight modifications. green	Different rocket types/thrust levels can be used to tailor to desired duration. Net strength limits maximum acceleration, and thus minimum mission duration. green
Harpoon	Not reusable red	Thrust/drag vector control only during burn times. Thrust can be switched off/on on demand but total burn time is very limited. SC must be connected to asteroid via cable. High TRL. Has failed to securely connect SC with asteroid in the past. red	COTS components with slight modifications. green	Different rocket types/thrust levels can be used to tailor to desired duration. Harpoon strength limits maximum acceleration, and thus minimum mission duration. green

Excellent, easily meets requirements, demonstrated in practice. blue	**Good, easily meets requirements.** green	**Acceptable, meets requirements.** yellow	**Correctable deficiencies, might meet requirements.** red

Figure 5.3: Graphical trade off of the various concepts. An enlarged version of this figure can be found in Appendix C

Table 5.4: Pugh matrix Trade-Off.

Criteria	**Weight**	**Gravity field tractor**	**Rocket attachment**
Sustainability	1	+	-
Risk	6	0	0
Cost	2	-	+
Mission Duration	2	0	+
	$\Sigma(+)$	1	2
	$\Sigma(0)$	2	1
	$\Sigma(-)$	1	1
	results	-1	3

considered. We choose the same weights as before and compare the concepts in each category, scoring again from 1 to 9 with the scores explained in Table 5.5.

This relative scoring resulted in the positive reciprocal matrices for the gravity tractor (row/column 1) and rocket attachment (row/column 2) shown in Table 5.6.

Then, using previous work of [6][1], we find the preference score for the two concepts (see Appendix A). The rocket attachment concept has a preference score of 54.5 % (i.e. according to the AHP it is roughly 10 % better than the gravity tractor). This reinforces the results from both the graphical and Pugh matrix trade-off. However, the sensitivity of the result is still unknown. Since an AHP was used for both weight and relative score determination the (rough) uncertainty of both aspects are known. In order to increase confidence we significantly round up both uncertainties to 40% and 20% relative error. This relative error is used as a scale in a normal distribution from which is drawn in the sensitivity analysis for each parameter. This will result in a very conservative sensitivity analysis, which is desirable as all three previous trade-offs resulted in very close scores. Using the code shown in Appendix A, for which the flow chart is shown in Figure 5.4, the sensitivity of the result is then determined by computing the concept preference scores in 1 million cases, all with independently varying parameters.

[1]We slightly modify the module source code to adapt it for this project, this only influences the program run-time not the actual function.

Table 5.5: Explanation of the scoring system used in the AHP, each w.r.t. the relevant criterion.

Score	Definition	Explanation
1	Same Performance	Both concepts are equally performing w.r.t to the criterion.
3	Medium Performance Difference	Knowledge and experience favor one concept for its performance w.r.t. the criterion.
5	Large Performance Difference	Knowledge and experience strongly favor one concept for its performance w.r.t. the criterion.
7	Very Large Performance Difference	Knowledge, experience and tests or past missions demonstrate strong favor for one concept for its performance w.r.t. the criterion.
9	Extreme Performance Difference	Past missions demonstrate extremely clearly the superior performance of one concept over the other.

Table 5.6: Positive reciprocal matrices for concept preference (each w.r.t. the indicated criterion) for the gravity tractor (row/column 1) and the rocket attachment (row/column 2).

Sustainability	
1	8
1/8	1

Risk	
1	2
1/2	1

Cost	
1	1/3
3	1

Mission Duration	
1	1/7
7	1

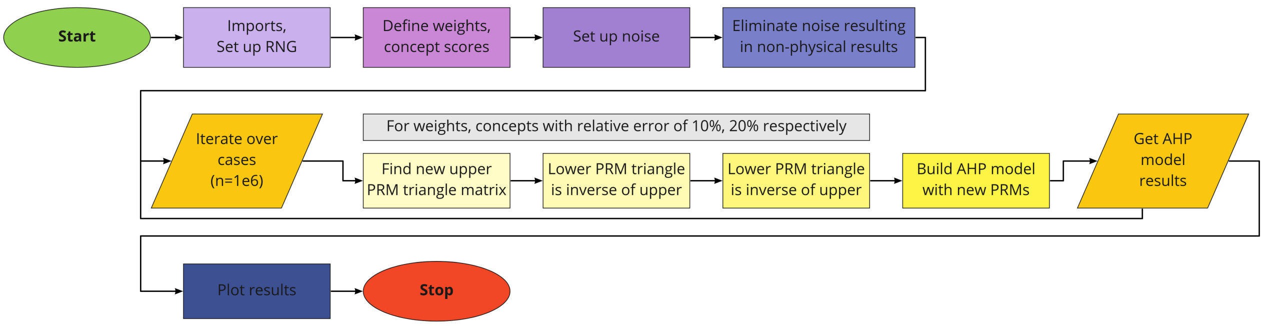
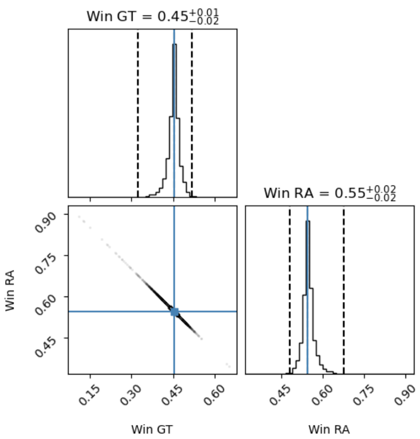
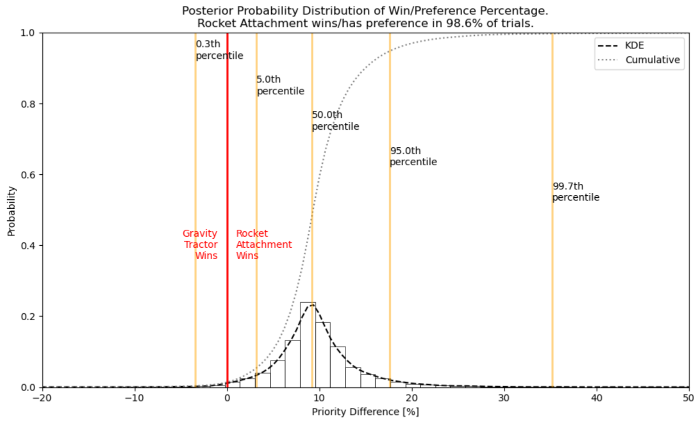


Figure 5.4: Flow chart of the sensitivity analysis.

The results are shown in the triangle plot in Figure 5.5a and the result histogram in Figure 5.5b. The triangle plot shows the correlation between the preferences which is of course linear since there are only two choices. The histogram shows the percentage difference in preference for the two concepts. It is clear that the result is very stable, roughly 50 % of all cases have a preference of at least 10 % towards the rocket attachment. Furthermore, preference towards the gravity tractor is in only 1.4% of the test cases. This is a very clear result in favor of the rocket attachment concept and shows that this result is not very sensitive, even though the concepts are very close in performance w.r.t. the chosen criteria. This means that, if the the trade-off can be repeated in more detail, care should be taken to check this preliminary result. It is notable that this sensitivity analysis was only possible due to the efficient initial trade-off process and the resulting decreased resource demand for follow-up trade-offs.



(a) Triangle plot of the sensitivity analysis. RA: rocket attachment, GT: gravity tractor.



(b) Histogram of the preference difference between the two concepts. The Sensitivity analysis indicates a preference for the rocket attachment concept with very high certainty.

Figure 5.5: Results of the sensitivity analysis

The result of the various trade-offs is that rocket attachment is the chosen concept. It performs roughly as well as or slightly worse then the gravity tractor in risk, which is the most important criterion. The sustainability of the rocket attachment is much worse, as it cannot be re-used for additional asteroids. However, it performs significantly better in both cost and mission duration, which are weighted higher. Cost-wise, the gravity tractor needs a lot of mass, which will need to be either launched from Earth or acquired in orbit, both of which are costly. The rocket attachment concept is not as high mass, and makes use of off-the-shelf rocket engines or whole rockets, resulting in a relatively low cost. Additionally, the rocket can produce much higher thrust than any of the other concepts, resulting in significantly lower mission duration; the thrust level can also be tailored to the desired mission duration. The gravity tractor is always very low thrust, resulting in a long mission duration.

In conclusion, the rocket attachment method is the best concept for this mission. The certainty of this result is very high, based on the conservative sensitivity analysis that showed that there is preference for the rocket attachment concept in 98.6% of all analyzed cases.

Chapter 6

Requirements

6.1 Critical Requirements

Critical system requirements are requirements that must be met in order for the system to fulfill its mission.

- **AM-SYS-01** The system shall be able to impart a total impulse of <TBD> newton seconds.
- **AM-SYS-02** The asteroid shall arrive at its final orbit without losing more than <TBD> kg of it's original mass.
- **AM-SYS-03** The system shall be able to attach itself to a C-type asteroid of up to 10 meters in size.
- **AM-SYS-04** The system shall have a maximum mass of <TBD> kg during the launch phase of the mission.
- **AM-SYS-05** The system shall remain in operation for the duration of the mission lifetime.

Critical system requirement 1 (**AM-SYS-01**) encompasses both the satellites ability to reach the target asteroid as well as its ability to bring it back. This is necessary to be kept as a single requirement for verification as

they both heavily depend on each other, if split up it would be possible to pass verification for both individual requirements without actually being able to do both as would be necessary in a real mission. This system requirement derives itself from stakeholder requirements **AM-SH-PFM-1** and **AM-SH-PFM-2**.
Critical system requirement 2 (**AM-SYS-02**) links several stakeholder requirements to the system requirements. Particularly, stakeholder requirements **AM-SH-PFM-4** and **AM-SH-PFM-6**, as they both deal with the overall integrity of the returning asteroid. While space mining corporations are mainly profit-driven and would require the asteroid to return intact for monetary reasons, research agencies would prefer the asteroid in one piece to study. The distinction is that the loss of small portions of the asteroid results in a profit loss for the company, while for the research bodies it would mean the loss of potential samples.
Critical system requirement 3 (**AM-SYS-03**) is a requirement very unique to this type of mission. Naturally the system must be able to attach itself to an asteroid, failure of the system to properly attach itself to the asteroid will result in loss of mission. It must also do so in a way to bring the entirety of the satellite as per requirement **AM-SYS-02**. This system requirement derives itself from stakeholder requirements **AM-SH-PFM-1** and **AM-SH-PFM-2**.
Critical system requirement 4 (**AM-SYS-04**) links the launch system stakeholder requirements **AM-SH-BDG-1** and **AM-SH-BDG-2** to the mission requirements. It is important to maintain this linkage, as without these requirements being fulfilled by the system, the launch company would be unable to provide their services, thus resulting in the termination of the mission before deployment.
Critical system requirement 5 (**AM-SYS-05**) connects several customer stakeholder requirements to the system requirements. In order to achievement requirements **AM-SH-PFM-3**, **AM-SH-PFM-7**, and **AM-SH-PFM-5**, this critical requirement must be fulfilled. This is due to these stakeholder requirements being dependent on the fulfillment of **AM-SYS-05**. If the system does not maintain its operational status, issues may arise with the placement of the asteroid into Earth or lunar orbit. The mission would also be deemed a failure if a vital system such as the communication or ADCS system fails, so this requirement is important to fulfill.
Naturally there are many parts and subsystems critical to any satellite and thus also to the success of our system and mission such as communication systems, ADCS, thermal systems etc. However these are not mentioned as critical system requirements as they do not encompass the unique challenges this mission provides but rather are one of the many essential parts of any common satellite.

6.1.1 Progress marking requirements

In order to track the progress of the mission, several requirements can be consulted. These requirements work well for tracking the mission as they can only be fulfilled once a certain amount of progress is achieved, and not simply when the concept and mission are designed. These requirements include **AM-SH-PRD-1**, **AM-SH-BDG-1**, **AM-SH-LEG-3**, **AM-SH-PFM-3**, **AM-SH-PFM-4**, **AM-SH-PFM-7**, **AM-SH-PFM-5**, and **AM-SH-PFM-6**.

When requirements **AM-SH-PRD-1** and **AM-SH-BDG-1** are fulfilled, it can be assumed that the manufacturing process has been completed. Once **AM-SH-LEG-3**, **AM-SH-PFM-4** and **AM-SH-PFM-6** have been fulfilled, it can be assumed that the asteroid has reached a stable orbit around the Earth or Moon. Orbital adjustments may have to be conducted during the final phases of the mission. These can be said to have been completed once **AM-SH-PFM-3**, **AM-SH-PFM-5** and **AM-SH-PFM-7** are fulfilled.

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Appendix A

AHP code

```
import json
import numpy as np
import emcee
import corner
from pyahp import parse
import pathos.multiprocessing as mp
import tqdm
import matplotlib.pyplot as plt
import seaborn as sns

rng = np.random.default_rng()


def reshuffle_prob(a, scale=0.1):
    upper_triangle_ind = np.triu_indices(a.shape[0], 1)
    lower_triangle_ind = np.tril_indices(a.shape[0], -1)
    upper_triangle = a[upper_triangle_ind]
    noise = scale * upper_triangle * rng.standard_normal(upper_triangle.shape)
    upper_triangle = upper_triangle + noise
    lower_triangle = 1 / upper_triangle

    a[upper_triangle_ind] = upper_triangle
    a[lower_triangle_ind] = lower_triangle
    return a


def main():
    def objective(scales):
        _alternatives = [reshuffle_prob(alt, scales[1]) for alt in alternatives]
        _criteria = reshuffle_prob(criteria, scales[0])

        model = {
            "name": "Asteroid Transport",
            "method": "approximate",
            "criteria": ["Sustainability", "Risk", "Cost", "Mission Duration"],
            "subCriteria": {},
            "alternatives": ["Gravity Tractor", "Rocket Attachment"],
            "preferenceMatrices": {
                "criteria": criteria,
                "alternatives:Sustainability": alternatives[0],
                "alternatives:Risk": alternatives[1],
                "alternatives:Cost": alternatives[2],
                "alternatives:Mission Duration": alternatives[3]
            }
        }

        ahp_model = parse(model)
        priorities = ahp_model.get_priorities()
        sub_err1 = np.logical_or(0 > priorities[0], priorities[0] > 1)
        sub_err2 = np.logical_or(0 > priorities[1], priorities[1] > 1)
        error = np.logical_or(sub_err1, sub_err2)

        priorities = error * np.array([0.5, 0.5]) + (-1. * error + 1) * priorities

        return priorities

    criteria = np.array([
```

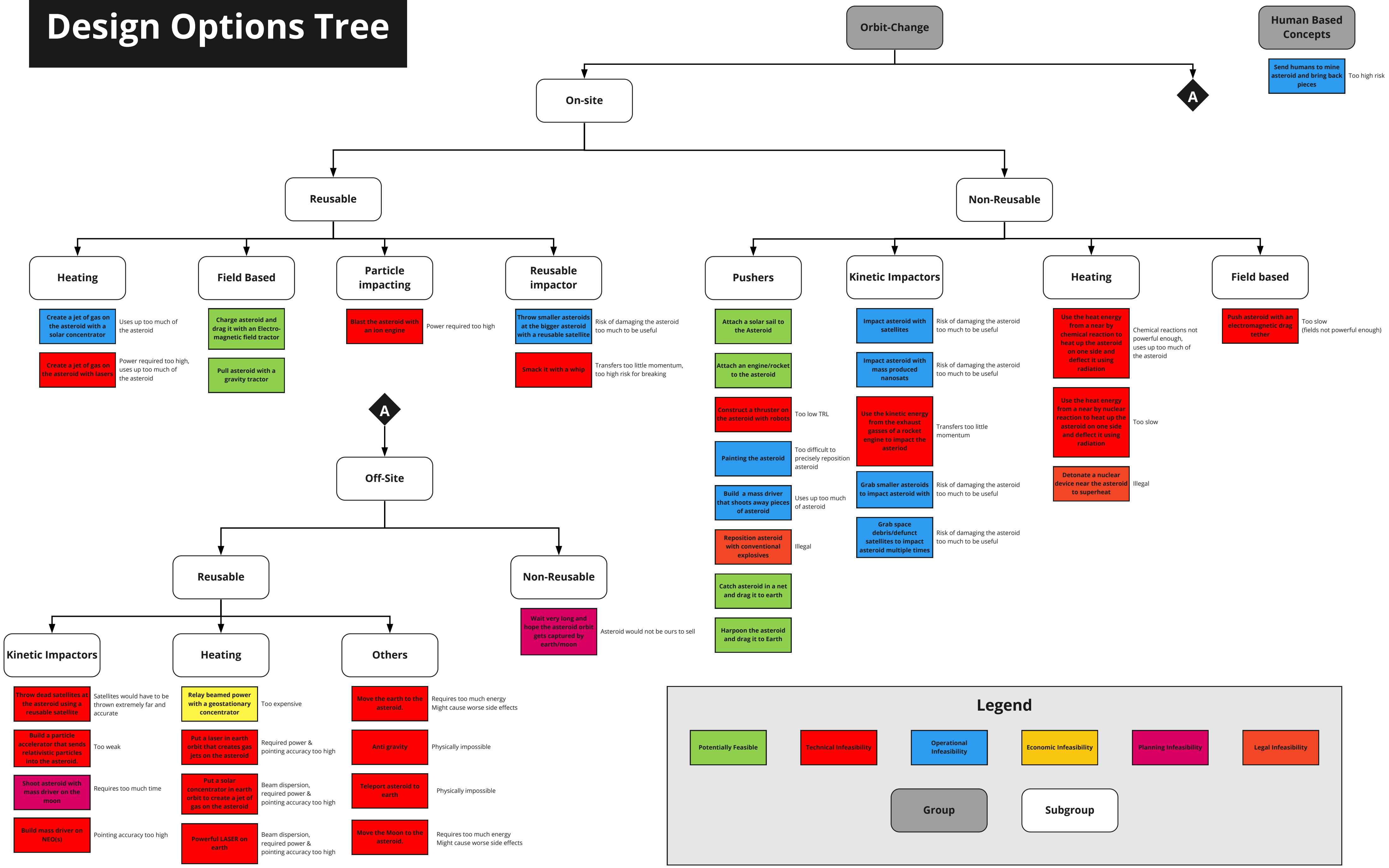
```
    [1.00, 0.40, 0.21, 4.29],
    [2.48, 1.00, 0.29, 3.62],
    [4.70, 3.45, 1.00, 6.33],
    [0.23, 0.28, 0.16, 1.00]
])

sustainability = np.array([[1, 8],
                           [1 / 8, 1],
                           ])

risk = np.array([
    [1, 2],
    [1 / 2, 1],
])
cost = np.array([
    [1, 1 / 3],
    [3, 1],
])
duration = np.array([
    [1, 1 / 7],
    [7, 1],
])

alternatives = np.stack((sustainability, risk, cost, duration), axis=0)

n_iter = 1e6
scale_criteria_weight = 0.4 * rng.standard_normal(n_iter)
scale_alternative_weight = 0.2 * rng.standard_normal(n_iter)

data = np.vstack((scale_criteria_weight, scale_alternative_weight)).T
result = np.full(shape=(n_iter, 2), fill_value=np.nan)

pool = mp.Pool(processes=int(0.9 * mp.cpu_count()))
for i, res in enumerate(tqdm.tqdm(pool.imap_unordered(objective, data), total=n_iter)):
    result[i] = res

truths = objective(np.array([0, 0]))

figure = corner.corner(result, labels=['Win GT', 'Win RA'], bins=50, figsize=(10, 10),
                       quantiles=[1 - 0.997, 0.50, 0.997], truths=truths,
                       show_titles=True, title_kwargs={"fontsize": 12})
plt.show()

diff = 100 * (result.T[1] - result.T[0])

fig, ax = plt.subplots(figsize=(10, 6), constrained_layout=True)

sns.histplot(data=diff, bins=75, stat='probability', alpha=0, kde=True,
             edgecolor='black', linewidth=0.5, color="black",
             line_kws=dict(color='red', alpha=1, linewidth=1.5, label='KDE', linestyle="dashed")
                                                                    ,
             ax=ax)
# ax.get_lines()[0].set_color('red')  # edit line color due to bug in sns v 0.11.0

sns.kdeplot(data=diff, cumulative=True, alpha=1,
            linewidth=1.5, color="grey", linestyle="dotted", label="Cumulative",
            ax=ax)

percentiles = [100 - 99.7, 100 - 95, 50, 95, 99.7]
ps = np.percentile(diff, percentiles)

for percentile, p, y_off in zip(percentiles, ps, np.linspace(0, 0.4, len(percentiles))):
    ax.axvline(p, color='orange', alpha=0.5, linewidth=2)
    ax.annotate(f'{percentile:.1f}th\npercentile', xy=(p, 0.95 - y_off), xytext=(p, 0.95 - y_off
                                                                        ),
                xycoords=('data', 'axes fraction'), textcoords=('data', 'axes fraction'),
                horizontalalignment='left', verticalalignment='center',
                arrowprops=dict(arrowstyle='-', fc='black', alpha=0))

ax.axvline(0, color='red', alpha=1, linewidth=2)

ax.annotate(f'Rocket\nAttachment\nWins', xy=(1, 0.4), xytext=(1, 0.4),
            xycoords=('data', 'axes fraction'), textcoords=('data', 'axes fraction'),
            horizontalalignment='left', verticalalignment='center',
            arrowprops=dict(arrowstyle='-', fc='red', alpha=0), color='red')

ax.annotate(f'Gravity\nTractor\nWins', xy=(-1, 0.4), xytext=(-1, 0.4),
```

```
                xycoords=('data', 'axes fraction'), textcoords=('data', 'axes fraction'),
                horizontalalignment='right', verticalalignment='center',
                arrowprops=dict(arrowstyle='-', fc='red', alpha=0), color='red')

    ax.set_xlabel('Priority Difference [%]')
    ax.set_ylabel('Probability')
    plt.legend()
    ax.set_xlim(-20, 50)
    ax.set_ylim(0, 1)
    ax.set_title(f"Posterior Probability Distribution "
                 f"of Win/Preference Percentage.\n"
                 f"Rocket Attachment wins/has preference in {len(np.argwhere(diff > 0.)) / len(diff)
                                                    * 100:.1f}% of trials.")
    plt.show()


main()
```

Appendix B

Design Option Tree

Design Options Tree



Appendix C

Graphical Trade-Off Table

	Sustainability	Risk	Cost	Mission Duration
EM field tractor	Can be reused, performance degradation might limit life-span. Can clean up space debris during operation. green	Full thrust/drag vector control during the entire mission. Field can be switched off/on on demand. SC is not connected to asteroid. Low TRL. yellow	Expensive high-powered electronics. Expected large launch mass. Additional mass can be collected (free-of-charge/with additional profit) before earth departure/in-situ. red	Acceleration on asteroid is quite small, resulting in long duration yellow
Gravity tractor	Fully reusable, potentially requires refueling. Can clean up space debris during usage. blue	Full thrust/drag vector control during the entire mission. Field cannot be switched off/on on demand but SC can be stationed at larger distance from asteroid, reducing its influence by 1/r^2. SC is not connected to asteroid. Medium TRL. Requires a lot of mass which might be difficult to aquire. yellow	Large launch mass. Additional mass can be collected (free-of-charge/with additional profit) before earth departure/in-situ. yellow	Acceleration on asteroid is quite small, resulting in long duration yellow
Solar sail	Potentially reusable, likely has very limited lifespan yellow	Limited thrust/drag vector control during the non-shadowed mission periods. Thrust cannot be switched off/on on demand but could potentially be lowered. SC must be directly connected to asteroid. TRL depending on sail size, from low to medium. yellow	Requires large solar sails, development/production is probably costly. yellow	Acceleration on asteroid is quite small, resulting in long duration yellow
Rocket attachment	Not reusable red	Thrust/drag vector control only during burn times. Thrust can be switched off/on on demand but total burn timeis very limited. SC must be directly connected to asteroid. Medium TRL. yellow	Relatively cheap technology (COTS), connector might require considerable development effort depending on thrust. green	Different rocket types/thrust levels can be used to tailor to desired duration. Allows for shorter mission durations than with other concepts. blue
Net	Not reusable red	Thrust/drag vector control only during burn times. Thrust can be switched off/on on demand but is very limited. SC must be connected to asteroid via cable. Low TRL. red	COTS components with slight modifications. green	Different rocket types/thrust levels can be used to tailor to desired duration. Net strength limits maximum acceleration, and thus minimum mission duration.
Harpoon	Not reusable red	Thrust/drag vector control only during burn times. Thrust can be switched off/on on demand but total burn time is very limited. SC must be connected to asteroid via cable. High TRL. Has failed to securely connect SC with asteroid in the past. red	COTS components with slight modifications. green	Different rocket types/thrust levels can be used to tailor to desired duration. Harpoon strength limits maximum acceleration, and thus minimum mission duration. green

Excellent, easily meets requirements, demonstrated in practice. blue

Good, easily meets requirements. green

Acceptable, meets requirements. yellow

Correctable deficiencies, might meet requirements. red