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1 Problem Statement

In this problem, we were asked to create a plan for maintaining the International Space Station for the next 10 years.Because the final United States Space Shuttle has landed, we need to find transportation from other sources, such as other countries and companies. We carried out this problem from NASA's perspective, because although this was not explicitly stated, it seemed reasonable to approach the problem in this manner because of the background information provided.

2 Assumptions and Reasoning

1. The plan with Russia to purchase seats on the Soyuz can continue past the ending date of the contract in 2017 and until 2022. We assume this because it is a mutually beneficial deal for the United States and the Russians. If not for letting the United States buy seats on their shuttles, Russia would not be able to support trips to the International Space Station at their current frequency due to the cost of sending people into space.

2. The United States inflation rate will not pass above 6.2 percent in the next 10 years. We assume this because in the past 30 years, it has not passed above that level, and in the past 100 years, when it has gone above that level, it has not stayed there for more than 2 or 3 years, giving it less of a total impact. Essentially, the inflation rate would not stay above 6.2% for a full 10 years. By assuming that the inflation rate will be higher than it likely will be, it will give us a cushion of extra funds to use in the program.

3. The United States inflation rate will directly affect the cost of of the ISS program. This is a safe assumption, as the value of goods tends to remain relatively stable even when the value of the money that is used on those goods is not.

4. For the basic flight schedule we assumed that NASA would not make any major adjustments to their planned schedule. The basic flight schedule, which will be shown in greater detail below, follows a general pattern of sending people up once every six months. It would be irrational to predict a change in this pattern.

5. The cost of supplying the space station is directly proportional to the mass of the supplies that are brought up. We assume this because all reputed

sources of information indicate that the cost of goods and equipment are negligible. For more expensive research equipment, we have a section analyzing its cost.

6. Deliveries will have a uniform waiting time duration. Given that the International Space Station's population stays fairly constant, we assume that the need for deliveries will stay constant as well.

7. The Progress resupply vehicle, a Soyuz spacecraft, does not undergo any significant adjustment or modification. We assume this because it is unrealistic to predict technological innovation, especially as that is not the purpose of this model. This would also increase operation costs for the Russians, and will be avoided unless the Progress is damaged.

8. A launch can be carried out in any month, and at any launch site According to information provided by NASA, the ISS passes over any given launch site for a time period of about seven minutes once per day. Even if the weather in a given day, or even a given week, prevents launching, there will still be plenty of opportunities in a given month to launch.

9. There is a flat base cost for maintaining the structural integrity of the ISS Most complications occur on a semi-regular basis and the primary cost is in terms of supply transportation, which is covered in a section separate from repairs.Looking at historical data, most complications on the ISS were resolved through astronaut spacewalks and extravehicular activity (EVA). Even major complications, such as the torn solar panel in 2007 or the potential ammonia leak in 2009, were resolved through EVA.

10. All parties will adhere to existing contracts for Cargo and Crew transportation NASA has already paid for these contracts, and would sustain a large loss if they broke the contract. SpaceX and other outside suppliers would lose all credibility as companies if they broke these contracts.

11. Political factors will not affect NASA's budget. It is easily observable that major political events, such as presidential elections, can have a major impact on the NASA's allocated funds. This model only takes into account the probable needed budget based on current schedules for the sake of simplicity.

12. Other nations remain committed to the ISS program and no change occurs in program members. The ISS program is currently heavily dependent on Russian support. In addition, the European and Japanese are beginning to contribute more which is marked by the planned regular yearly delivery of cargo. Our model assumes that their commitments do not change and that things proceed as scheduled. Finally, more nations including China, South Korea, and India are interested in joining the ISS. Since we cannot properly measure their influence, our model ignores their presence and focuses on the plans of the current member space programs and nations.

13. All spacecraft will have optimal conditions in their window when they launch. For Low Earth Orbit missions requiring docking, which is every mission related to the ISS, research and information provided by NASA suggests there are two small launch windows per day with only one of those windows having optimal conditions. These conditions include factors such as good weather and proper angle of sunlight. In addition, the payload a spacecraft can deliver is affected by the angle of inclination which is the angle between the ISS and the launchpad. We assume that when a spacecraft launches, the necessary angle of inclination to deliver that much cargo is achieved. Furthermore, we make the assumption that proper conditions are achieved for launch and docking.

3 Basic Analysis

One of the most important components of a comprehensive 10-year plan for maintaining the International Space Station is detailing NASAs budget year by year. These costs come in the form of the US Space Shuttle System, the Russian Soyuz transportation program, research conducted on the ISS, and the cost of maintaining the structural integrity of the ISS. While many of these costs, such as the cost of repairing the ISS or conducting research, are quite transparent and is public information, information such as the cost of training astronauts and cargo equipment is hidden. In order to overcome this lack of information, we determined that it would be reasonable to assume the cost per pound of payload multiplied by the pounds of cargo delivered would provide a method of summing all these costs together. After arriving at this conclusion, we conducted cost-analysis to find the cost per pound of payload for the Russian Soyuz. In the year 2010, 27,561lbs of supplies were delivered across 4 separate trips. In addition, NASA purchased 5 seats from the Russians at the cost of 51 million per seat (this cost, as you will notice later on, changed for 2011). NASAs total ISS transportation costs for the year 2010, which is composed of the seats purchased from the Russians and the cost of cargo, was valued at about 638 million. Thus, the cost is

$$638,000,000 = 5(51,000,000) + x(27,561),$$

where x represents the cost in USD per pound of payload. A little bit of arithmetic informs us that $x \approx \$13,530/\text{lb.}$ of payload This x value is much higher than just the transportation fee and is representative of all the hidden costs as well.

NASA does not publish exactly how much food is brought up into the space station, although they say that there is a weight cap on the food, of 3.8lbs per person per day. So, we took this to be the actual poundage of food that people would consume each day. Then, for a person to be up there, they would consume 114lbs of food per month, assuming a 30-day month. Because we were given such a large range of the cost per pound of transporting the food, we decided that the material cost of the food was negligible. Because material costs NASA $13,530 per pound to to bring to the space station, food will cost $1,542,420 per astronaut that they have in the station per month.

Then, we looked at the cost for water. The International Space Station uses all of its water to its maximum potential. Everything is reused, even condensation from breathing. It is estimated that if the water was not reused in this manner, 40,000lbs of water per year would be brought up into the space station. Because the station is 95% efficient with its water, 2,000lbs need to be brought up every year. In this, we assume that the cost of the water itself is negligible, as the transportation costs are so high. Since this figure is for the space station as a whole, 334lbs of water need to be brought up for a year for a person, so we need 28lbs of water for a person for a month. This costs $378,840 per person per month.

Finally, we need to pay to get a person up into the space station. The Russians have offered to sell seats on The Soyuz, their space shuttle, for $60,000,000$. A US Astronaut will be up there on their mission for a limited amount of time, which say will be of a full month in length, so the total cost for having an astronaut in the space station for m months will be $60,000,000 + 1,921,260m$. Due to inflation alone, the cost per month $C(m)$ of putting an American Astronaut into the space station will be

$$C(m) \approx (60,000,000 + 1,921,260m) \cdot (1.062)^y.$$

In addition to this cost, there will also be a brief period of time in which three US astronauts occupy the ISS instead of the regular two. This brief period of time is denoted as d where d is the number of days of having an "extra" person to account for in our costs. Taking a look at the table representing the historical data of how long this third astronaut remained on the ISS (which is left in an appendix), we generate this table:

d	9	10	11	12	13	14	15	16	17	18	19	20
Count	1	2	3	4	5	6	6	2	2	0	0	3

From here, we can take the mean of d,

$$\begin{aligned} d =& \frac{1(9) + 3(10) + 3(11) + 4(12) + 5(13) + 6(14) + 6(15) + 2(16) + 2(17) + 3(20)}{1 + 3 + 3 + 4 + 5 + 6 + 6 + 2 + 2 + 3} \\ d =& \frac{485}{35} \\ d \approx& 13.86 \end{aligned}$$

Telling us that an astronaut will spend 14 days longer than already planned for in the International Space Station. Adding one half of a month to our previous estimate for (as we do not account for this in the mission length in months) $C(m)$ gives

$$C(m) \approx (60,960,630 + 1,921,260m) \cdot (1.062)^y.$$

From here, we should find the length, m, of a mission. To do this, we use the data for when planned missions are set to occur.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2011											X	X
2012			X		X				X		X	
2013			X		X				X		X	
2014			X		X				X		X	

An X denotes that NASA intends to send one astronaut to the International Space Station during the month. The first expedition astronaut transition begins on November, 2011. That astronaut will serve until March of 2012. The astronaut starting service on December 2011 will serve until May of 2012. As can be seen by this table, with the exception of the two astronauts serving from November of 2011-March of 2011 and December of 2011-May of 2011, all astronauts will serve on the space station for duration of approximately 6 months. This notion agrees with the initial information set forth that suggested missions on the ISS lasted about 6 months. By continuing this trend, future expedition missions would always take place in March, May, September, and November.

Then, from the knowledge that the average mission will last for six months, we can substitute six for m, yielding

$$C(m) \approx (72,488,190) \cdot (1.062)^y.$$

We can use this to create a table of the cost for one astronaut to go on a mission in a given year, y.

y	1	2	3	4	5
Cost	\$76,982,458	\$81,755,370	\$86,824,203	\$92,207,304	\$97,924,157
y	6	7	8	9	10
Cost	\$103,995,454	\$110,443,172	\$117,290,649	\$124,562,669	\$132,285,555

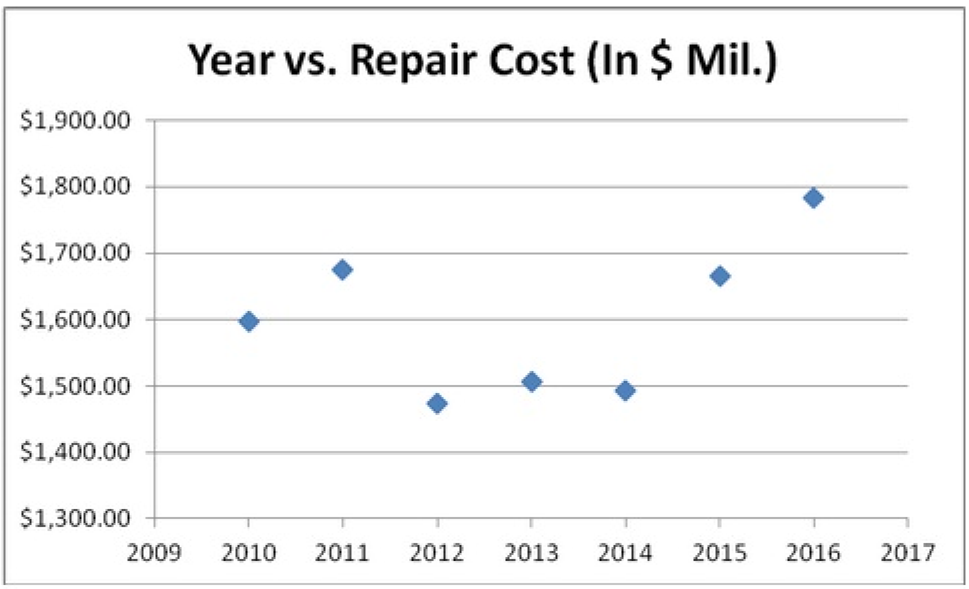
Knowing these costs per mission, we can create a schedule of future launches, based upon the current plan up until 2014.

For the manned flight schedule, we will continue with the current schedule that was shown above. A manned flight schedule is composed of two types of flights: the Expedition flights for moving crew to and from the ISS, and manned deliveries and installations of ISS components, including modules, robotic arms and trusses. For our modeled schedule, we decided to examine just the Expedition flights, as the scheduling for component deliveries is highly dependent on when said components are actually developed, a factor we cannot accurately anticipate in our model.The weight of provisions for an astronaut on a six-month mission as well as the total cost for having the astronaut on the mission are included here although the provisions are not on this launch. The Mission Cost is included here, though not used later on in the model, simply as a way of giving the reader an idea of the cost of putting somebody into space, and then keeping them there.

Mission Name	Date of Launch	Cost of Launch	Weight of Provisions	Mission Cost
Soyuz TMA-04M	Mar 2012	$63,720,000	433lbs	$76,982,458
Soyuz TMA-05M	May 2012	$63,720,000	433lbs	$76,982,458
Soyuz TMA-06M	Sept 2012	$63,720,000	433lbs	$76,982,458
Soyuz TMA-07M	Nov 2012	$63,720,000	433lbs	$76,982,458
Soyuz TMA-08M	Mar 2013	$67,670,640	433lbs	$81,755,370
Soyuz TMA-09M	May 2013	$67,670,640	433lbs	$81,755,370
Soyuz TMA-10M	Sept 2013	$67,670,640	433lbs	$81,755,370
Soyuz TMA-11M	Nov 2013	$67,670,640	433lbs	$81,755,370
Soyuz TMA-12M	Mar 2014	$71,866,220	433lbs	$86,824,203
Soyuz TMA-13M	May 2014	$71,866,220	433lbs	$86,824,203
Soyuz TMA-14M	Sept 2014	$71,866,220	433lbs	$86,824,203
Soyuz TMA-15M	Nov 2014	$71,866,220	433lbs	$86,824,203
Soyuz TMA-16M	Mar 2015	$76,321,925	433lbs	$92,207,304
Soyuz TMA-17M	May 2015	$76,321,925	433lbs	$92,207,304
Soyuz TMA-18M	Sept 2015	$76,321,925	433lbs	$92,207,304
Soyuz TMA-19M	Nov 2015	$76,321,925	433lbs	$92,207,304
Soyuz TMA-20M	Mar 2016	$81,053,885	433lbs	$97,924,157
Soyuz TMA-21M	May 2016	$81,053,885	433lbs	$97,924,157
Soyuz TMA-22M	Sept 2016	$81,053,885	433lbs	$97,924,157
Soyuz TMA-23M	Nov 2016	$81,053,885	433lbs	$97,924,157
Soyuz TMA-24M	Mar 2017	$86,079,226	433lbs	$103,995,454
Soyuz TMA-25M	May 2017	$86,079,226	433lbs	$103,995,454
Soyuz TMA-26M	Sept 2017	$86,079,226	433lbs	$103,995,454
Soyuz TMA-27M	Nov 2017	$86,079,226	433lbs	$103,995,454
Soyuz TMA-28M	Mar 2018	$91,416,138	433lbs	$110,443,172
Soyuz TMA-29M	May 2018	$91,416,138	433lbs	$110,443,172
Soyuz TMA-30M	Sept 2018	$91,416,138	433lbs	$110,443,172
Soyuz TMA-31M	Nov 2018	$91,416,138	433lbs	$110,443,172
Soyuz TMA-32M	Mar 2019	$97,083,938	433lbs	$117,290,649
Soyuz TMA-33M	May 2019	$97,083,938	433lbs	$117,290,649
Soyuz TMA-34M	Sept 2019	$97,083,938	433lbs	$117,290,649
Soyuz TMA-35M	Nov 2019	$97,083,938	433lbs	$117,290,649
Soyuz TMA-36M	Mar 2020	$103,103,142	433lbs	$124,562,669
Soyuz TMA-37M	May 2020	$103,103,142	433lbs	$124,562,669
Soyuz TMA-38M	Sept 2020	$103,103,142	433lbs	$124,562,669
Soyuz TMA-39M	Nov 2020	$103,103,142	433lbs	$124,562,669
Soyuz TMA-40M	Mar 2021	$109,495,537	433lbs	$132,285,555
Soyuz TMA-41M	May 2021	$109,495,537	433lbs	$132,285,555
Soyuz TMA-42M	Sept 2021	$109,495,537	433lbs	$132,285,555

Soyuz TMA-43M	Nov 2021	$109,495,537	433lbs	$132,285,555

In addition to the cost of people, another main cost to take into consideration is the cost of making routine repairs. The space station goes through wear and tear just like any other machine and must be repaired. We analyzed the predictions of NASA's budget past 2010 because many costs associated with past ISS maintenance are related to the cost of modules. In addition, as mentioned earlier, it would be fair to conclude that there is a base maintenance cost for the ISS. The base cost will also be expected to slowly increase over time since, as the parts of the ISS age, their structural integrity will slowly erode.

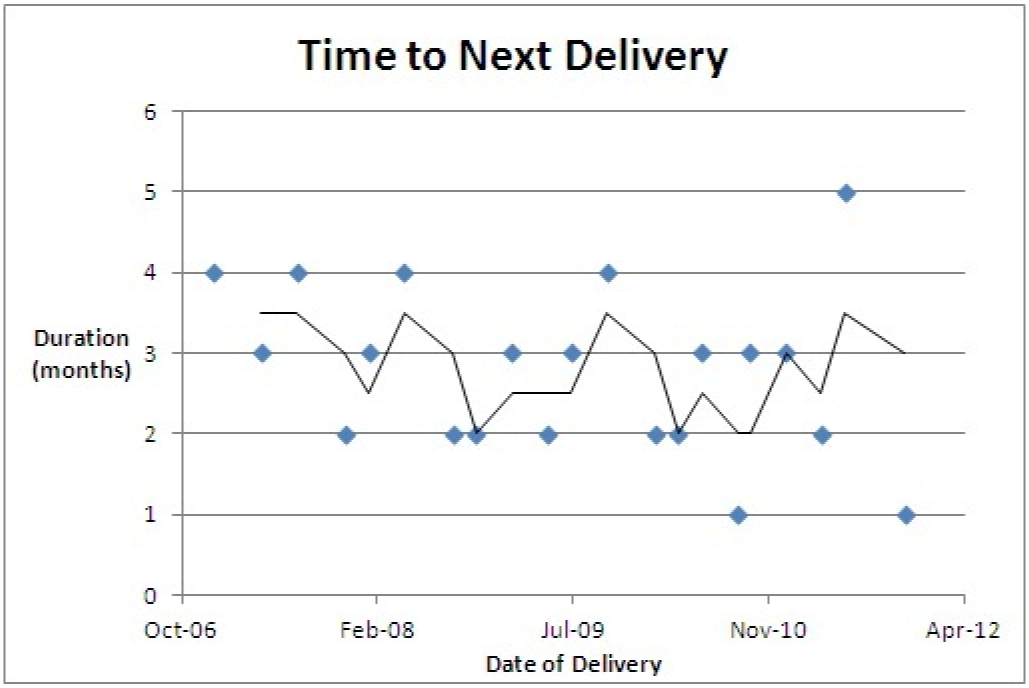


A simple linear regression reveals that the base cost is around $1539.7 million in 2010 dollars and is expected to increase at a rate of 19.85 million in 2010 chained dollars per year after 2010. While this simple linear model may not predict the exact values on a year to year basis very accurately, over time, it should provide a good approximation. Below is a table of the base repair cost per year in both the chained 2010 value and in the inflated dollar amount, both listed in millions of dollars.

Year	2010 Dollars	Inflated Dollars
2012	1,579	1,677
2013	1,599	1,804
2014	1,619	1,939
2015	1,638	2,085
2016	1,658	2,241
2017	1,679	2,408
2018	1,699	2,588
2019	1,718	2,780
2020	1,738	2,987
2021	1,758	3,208

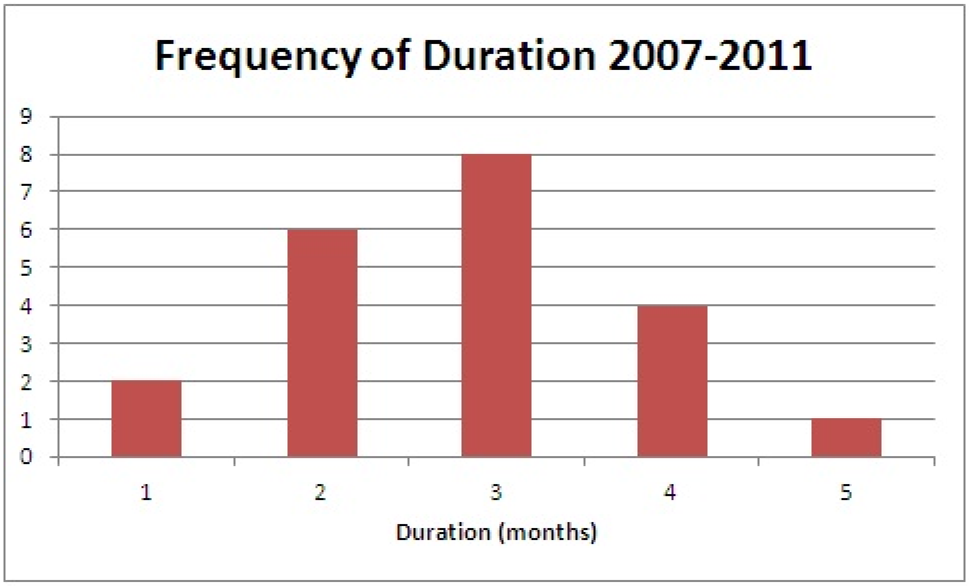
4 Basic Supply Transportation

The Soyuz unmanned spacecraft cargo ship is the only regular supplier of the ISS. This is evident by a simple glance at historical data. Although other organizations such as the European Space Agency have attempted to send unmanned cargo, as demonstrated by the Johannes Kepler ATV mission in February of 2011, they still have yet to demonstrate the consistency the Soyuz cargo ships have. In this section, the abilities of spacecraft other than the Soyuz will be noted but not taken into account. That factor will be addressed in a separate section; this portion focuses only on the Russian supply. So, we look to historical data to determine the time between each shuttle. In the figure below, the blue dots represent individual deliveries. Their x-positions indicate the date of that delivery, while the y-position indicates how many months it would be until the next delivery arrives. The black line represents a moving average that indicates the bounds on an appropriate uniform duration between deliveries.

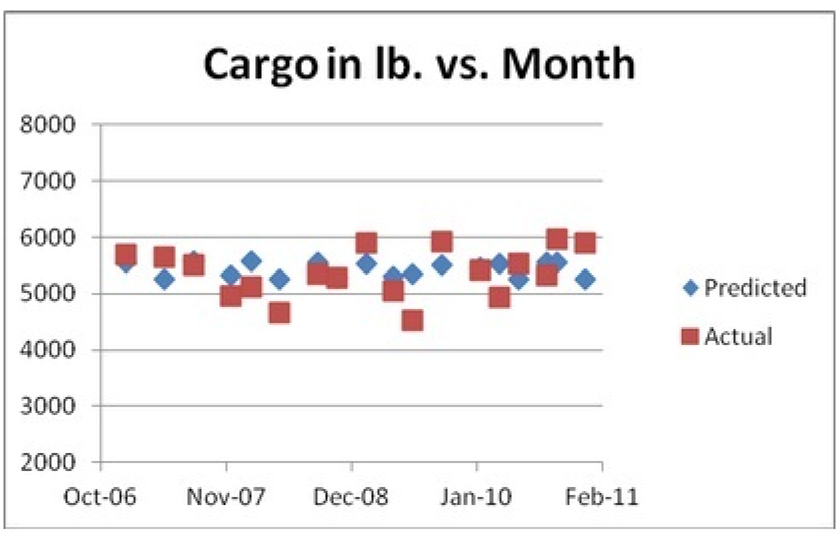


We have devised a constant duration between deliveries, 2.81 months, based upon analysis of previously scheduled Soyuz-U flights from the Progress M-59 docking in January 2007 to the Progress M-14M docking in December 2011. We chose this time period because at this point in time, NASA has created a semi-stable schedule. This means that when we base our projected flight schedule on data from this time period, it should accurately model the flight schedule of the next decade. In this given period, there were 21 flights, the time between each being anywhere between one to five months. The total duration of this period was 59 months, with the time between deliveries around 2 or 3 months. We then divide 59 months by 21 flights to acquire the average duration between flights: approximately 2.81 months. A strong flight schedule consists of routine deliveries each within 2.81 months of each other.

The figure below indicates the solidity of our choice of 2.81 months as the waiting duration between resupply flights. As indicated, several deliveries in this time frame were made within two or three months of each other.



To find the payload of the shuttle, we used recent historical data starting from 2007. We generated a graph of the Cargo Weight vs. Trip. Given that the human presence on the ISS is somewhat constant with the occasional influx of astronauts due to the space shuttle missions and expedition transition period, the cargo needed should be somewhat cyclical. As a result, the closest approximation of the cargo transported vs. month in the number of months,t, away from base January of 2007 will be sinusoidal. The graph of the actual and approximation is shown below.



In this graph, the blue represents the predicted cargo and the red represents the actual weight of the cargo. The prediction model follows the peaks and valleys of cargo supply quite well. We used this equation to model the amount of cargo to be brought up in each shuttle. Our equation for the payload over time, P(t) is as follows:

$$P(t) = 163sin(t) + 5412$$

Then, to find the cost of flying that payload up, we must multiply the actual payload by $\$13530(1.062)^{t/12}$. So, to have cost of supplying the station based upon time, G(t), we take

$$G(t) = (163sin(t) + 5412)13530(1.062)^{t/12}$$

Now that we have a constant amount of time between each supply shuttle as well as a payload estimate along with its cost, we can create a schedule of when each will launch, along with the payload in each shuttle. There are also other flights included in this schedule. These come from various contracts that NASA currently has for future launches. These are extended through this ten year period assuming the same contract price.

Mission Name	Launch Date	Payload (lb)	Cost
ATV-003	Feb 2012	16,900	\$300,000,000
Progress M-15M	Mar 20, 2012	5,440	\$84,260,000
Progress M-16M	June 14, 2012	5,410	\$85,040,000
Cygnus-01	July, 2012	5,950	\$237,500,000
HTV-004	Aug 2012	13,228	\$200,000,000
Progress M-17M	Sept 8, 2012	5,390	\$86,100,000
Progress M-18M	Dec 2, 2012	5,450	\$88,380,000
Progress M-19M	Feb 25, 2013	5,250	\$85,960,000
ATV-004	Mar 2013	16,900	\$300,000,000
Progress M-20M	May 19, 2013	5,575	\$92,640,000
Progress M-21M	Aug 13, 2013	5,250	\$88,560,000
Cygnus-02	Sept, 2013	5,950	\$237,500,000
Progress M-22M	Nov 7, 2013	5,570	\$95,380,000
Progress M-23M	Feb 1, 2014	5,260	\$91,470,000
Progress M-24M	Apr 26, 2014	5,420	\$95,130,000
Progress M-25M	July 20, 2014	5,370	\$96,780,000
HTV-005	Aug 2014	13,228	\$200,000,000
Progress M-26M	Oct 14, 2014	5,470	\$97,210,000
Cygnus-03	Nov, 2014	5,950	\$237,500,000
Progress M-27M	Jan 8, 2015	5,330	\$100,550,000
Progress M-28M	Apr 2, 2015	5,575	\$99,380,000
Progress M-29M	June 27, 2015	5,250	\$105,000,000
Progress M-30M	Sept 21, 2015	5,560	\$100,500,000
ATV-005	Oct, 2015	16,900	\$300,000,000
HTV-006	Nov 2015	13,228	\$200,000,000
Progress M-31M	Dec 15, 2015	5,270	\$108,000,000

Cygnus-04	Jan, 2016	5,950	$237,500,000
Progress M-32M	Mar 9, 2016	5,540	$103,900,000
Progress M-33M	June 3, 2016	5,450	$110,800,000
Progress M-34M	Aug 26, 2016	5,350	$110,100,000
HTV-007	Sept 2016	13,228	$200,000,000
Progress M-35M	Nov 20, 2016	5,490	$109,800,000
Progress M-36M	Feb 14, 2017	5,311	$114,400,000
Cygnus-5	Mar, 2017	5,950	$237,500,000
ATV-006	Apr, 2017	16,900	$338,353,200
Progress M-37M	May 8, 2017	5,530	$112,300,000
Progress M-38M	Aug 2, 2017	5,260	$118,700,000
Progress M-39M	Oct 27, 2017	5,550	$114,000,000
HTV-008	Nov 2017	13,228	$200,000,000
Progress M-40M	Jan 21, 2018	5,280	$122,200,000
Progress M-41M	Apr 15, 2018	5,525	$118,000,000
Cygnus-6	May, 2018	5,950	$237,500,000
Progress M-42M	July 9, 2018	5,320	$125,300,000
HTV-009	Sept 2018	13,228	$200,000,000
Progress M-43M	Oct 3, 2018	5,330	$122,400,000
Progress M-43M	Dec 28, 2018	5,510	$124,000,000
Progress M-44M	Mar 22, 2019	5,295	$130,100,000
Progress M-45M	June 16, 2019	5,540	$126,900,000
Cygnus-7	July, 2019	5,950	$237,500,000
ATV-007	Apr, 2019	16,900	$381,609,600
Progress M-46M	Sept 10, 2019	5,270	$134,800,000
HTV-010	Oct 2019	13,228	$200,000,000
Progress M-47M	Dec 4, 2019	5,540	$130,100,000
Progress M-48M	Feb 27, 2020	5,300	$138,200,000
Progress M-49M	May 21, 2020	5,510	$134,100,000
Progress M-50M	Aug 15, 2020	5,335	$141,600,000
HTV-011	Sept 2020	13,228	$200,000,000
Progress M-51M	Nov 9, 2020	5,470	$139,200,000
Progress M-52M	Feb 3, 2021	5,530	$144,800,000
Cygnus-8	Apr, 20121	5,950	$237,500,000
Progress M-53M	May 26, 2021	5,280	$147,900,000
Progress M-54M	Aug 20, 2021	5,555	$143,400,000
HTV-012	Sept 2021	13,228	$200,000,000
Progress M-55M	Nov 14, 2021	5,260	$147,200,000

Also contributing to the cost of the ISS is purchasing research equipment. Research equipment is regularly brought up in Progress shuttles, so we do not need to account for the costs of transporting the equipment. However, we do need to account for the cost of the research equipment that is bought for the ISS. According to NASA's budget, in 2010, they spent $129.5 million on research equipment for the ISS. They also plan for future years, allocating $221.1 million, $210.7 million, $213.2 million, $221.1 million, and $223.5 million to 2012, 2013, 2014, 2015, and 2016 respectively. If we ignore the data for 2012, we see that NASA's predicted budget for the ISS research equipment rises fairly linearly, going up by about 4.6 million dollars per year. Then, after adjusting for inflation, we see the following:

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Spending (Millions)	234.8	237.6	255.4	281.2	301.9	327.2	354.5	384.0	415.7	450.0

5 Future Launch Possibilities

NASA, in late 2008, established a contract with the space transport company SpaceX to guarantee a minimum of 44090 lb. would be delivered over 12 launches, starting in 2012, to the ISS in exchange for 1.6 billion USD (133.33 million USD per launch). Under the contract, more launches could be ordered, presumably at the same rate, up to a total of 3.1 billion USD, meaning up to roughly 11 more launches.

The launches would utilize SpaceXs Falcon 9 Rocket to lift the Dragon spacecraft, which could deliver a payload of 13230 lb to the ISS. The Dragon spacecraft is also able to reenter the earths atmosphere for with a return payload of 6610 lb. Thus, for a total of 133.33 million USD, NASA could supply the ISS with 13230 lb of supplies (10080 USD per lb) and return with 6610 lb of supplies (20160 USD per lb), per trip. The Dragon spacecraft will soon be man-rated, and will then be able to carry a crew of 7. The contract, however, does not mention any manned flights, and it is unknown whether SpaceX will allow NASA to use the crew version of the Dragon spacecraft, or even if SpaceX does, how much will be charged.

NASA also made a similar contract with Orbital Sciences Corporation: carry a minimum of 44090 lb to the ISS over 8 launches in exchange for 1.9 billion USD (237.5 million USD per launch). Launches would be conducted though the Taurus II Rocket and the Cygnus Capsule, which has a delivery payload of 5950 lb and has the feature to take 2650 lb of waste and burn up in the atmosphere. In summary, for 237.5 million USD, NASA could supply the ISS with 5950 lb of supplies (39900 USD per lb) and remove 2650 lb (89770 USD per lb).

Company	Rocket	Spacecraft	Payload Up (lb)	Cost per Flight (Million USD)	Cost per lb payload up (USD)
SpaceX	Falcon 9	Dragon	13,230	133.33	10,080
Orbital Sciences	Taurus II	Cygnus	5,950	237.5	39,900

Launches for SpaceX are scheduled into 2015, with three launches per year. Continuing that trend NASA could purchase enough launches through the contract extension to go into 2019.The additional launches would cost, in total

$$1,600,000,000 + N_F \cdot \frac{400,000,000}{3}$$

where N_F is the number of additional flights. The sum must remain less than 3.1 billion USD to remain in the bounds of contract. The "years" on this graphic assume that there are three launches of the Dragon per year. This is by no means a final figure.

Year	Flight	Total Cost (million USD)
2011	1	133.33
2012	2	266.67
2012	3	400
2012	4	533.33
2013	5	666.67
2013	6	800
2013	7	933.33
2014	8	1067
2014	9	1200
2014	10	1333
2015	11	1467
2015	12	1600
Contract extension begins		
2015	13	1733.33
2016	14	1866.67
2016	15	2000
2016	16	2133.33
2017	17	2266.67
2017	18	2400
2017	19	2533.33
2018	20	2666.67
2018	21	2800
2018	22	2933.33
2019	23	3066.67
~~2019~~	~~24~~	~~3200~~

The above discussion focuses on bringing supplies. Another important aspect is the transportation of astronauts. Currently, NASA purchases seats on Russias Soyuz spacecraft at about 60 million USD a seat. SpaceX has stated that their Dragon spacecraft is designed to soon carry 7 astronauts, at 20 million USD each.

In addition to commercial spacecraft, NASA has formed deals with international government agencies JAXA and ESA, or the Japan Aerospace Exploration Agency and the European Space Agency. Their supply spacecraft were briefly noted in the basic launch schedule, but we now talk more about them. Both organizations and their respective resupply spacecraft passed testing and completed a mission in 2011, with several launches planned in the next few years.

With the assistance of the H-2 B launch system, JAXA can launch their H-2 Transfer Vehicle, a spacecraft capable of handling 13,228 pound launch payloads; however, it is unable to safely return a payload, limiting its utility after the mission to garbage disposal through destructive re-entry. With a cost of $200,000,000 per launch, transporting a pound of cargo will cost a little more than $15000. JAXA has plans to build upon the HTV model with the HTV-R, a new model capable of returning 3527 lb payloads from the ISS to Earth that is predicted to be released in 2017.

ESA created the Automated Transfer Vehicle, or ATV, to be launched with the Ariane 5 rocket. The ATV costs $300,000,000 has a launch payload capacity of 16,900 pounds, making for a payload cost efficiency of $17751.48 per pound. Similar to the HTV, it is unable to return a payload; thus, after its mission is accomplished, it will dispose of trash through re-entry burning. The ESA is also planning to evolve their capsule with payload retrieval, but are also investigating improving its utility as a crew transporter or miniature space station.

Currently also in development are the Ares I rocket, the Orion Multi-Purpose Crew Vehicle, the Dream Chaser, and the CST-100. Various Ares I parts manufacturing contracts have already been established, ensuring at least minimal progress on the rocket despite decreased funding as per the 2010 NASA authorization bill. Under current budget, the Ares I rocket will not have launch until at least 2017. Even with an unlimited budget, however, first launch would take at least until 2016. Current cost estimates put the Ares I Rocket on rocky footing; the Augustine Commission found it would cost as much as 1 billion USD per launch if the Ares I only launched once per year. This cost would decrease to a nominal 138 million USD, however, if multiple launches were made per year. A prototype Ares I rocket has already had a successful launch.

The Ares I timeline puts it in line for potentially being employed as a supply vehicle for the ISS, replacing the Falcon 9 or Soyuz-U Rocket. The Ares I would use the Orion spacecraft, and whether it would be cost effective to switch to the Ares I depends on the payload of the Orion.

The payload of the Orion is currently unknown. The correct name for the Orion, after the 2010 NASA authorization bill, is the Orion Multi-Purpose Crew Vehicle. With room for a crew of 2 to 4 and more modernized features than its predecessors, such as auto-docking, it could be used for manned or unmanned launches, to LEO, the ISS, or even beyond. The Orion has numerous tests scheduled for the coming years, and the first crewed launch is scheduled for 2016, while unmanned launches are for 2014. If the Orion is viable and ready for launch by the time of completion of the Ares I rocket, and has a payload greater than 13700 pounds, it will be most cost efficient as long as multiple launches are conducted per year. In the following calculations, R is the payload of the Orion rocket.

$$138,000,000/R < 10,079.83lb$$

$$R > 13,690.7lb$$

If only one launch is conducted, a payload of nearly 100,000 would be required to make the Orion/Ares I launch the most cost effective at supplying the ISS.

$$1,000,000,000/R < 10,079.83lb$$

$$R > 99,208.02lb$$

Because of the current lack of information on the Orion, we will not integrate it into our model. The Dream Chaser and CST-100 are currently under development, and not enough detail has been released regarding their cost per flight or payload for them to be considered for integration into our model.

Name of Spacecraft	Company	Payload Up	Cost per Flight	Cost per lb of Payload
H-2 Transfer Vehicle (HTV)	Japan Aerospace Exploration Agency	13,228 lb	\$200 million	\$15119
Automated Transfer Vehicle (ATV)	European Space Agency	16,900 lb	\$300 million	\$17751

Over the course of the next 10 years, we currently plan for the Progress to bring 216,480 lb of supplies to the station, at a cost of \$13530 per pound. It is clear from our analysis that using the Dragon to bring supplies to the station is cheaper than using the Progress, so we will use the Dragon as much as possible, while remaining within the bounds of the contract. Because we have 23 flights available to us on the Dragon, and because those flights have a maximum payload of 13,230, we multiply 13,230 by 23, yielding \$304,290. So, we will be able to sustain the station with deliveries from the Dragon totally replacing deliveries from the Progress. Sending the Dragon 20 times over the next 10 years lets us transport 264,600 lb of supplies, which is more than the Progress ships to us. This is also a convenient number to work with, as it lets us make the shipments twice a year.

On top of knowing the frequency of the Dragon's launches, we must now determine the payload that the Dragon should bring up. To do this, we use the same function as before, $P(t) = 163sin(t) + 5412$, only in this time, we are trying to find a h such that

$$h(163\sin(t) + 5412) \leq 13,230$$

We keep our function below this value so that we do not exceed the maximum payload of the Dragon. Because the max of $\sin(t)$ is 1, we can substitute 1 for $\sin(t)$ and still have this inequality hold true. Some simple algebra yields $h = 2.37$, so the function modeling the dragon payload will be, $P_D(t)$ will be

$$P_D(t) = 386\sin(t) + 12826$$

6 Unmanned Flight Schedule

Now that we have payload and cost information on possibilities besides just the Progress, we can adjust the flight schedule, totally eliminating the Progress from it, replacing it with the Dragon. Because NASA already has contracts with many other suppliers, we keep those intact from the previous schedule. Because all things bought in this table are paid for in contracts made in 2011, all costs will be in 2011 dollars.

Mission Name	Launch Date	Payload (lb)	Cost
ATV-003	Feb 2012	16,900	$300,000,000
Dragon-3	Mar 2012	13,128	$133,000,000
Cygnus-01	July, 2012	5,950	$237,500,000
HTV-004	Aug 2012	13,228	$200,000,000
Dragon-4	Sept 2012	12,991	$133,000,000
Dragon-5	Mar 2013	12,449	$133,000,000
ATV-004	Apr, 2013	16,900	$300,000,000
Dragon-6	Sept 2013	12,833	$133,000,000
Cygnus-02	Oct, 2013	5,950	$237,500,000
Dragon-7	Mar 2014	13,200	$133,000,000
HTV-005	Aug 2014	13,228	$200,000,000
Dragon-8	Sept 2014	12,649	$133,000,000
Cygnus-03	Nov, 2014	5,950	$237,500,000
Dragon-9	Mar 2015	12,533	$133,000,000
Dragon-10	Sept 2015	13,137	$133,000,000
ATV-005	Oct, 2015	16,900	$300,000,000
HTV-006	Dec 2015	13,228	$200,000,000
Cygnus-04	Jan, 2016	5,950	$237,500,000
Dragon-11	Mar 2016	12,978	$133,000,000
Dragon-12	Sept 2016	12,446	$133,000,000

HTV-007	Nov 2016	13,228	$200,000,000
Cygnus-05	Jan, 2017	5,950	$237,500,000
Dragon-13	Mar 2017	12,847	$133,000,000
ATV-006	Apr, 2017	16,900	$338,353,200
Dragon-14	Sept 2017	13,196	$133,000,000
HTV-008	Nov 2017	13,228	$200,000,000
Dragon-15	Mar 2018	12,636	$133,000,000
Cygnus-06	May, 2018	5,950	$237,500,000
Dragon-16	Sept 2018	12,542	$133,000,000
HTV-009	Nov 2018	13,228	$200,000,000
Dragon-17	Mar 2019	13,145	$133,000,000
ATV-007	Apr, 2019	16,900	$381,609,600
Cygnus-07	July, 2019	5,950	$237,500,000
Dragon-18	Sept 2019	12,965	$133,000,000
HTV-010	Oct 2019	13,228	$200,000,000
Dragon-19	Mar 2020	12,444	$133,000,000
Dragon-20	Sept 2020	12,861	$133,000,000
HTV-011	Oct 2020	13,228	$200,000,000
Dragon-21	Mar 2021	13,192	$133,000,000
Cygnus-08	Apr, 2021	5,950	$237,500,000
Dragon-22	Sept 2021	12,624	$133,000,000
HTV-012	Oct 2021	13,228	$200,000,000

7 Manned Flight Schedule

Through our research, we have found cheaper ways of transporting our astronauts to the ISS, specifically by using the Dragon Crew. We can buy seats on the Dragon Crew for $20,000,000, which is far better than the cost of buying a seat on the Soyuz. However, we have already paid to use the seats on the Soyuz through 2017, and it would be wasteful to do anything but use them. But, we will begin using the Dragon Crew to get to the ISS from 2017 onwards, and not renewing our contract with the Russians. In this table, we adjust the future cost for inflation using our inflation cap.

Mission Name	Date of Launch	Cost of Launch
Soyuz TMA-04M	Mar 2012	$63,720,000
Soyuz TMA-05M	May 2012	$63,720,000
Soyuz TMA-06M	Sept 2012	$63,720,000
Soyuz TMA-07M	Nov 2012	$63,720,000
Soyuz TMA-08M	Mar 2013	$67,670,640
Soyuz TMA-09M	May 2013	$67,670,640
Soyuz TMA-10M	Sept 2013	$67,670,640
Soyuz TMA-11M	Nov 2013	$67,670,640
Soyuz TMA-12M	Mar 2014	$71,866,220
Soyuz TMA-13M	May 2014	$71,866,220
Soyuz TMA-14M	Sept 2014	$71,866,220
Soyuz TMA-15M	Nov 2014	$71,866,220
Soyuz TMA-16M	Mar 2015	$76,321,925
Soyuz TMA-17M	May 2015	$76,321,925
Soyuz TMA-18M	Sept 2015	$76,321,925
Soyuz TMA-19M	Nov 2015	$76,321,925
Soyuz TMA-20M	Mar 2016	$81,053,885
Soyuz TMA-21M	May 2016	$81,053,885
Soyuz TMA-22M	Sept 2016	$81,053,885
Soyuz TMA-23M	Nov 2016	$81,053,885
Dragon-C1	Mar 2017	$28,693,075
Dragon-C2	May 2017	$28,693,075
Dragon-C3	Sept 2017	$28,693,075
Dragon-C4	Nov 2017	$28,693,075
Dragon-C5	Mar 2018	$30,472,046
Dragon-C6	May 2018	$30,472,046
Dragon-C7	Sept 2018	$30,472,046
Dragon-C8	Nov 2018	$30,472,046
Dragon-C9	Mar 2019	$32,361,313
Dragon-C10	May 2019	$32,361,313
Dragon-C11	Sept 2019	$32,361,313
Dragon-C12	Nov 2019	$32,361,313
Dragon-C13	Mar 2020	$34,367,714
Dragon-C14	May 2020	$34,367,714
Dragon-C15	Sept 2020	$34,367,714
Dragon-C16	Nov 2020	$34,367,714
Dragon-C17	Mar 2021	$36,498,512
Dragon-C18	May 2021	$36,498,512
Dragon-C19	Sept 2021	$36,498,512

Dragon-C20	Nov 2021	$36,498,512

8 Module Failure Contingency Plan

The US involvement in the development of the ISS has been very heavy and costly. Currently, NASA has no way of delivering or replacing modules until technological developments allow for rockets such as the Falcon 9 to deliver modules to the ISS. Once that technology is available, the cost of transporting a replacement module is listed in the table below in the event the module fails or is severely damaged in a catastrophic incident. Note that while such events are extremely rare, in 2007, a large solar panel was damaged. Luckily, American astronauts were able to repair the damage; however, NASA may not be so fortunate in the future. This provides the necessary information in the event such an accident occurs. For the costs of each module, refer to Section 14 of this paper. All information presented is in 2010 chained dollars and needs to be multiplied by the inflation constant (1.062^y where y is in years since 2011).

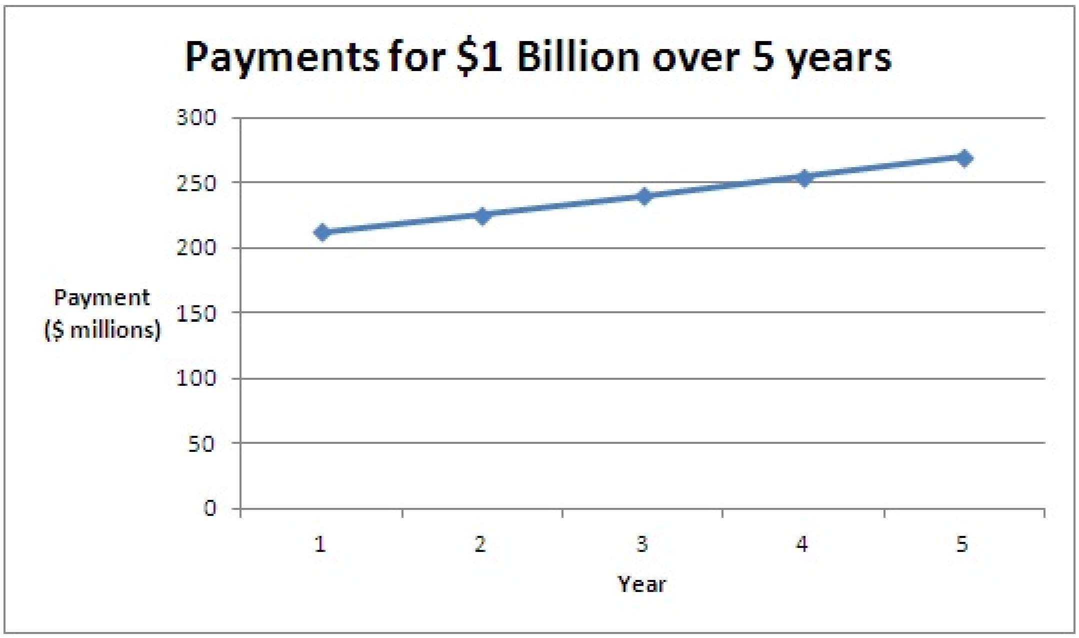
Given that a module or major component sustains catastrophic damage beyond repair and that it must be replaced for C dollars, we may pay off the costs replacement over D years for a total payment of

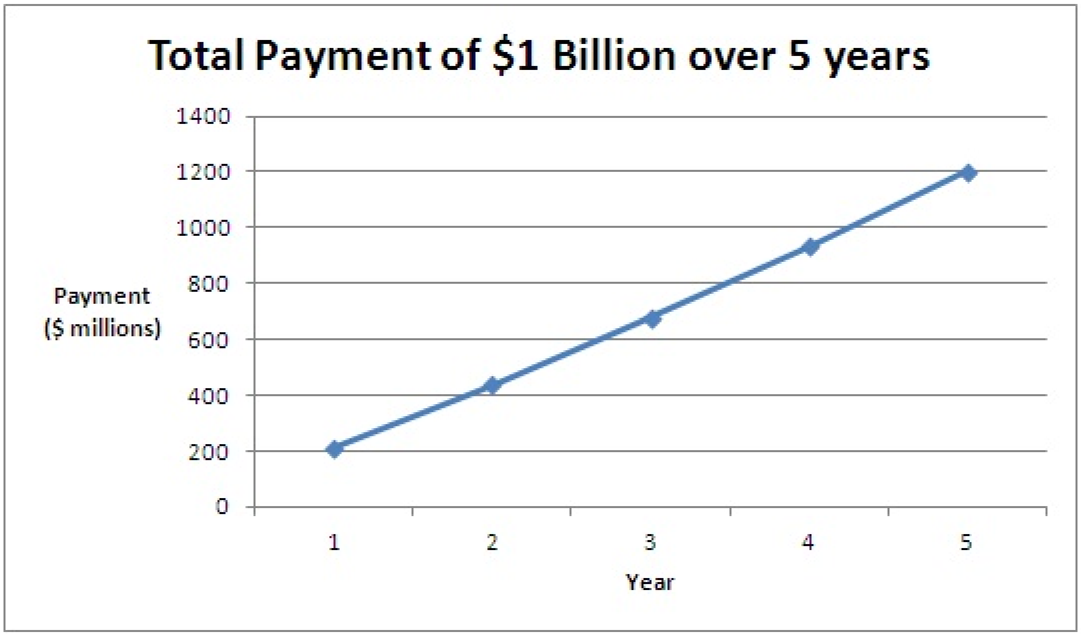
$$\sum_{y=1}^{D} \frac{C}{D} \cdot 1.062^y.$$

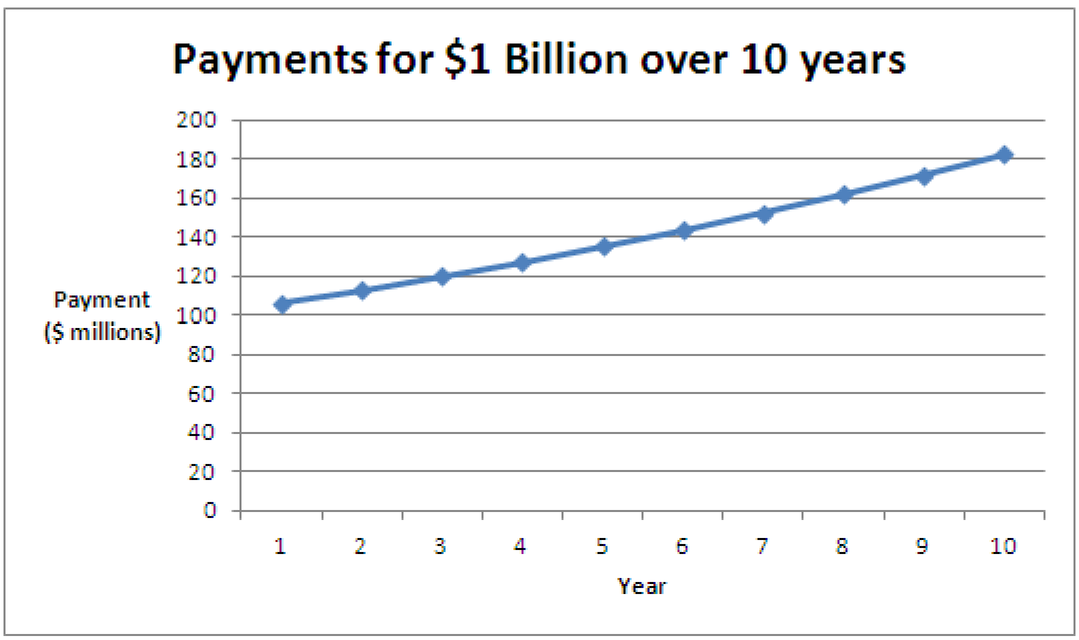
The cost depends on the component damaged. However, D can be modified based on the amount of money we can set aside from the budget to remedy the damage. The following is a table showing the total cost of repairing a component over a certain period of time. Based on the cost of development for various modules and ISS components, we will make the assumption of a lower bound and upper bound on severe damage between $250,000,000 and $2,500,000,000. A table of values of the summation with different initial values is as follows:

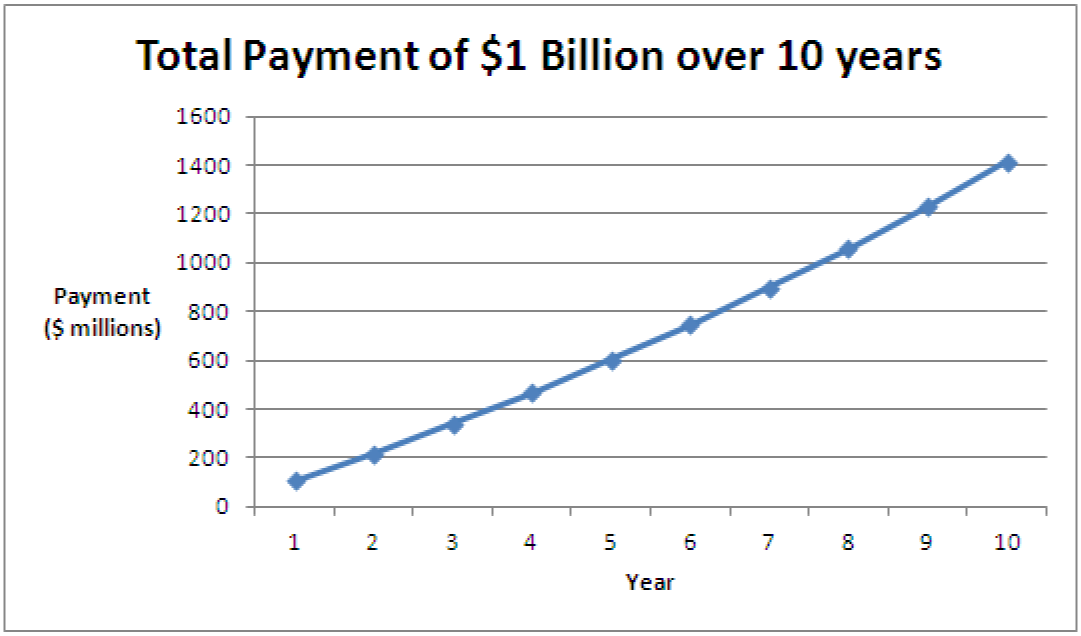
Cost	2 year	3 year	4 year	5 year	6 year	8 year	10 year	15 year
\$250M	\$273.7M	\$282.3M	\$291.2M	\$300.5M	\$310.2M	\$330.8M	\$353.3M	\$418.3M
\$500M	\$547.5M	\$564.6M	\$582.5M	\$601.1M	\$620.4M	\$661.7M	\$706.5M	\$836.6M
\$750M	\$821.2M	\$846.9M	\$873.7M	\$901.6M	\$930.6M	\$992.5M	\$1060M	\$1255M
\$1000M	\$1095M	\$1129M	\$1165M	\$1202M	\$1241M	\$1323M	\$1413M	\$1673M
\$1250M	\$1369M	\$1412M	\$1456M	\$1503M	\$1551M	\$1654M	\$1766M	\$2092M
\$1500M	\$1642M	\$1694M	\$1747M	\$1803M	\$1861M	\$1985M	\$2120M	\$2510M
\$2000M	\$2190M	\$2258M	\$2330M	\$2404M	\$2482M	\$2647M	\$2826M	\$3347M
\$2500M	\$2737M	\$2823M	\$2912M	\$3005M	\$3102M	\$3308M	\$3533M	\$4183M

The individual terms in the summation represent yearly payments made towards the repair costs, as indicated by the following graphs which simulates the appropriate payment plan for a billion-dollar repair over 5 and 10 years:




Total Payment of $1 Billion over 5 years
Payment ($ millions)
1400
1200
1000
800
600
400
200
0
1
2
3
4
5
Year


Payments for $1 Billion over 10 years
Payment ($ millions)
200
180
160
140
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
Year



Note the sharp change in individual payment when the period is altered. If the ISS encounters a catastrophic accident significant enough to exceed the capital allocated by ISS maintenance budget (which is determined by NASA), the appropriate course of action is to select a period of time to pay off a repair cost so that the yearly payment does not overwhelm the restrictions set forth by NASAs maintenance budget.

9 De-Orbitization

In October 2010, NASA created an End-of-Life Disposal Plan for the ISS. Though it did not state a date for when the end of mission for the ISS should occur, it detailed the process that must be undertaken upon such an event. Our model extends through 2021, and the ISS is currently scheduled only to remain in service at least until 2020, making it possible end-of-life might occur during our models effective timespan.

Successful return of an intact ISS to Earth would require at least 27 shuttle missions, much too costly. Natural orbital decay and subsequent random reentry would endanger human lives. Controlled de-orbit and reentry of the ISS was found to be the only viable option of ending the ISS mission with regards to safety, technical difficulty, and funding. The option would require the use of the Orion spacecraft or a variant of it, such as a modified Russian

Progress spacecraft, a combination of the Europen ATV and Progress, or some dedicated de-orbit design.

Should de-orbiting occur during our models scope, a minimum of 1 year advance notice will need to be given, meaning the earliest year would be 2019. At that point, it must be assured the ISS had adequate propellant reserves for de-orbiting. This ISS would need to be specially configured for de-orbit controllability, and the deorbiting vehicle or vehicles, whatever it is eventually chose to be, to be docked with the ISS. The vehicle would require a rocket for launch, but could adapt one of the otherwise- scheduled supply rockets.

The decision to de-orbit the ISS should not incur any additional costs beyond our model, since the rocket required could be taken from what would otherwise be a resupply mission. Any additional propellant required beyond normal upkeep maintenance could be brought up in place of food through earlier supply missions. Since the ISS would deorbit within a year, adequate supplies of food storage could be alleviated. The modified Progress or Orion spacecraft used as a de-orbiting vehicle would, in the first case, be funded by Russia, or, as in the second case, be developed regardless of ISS de-orbiting.

The issue of early termination of the ISS is a rare scenario, and would only occur, if, as defined by NASA in their End-of-Life Disposal Plan, a catastrophic event caused an early evacuation of the ISS, the ISS could not maintain control, and the catastrophic event prevented docking. Should early termination occur, the ISS could be boosted to a greater altitude so as to provide time to address the recovery of crew or the supplying of de-orbiting propellant.

10 Flight Summary

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Supply Payload (lb)	62197	48132	45027	55798	44602	62121	44356	62188	38533	44994
Expeditions	4	4	4	4	4	4	4	4	4	4
Supply Flights	5	4	4	4	4	5	4	5	3	4
Total Flights	9	8	8	8	8	9	8	9	7	8

11 Expenditure Summary

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Total Spending (in Million USD)	**3169**	**3115**	**3185**	**3437**	**3571**	**3893**	**3769**	**4179**	**4206**	**4508**
ISS Maintenance and Repair	**1676**	**1803**	**1939**	**2085**	**2241**	**2409**	**2589**	**2780**	**2987**	**3208**
Research Materials	**235**	**238**	**255**	**281**	**302**	**327**	**355**	**384**	**416**	**450**
Crew and Cargo	**1258**	**1074**	**991**	**1071**	**1028**	**1157**	**825**	**1015**	**803**	**850**
Seats on the Soyuz	255	271	287	305	324	0	0	0	0	0
Cargo Transportation	1003	804	704	766	704	1042	704	885	666	703.5
Crew Transportation	0	0	0	0	0	115	122	129	137	146

12 Strengths and Weaknesses

Strengths

1. Our model is based upon real world data from very reliable sources such as NASA.
2. Our model avoids arbitrary values and justifies every modeled result.
3. Our model provides a budget contingency plan in the event that some module(s) experiences a major failure.
4. Our model presents information in easy-to-understand tables.
5. Our model starts with a simple core plan which becomes modified as possible improvements are identified.
6. Our model assumes an inflation rate greater than will likely be, providing a cushion for our budget.
7. Our model displays results comparable to past NASA estimates.
8. Our model rigorously analyzes launch patterns, leading to realistic dates for projected launches.
9. Our model considers less well-known issues such as launch window conditions.
10. Our flight schedules and budget plans are specific and thorough.

Weaknesses

1. Our model requires a lot of information and occasionally, this information is lacking or perhaps even inaccurate. The lack of information makes the model less clear,l while inaccurate information would lead to an inaccurate conclusion timetable.

2. The launch dates for all ISS flights are dependent on future circumstances (scope of experiments, pressing resupply needs), and will thus be inaccurate to that end.

3. Lack of knowledge regarding the technological progression of spacecraft restricts our model to the unrealistic assumption that we will continue to use 2011 technology a decade later.

4. Our model focuses on NASAs budget for the ISS, which means costs indirectly related to the ISS but located in other parts of the budget such as Space Flight Crew Operations are not included.

5. Our model attempts to use cost per pound when analyzing costs and confronted with a general lack of information. However, this may not be the best or most accurate and reliable approach.

6. We do not have full knowledge of all contracts that NASA has made, and as a result, there may be other important contracts that we have overlooked. Additionally, we are not privy to the specifics of said contracts, and must make assumptions to compensate.

7. Our model does not account for important events that could affect budget, such as the 2012 presidential election, nor does it factor in political environment, such as the current focus on reducing the deficit, in terms of budget request.

8. Our model does not take into account the potential de-orbit of the ISS and assumes other member nations, particularly Russia, will remain committed to the ISS project.

13 Variables and Functions

Variable	Use
$C(m)$	A function relating the the cost of sending an astronaut on a mission to m
C	Represents the total cost of damage when it occurs.
D	The number of years spent paying off a repair, selected based on budget.
$G(t)$	A function relating the cost of supplying the station based upon t
N_F	The number of flights into the contract extension with SpaceX
$P(t)$	A function relating the mass of the payload to be delivered to t
$P_D(t)$	A function relating the Dragon's payload to be delivered to t
R	The payload of the Orion rocket.
t	The number of months since January of 2007.
x	The price per pound of payload on the Soyuz
y	The number of years since the base year of 2011. Used for inflation calculations.

14 Module Costs

Falcon Nine Heavy	Over 13,000 lb.			
Module Name	Weight lb.	Development Cost	Transportation Fee	Total Expected Cost
Quest (Joint Airlock)	13365	$164,000,000	$14,287,185	$14,287,185
Alpha Magnetic Spectrometer	14840	$1,500,000,000	$15,863,960	$15,863,960
Unity (Node 1)	19065	Unpublished	$20,380,485	$20,380,485
Z1 Truss	19300	Unpublished	$20,631,700	$20,631,700
Tranquility (Node 3)	27000	Unpublished	$28,863,000	$28,863,000
S5 Truss	27770	Unpublished	$29,686,130	$29,686,130
P1 Truss	30865	Unpublished	$32,994,685	$32,994,685
S1 Truss	31130	Unpublished	$33,277,970	$33,277,970
Harmony (Node 2)	31500	Unpublished	$33,673,500	$33,673,500
S0 Truss	31790	Unpublished	$33,983,510	$33,983,510
Destiny	32000	$1,380,000,000	$34,208,000	$1,414,208,000
P6 Truss (w/ solar arrays)	34890	Unpublished	$37,297,410	$37,297,410
P3 Truss	35050	Around $275,968,083	$37,468,450	$37,468,450
S3 Truss	35050	Unpublished	$37,468,450	$37,468,450
S6 Truss	35050	Unpublished	$37,468,450	$37,468,450
Zarya (FGB)	42600	$275,700,000	$45,539,400	$321,239,400
Falcon Nine	Under 13,000 lb.			
Module Name	Weight lb.	Development Cost	Transportation Fee	Total Expected Cost
PMA-2	3030	Unpublished	$12,847,200	$12,847,200
PMA-3	2610	Unpublished	$11,066,400	$11,066,400
PMA-2	3030	Unpublished	$12,847,200	$12,847,200
Mobile Base System	3200	Unpublished	$13,568,000	$13,568,000
PMA-1	3505	Unpublished	$14,861,200	$14,861,200
Cupola	3970	Unpublished	$16,832,800	$16,832,800
P5 Truss	4010	Unpublished	$17,002,400	$17,002,400
ESP-2	5900	Unpublished	$25,016,000	$25,016,000
Canadarm2	10800	$896,000,000	$45,792,000	$941,792,000

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