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2011

14th Annual High School Mathematical Contest in Modeling (HiMCM) Summary Sheet

(Please attach a copy of this page to each copy of your Solution Paper.)

Team Control Number: 2929

Problem Chosen: A

Please type a summary of your results on this page. Please remember not to include the name of your school, advisor, or team members on this page.

The United States Space Shuttle Program officially ended with the landing of *Atlantis* in Florida July this year. Without the Space Shuttle, National Aeronautics Space Administration (NASA) will be required to find other spacecraft to transport its astronauts to the International Space Station (ISS) for research and maintenance operations. Our group has developed a comprehensive, ten-year program for NASA that outlines costs, payloads, and flight schedules to maintain the ISS from 2012 to 2021.

We first determined the areas that we needed to allocate NASA's budget to. The four categories we decided on were personnel, operation, research, and resupply. Personnel includes the cost of the astronaut crew (NASA will be reliant on the Russians for transport to the ISS for the duration of the plan and each seat on the Soyuz spacecraft will cost $62.75 million) and the salaries of all of NASA's astronauts and ground operations crew. Operation includes the operation and maintenance costs for all of the ISS during the plan. As hardware on the ISS will soon exceed their certification limit, total operation costs include equipment re-certification and replacement costs. As it is difficult to determine the cost of the research equipment needed to be transported to the ISS for as yet undetermined research programs, a model of future cost-per-kilogram rates on Commercial Orbital Transportation Services (COTS) was developed to allow calculation of cost by research material mass. Expenses for

procurement of research materials was projected using data from NASA's budget estimates. Resupplying of the ISS with food, water, air, dry cargo etc. by NASA through unmanned commercial spacecrafts were determined to be necessary 3 times a year based upon the regular resupply missions of the Russian Progress spacecraft for the past decade.

Flight schedules for the crew and resupplying cargo were determined based upon NASA's existing flight schedules. This ten-year plan will allow NASA to continue maintaining and operating the ISS at least until the year 2021.

Restatement of the Problem

On July 21, 2011, the 135th and final US Space Shuttle arrived back on Earth, marking the end of the US Space Shuttle program. The National Aeronautics and Space Administration (NASA), previously dependent on this shuttle program for the resupplying and maintaining of the International Space Station (ISS), is now completely reliant on the shuttles of foreign countries and private companies. Our group will develop a comprehensive plan that outlines the costs, payloads, and flight schedules NASA will have to field over the next ten years (2012 – 2021) in order to properly maintain the ISS. In this model, we will consider four major areas that constitute the cost of maintaining the ISS: personnel, resupply, operation, and research.

Definition of Variables

t = Time (years)

M = Total ISS maintenance cost (USD)

R = Non-transport Research Expenses (USD)

Q = Cost per kilogram of Payload

c = Cost per year of Maintaining Crew Members

s = Price per Seat

A = Total Cost per Year from Astronaut Salary (USD)

r = Average Astronaut Salary (USD)

G = Total Ground Operation Expenses (millions of USD)

E = Total cost of Transporting Research Material (USD)

m = Total mass transported (kg)

Z = Total Cost of Research (USD)

Assumptions

1. The ISS is maintained for the purpose of scientific research.

Because the function of the ISS is to provide an environment for scientific research, we consider the availability of research materials and equipment to be an integral part of maintaining the ISS. Thus, we have incorporated the costs associated with research, such as the cost of the actual equipment and the cost of transporting that equipment to the ISS, into our ten-year plan.

2. The ISS will require 26,776 kg of supplies (including dry cargo, food, water, and air) per year.

Table 1: Mass of Supplies (kg) Transported to the ISS by Contributing Entity per Year

	2008	2009	2010	2011
Russia	10,704	9,352	10,203	10,348
Europe	2297	0	0	7084
Japan	0	4082	0	4808
USA	4,536	4,536	4,536	4,536
TOTAL	13,001	13,434	10,203	**26,776**

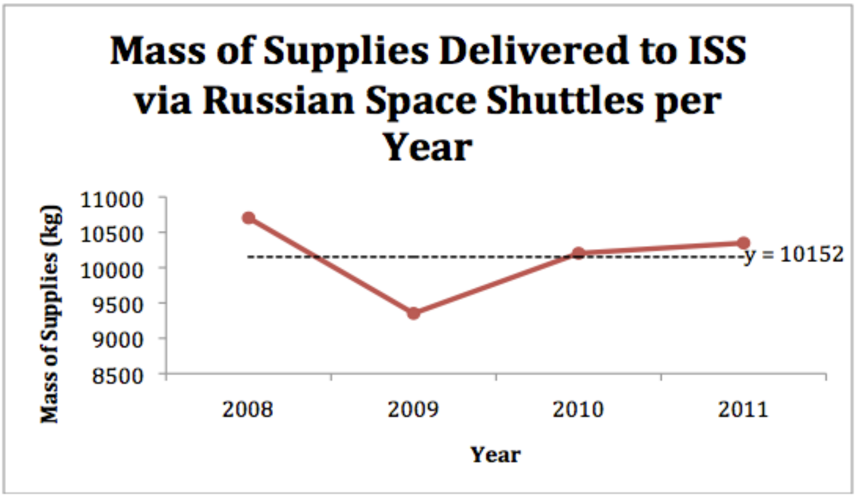
2011 was the only year in which all four major contributing entities (the USA, Russia, Japan, and Europe) transported supplies to the ISS. Because all four entities are expected to continue their supply services in the years to come, we will use the combined mass of the supplies provided in the year 2011 (26,776 kg) as the benchmark for the supply mass to be provided to the ISS per year from 2012 to 2021.

3. Russia will send 4 shuttles per year from 2012 to 2021 to the ISS with an average supply total of 10,152 kg per year. Europe will send 1 shuttle per year from 2012 to 2021 with an average supply total of 7084 kg per year. Japan will send 1 shuttle per year from 2012 to 2021 with an average supply total of 4445 kg per year.

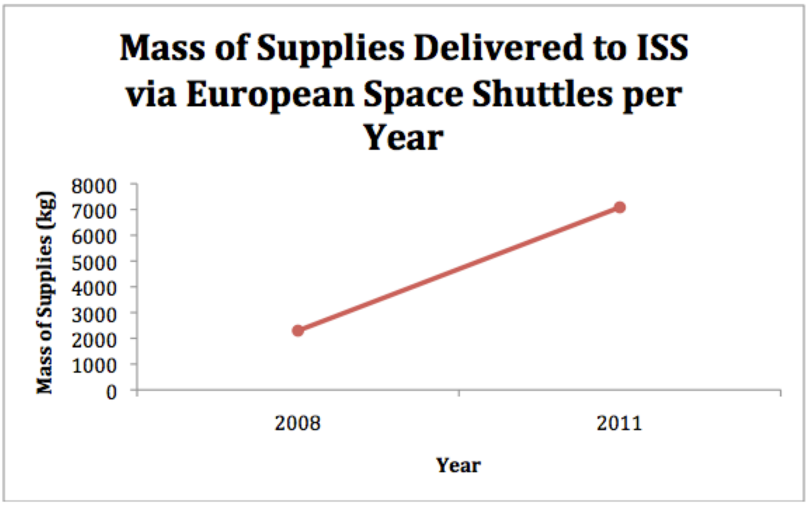
Table 2: Projected Future Supply Values (kg) of Contributing Entities

	2008	2009	2010	2011	Future Supply per Year
Russia:	10,704	9,352	10,203	10,348	**10,152**
Europe:	2297	0	0	7084	**7,084**
Japan:	0	4082	0	4808	**4,445**

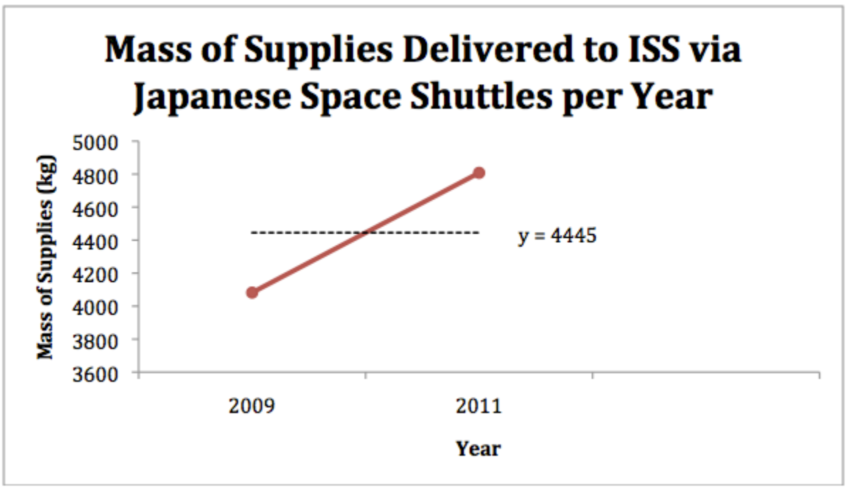
Russia's future supply value per year was found by averaging the supply mass sent by Russia each year from 2008 to 2011. This comes out to a value of 10,152 kg per year. Russia does not publicly release any plans concerning their future supply missions, but because they have consistently delivered a supply value close to 10,152 kg per year for the past ten years, we think that it is reasonable to assume that Russia will continue its supply missions at the same rate and with the same supply mass until 2021. We assume this in order to be able to reasonably predict the supply masses NASA will have to contribute in the next ten years.



Europe's future supply value per year was found differently. Instead of averaging Europe's two very different supply values, 2,297 kg and 7,084 kg in 2008 and 2011 respectively, we decided that the 2011 supply mass value (7,084 kg) was more representative of what Europe will be able to send in the future. This is because Europe's increase in supply mass was due to an improvement in the design of their European Automated Transfer Vehicle, enabling a greater amount of supply mass to be sent at a lower cost. Although in the past, Europe only *sent two supply loads over a period of four years, Europe has planned a future schedule of one supply mission per year. Although they have not released any plans past the year 2014, we have to assume that they will continue at a rate of one supply mission per year in order to be able to predict the need for NASA's contribution in the next ten years. Thus, we assume Europe's future supply value to be 7,084 kg per year.*



Japan's future supply value per year was found the same way Russia's was found – through averaging the supply mass sent per year in the past. Although, like Europe, Japan only sent two supply shuttles over a course of four years, Japan too has scheduled one supply mission per year until the year 2015. We think that it is reasonable to assume these missions will continue until at least 2021. Thus, we assume Japan's future supply value to be 4,445 kg per year.



4. The costs due to NASA's involvement in the development of other space shuttles (such as the Orion Multi-Purpose Crew Vehicle) and in its investment in the development of commercial vehicles is not related to the maintenance of the ISS in the 2012 to 2021 period.

This is consistent with NASA's previous non-inclusion of the developmental costs of their Space Shuttle Program in their ISS maintenance costs. Despite the fact that the Space Shuttles were used almost exclusively for ISS missions (35 of 41 missions), NASA considered the Space Shuttle Program to be an independent project from the ISS. Thus, we do not consider NASA's investments in the development of new shuttles as part of the plan to maintain the ISS.

5. 4 NASA astronauts will be sent to the ISS per year.

In the past there have been 6 astronauts at the ISS at all times, with 3 astronauts switching around every 3 months. An average of 1 out of every 3 astronauts has been a NASA astronaut. Because this same system of rotation and spot allocation has been in place since the inception of the ISS, it is reasonable to assume this system will continue throughout our ten-year plan. This assumption enables us plan for the sending of NASA astronauts to the ISS.

6. The cost for an astronaut to travel to the ISS also covers the return costs.

When the cost of transporting an astronaut is given, we assume that it includes both the launch cost and the return cost.

7. The number of astronauts in NASA stays constant at 64.

Because the NASA Space Shuttle program has been discontinued, it is unlikely that the number of astronauts will increase. Because there is no way of knowing whether NASA will choose to decrease the number, we assume that the number will stay constant.

8. The Russian, European, and Japanese unmanned cargo shuttle flights are funded by Russia, Europe, and Japan, respectively.

We assume that NASA is not responsible for any expenses necessary in the supply shuttle flights conducted by the other contributing entities.

9. The Dragon C and Cygnus shuttles will both be ready for use in 2012.

According to SpaceX and Orbital, the private companies funded by NASA and in charge of the development of the Dragon C and Cygnus shuttles, respectively, both the Dragon C and the Cygnus will have finished development and will be ready for use in 2012. We assume that there will not be any delays in the development of these shuttles, and that use of the private shuttles will start in 2012.

Model Building Discussion

In order to build a comprehensive ten-year plan for NASA's role in maintaining the International Space Station (ISS), we first had to understand NASA's current operations and responsibilities with regards to the ISS. Thorough research reveals that NASA's operations and expenses related to the ISS can be divided into 4 broad categories:

I. Personnel

II. Operation

III. Research

IV. Resupply

The termination of the US Space Shuttle program will require vast changes in all four areas if operations are to continue. After determining this, our team sought to address each section individually, and begin developing a plan of action for each area, including the total expense for NASA, cost breakdown, and specific flight schedules – as necessary – in our plan.

I. Personnel

Under the first section concerning personnel, the majority of the plan is directed towards ensuring transportation for the NASA astronauts scheduled to be part of the approximately 6-month expeditions on the ISS. To begin with, we considered one of our main goals to reduce dependence on transportation via the Russian Soyuz spacecrafts because of both the high cost and also the inadvisability of becoming too reliant on NASA's partners in the ISS. However, progress on the development and production of commercial spacecrafts is still in its early stages for both companies currently part of the Commercial Orbital Transportation Services (COTS) program, SpaceX and Orbital. Furthermore, only SpaceX is developing a spacecraft, Dragon, for the purposes of transporting not just cargo but crewmembers. With funding under the second phase of the Commercial Crew Development (CCDev) program, the earliest manned commercial flight to the ISS is projected to be in 2015 or 2016.

Another option would be for NASA to develop its own manned spacecraft to replace the US Space Shuttle Program. A good candidate for this is the Orion Multi-Purpose Crew Vehicle (Orion MPCV). Not only is the Orion MPCV currently NASA's only spacecraft in development, one of NASA's original goals of converting the Orion spacecraft from the Constellation project to the Orion MPCV project was to allow the MPCV to function as a space shuttle for other purposes. Preliminary MPCV plans project initial completion and usage in 2016. From this information, we produced this two-part initial proposal:

1. From the commencement of the ten-year plan at 2012 to 2015, NASA should transport the NASA astronauts that are part of the ISS regular crew expeditions on Russian Soyuz spacecrafts.

The cost per year of maintaining crewmembers on the ISS can be modelled by the following equation:

$C = (\text{Number of crew members}) * s$

Based on the assumption above that every year NASA will send 4 astronauts to ISS as part of the regular crew, we can further define our equation:

$C = 4 * s$

NASA negotiated in March 2011 for 12 seats on board Soyuz missions between 2014 and 2016 for $753 million in total – $62.75 million per seat. This was an increase from the $55.8 million per seat agreed upon for 6 flights in 2013 and 2014. According to NASA spokesman Joshua Buck, "the increase covers just the general inflation rate in Russia for the cost of processing and preparation". While we considered using this data to model the increasing cost of seats on the Soyuz, the remaining parts of the ten-year plan do not, and due to lack of appropriate data, cannot feasibly take inflation into account. Therefore the $62.75 million figure will be used as a reasonable estimate in the ten-year plan as the constant for all future Soyuz seat prices through 2021. As neither the number of NASA astronauts despatched as ISS crewmembers nor the cost of a seat on the Soyuz changes, the total cost will remain constant as well. Thus we can now use our equation to determine the cost per year:

$$C = 4 * (62,750,000)$$

$$C = 251,000,000$$

The cost per year to send NASA astronauts to crew the ISS: **$251 million**

2. From 2016 until the end of the ten-year plan in 2021, NASA should begin using a combination of commercial vehicles and Orion MPCV to transport ISS regular expedition astronauts to the ISS.

When the Orion MPCV, SpaceX's Dragon spacecraft, and Orbital's Cygnus spacecraft are ready for use in 2016, NASA will switch from relying on the Russian Soyuz to using these commercial and NASA-owned spacecrafts. Determining the cost of this part of the plan, particularly the costs of launching the MPCV would be much more difficult as a completed version of the MPCV has yet to be built and tested. One method would be to approximate the cost from the costs of launching NASA's last spacecrafts from the US Space Shuttle Program, but the MPCV and the Space Shuttles have significant differences in design, size, and weight that would put this method into question.

Upon further study of the records of previous manned missions to the ISS, however, we realized that Part Two of our plan was inconsistent with these records. For the past decade, the Soyuz has transported all ISS Expedition astronauts, including NASA astronauts, to the ISS. This implies that relying on the Russian Soyuz in this area, even when commercial spacecrafts and NASA spacecrafts are available, is the most advisable method of continuing NASA's current role in maintaining the ISS. Therefore, the two parts of our original plan can now be combined into one. As calculated above, the cost per year to send NASA astronauts to crew the ISS will be **$251 million** every year of the ten-year plan from 2012-2021.

Other demands of NASA that fall into the category concerning personnel include the salary of the astronauts involved in the ISS and the ground operations expenses. Using this equation, we can model the total cost per year from astronaut salary:

$A = (\text{Number of NASA astronauts involved in the ISS}) * r$

As stated in our assumptions, the number of NASA astronauts involved in the ISS will be 64, and remain the same for all years in this model.

$A = 64 * r$

Salaries for NASA astronauts are based on the US Government's General pay scale for grades GS-12 through GS-13 according to academic achievement and experience, ranging from $65,140 per year up to $100,701 per year. As NASA does not disclose specific employee details, the ten-year plan will take the average of the salary range multiplied by the number of astronauts as a relatively close estimate.

$A = 64 * (82{,}920)$

$A = 5{,}306{,}880$

The cost per year of the salary of NASA astronauts involved with the ISS: **$5,306,880**

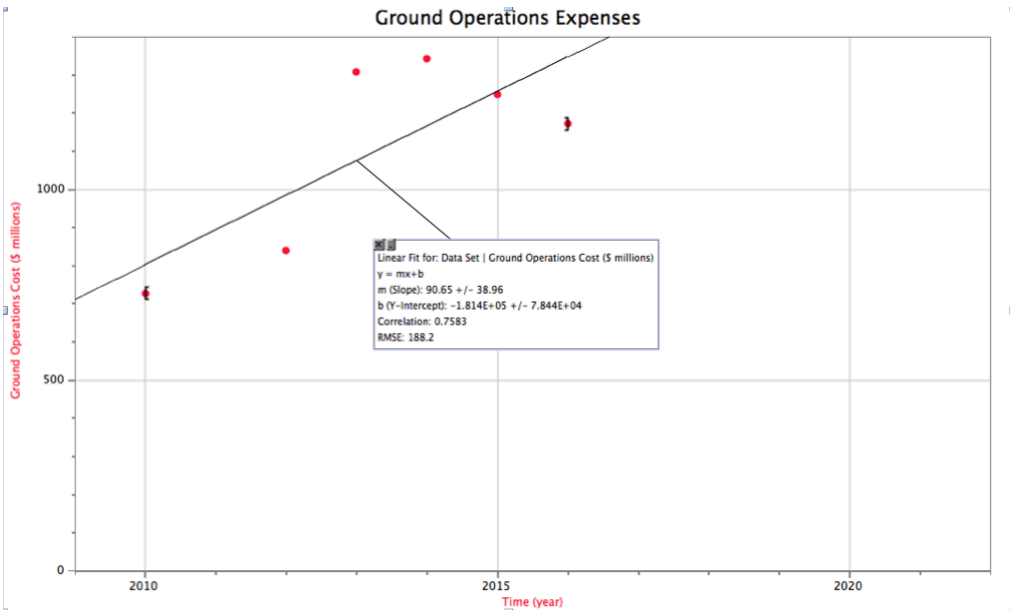
Expense from ground operations also needs to be accounted for. As seen in the table from NASA's 2012 Budget Request Report, the ground operation expenses will generally increase.

Table 1.1: NASA's Space and Flight Support 2012 Budget Request

Budget Authority, $ in millions	Actual FY2010	Ann. CR FY2011	FY2012	FY2013	FY2014	FY2015	FY2016
Space and Flight Support (SFS)	**$727.7**		**$840.6**	**$1,306.8**	**$1,340.7**	**$1,248.1**	**$1,171.2**
21st Century Space Launch Complex	$0.0		$168.0	$175.3	$168.1	$54.8	$42.9
21st Century Space Launch Complex	$0.0		$168.0	$175.3	$168.1	$54.8	$42.9
Space Communications and Navigation	$482.3		$436.0	$477.5	$484.5	$483.6	$481.9
Space Communications Networks	$363.3		$364.5	$398.2	$417.9	$425.2	$423.2
Space Communications Support	$93.5		$66.3	$65.7	$66.6	$58.4	$58.7
TDRS Replenishment	$25.4		$5.1	$13.7	$0.0	$0.0	$0.0
Human Space Flight Operations	$104.0		$111.4	$112.5	$112.6	$115.8	$116.4
Human Space Flight Operations	$104.0		$111.4	$112.5	$112.6	$115.8	$116.4
Mission Operations Sustainment	$0.0		$0.0	$415.2	$443.8	$459.1	$391.4
Mission Operations Sustainment	$0.0		$0.0	$415.2	$443.8	$459.1	$391.4
Launch Services	$89.4		$81.3	$80.3	$84.6	$87.0	$90.4
Launch Services	$89.4		$81.3	$80.3	$84.6	$87.0	$90.4
Rocket Propulsion Test	$43.3		$43.9	$46.0	$47.1	$47.8	$48.2
Rocket Propulsion Testing	$43.3		$43.9	$46.0	$47.1	$47.8	$48.2
Crew Health & Safety	$8.8		$0.0	$0.0	$0.0	$0.0	$0.0
Crew Health and Safety	$8.8		$0.0	$0.0	$0.0	$0.0	$0.0

A model was constructed with the above data points from 2010 to 2016 to determine the ground operation costs from 2017 to 2021.

Graph 1.1: Ground Operations Expenses per Year



A linear regression was used to create a line of best fit. We will use the equation of this line of best fit to model future ground operations expenses. (We will only use the model to predict points not already included in NASA's original extrapolations)

The equation gained from the line of best fit is:

$$G = 90.65t - 180000$$

Where G represents the total ground operation expenses in millions of dollars and t represents the time in years. From this equation, we can determine the ground operation expenses for the years till 2021 not projected in the NASA 2012 Budget Request, a summary of which is shown in the table below.

Table 1.2: Forecasted Ground Operation Expenses per Year ($ millions)

Time (Year)	Ground Operation Expenses ($ Millions)
2012	840.6
2013	1306.8
2014	1340.7
2015	1248.1
2016	1171.2
2017	1441.05
2018	1531.7
2019	1622.35
2020	1713
2021	1803.65

II. Operation

The ISS has a variety of equipment that can start to malfunction and deteriorate over time. Thus, it is necessary to allocate costs to maintain the various systems on the ISS. Specific aspects of maintenance include: re-certification of ISS structures, purchase of additional spare parts, extending baseline operational services, and initiating activities that increase ISS upgrade efforts by improving new space technologies and increasing research capacity.

Initially, it was uncertain whether maintenance costs were constant or if they depended on the conditions of the ISS's equipment. It was discovered that there have been many hardware and software failures and malfunctions on the ISS that have had a major impact on its maintenance costs. We also figured that maintenance on the ISS would be a routine; crewmembers would regularly check the status of the ISS's modules and equipment for errors or deterioration.

Finally, it was concluded that maintenance costs would include both regular maintenance and operational costs and the costs to repair accidence or malfunctions. However, we researched data for both regular maintenance and operational costs and costs that account for equipment failures, and discovered that accounting for malfunctions is impractical because there is very little information on the cost of repairing the failures. Additionally, we realized that the range of the costs for equipment failure repair is extremely large. Even if the cost of each equipment failure was determined, it would be impractical to predict the costs of future malfunctions from that data because it is difficult to know which pieces of equipment might fail spontaneously and the cost of replacement for the failed equipment.

Regular maintenance and operational costs

According to NASA's 2012 budget estimate, the total regular maintenance and operational costs of the ISS in 2010 was $1,555,200,000. The total operation costs estimated until 2016 increase due to the ISS Life Extension program--needed to continue ISS operation until 2020. As hardware on the ISS starts to exceed their certification limits in 2013, each piece of hardware will need to be re-evaluated and re-certified in three phases, the first of which is already under way, and the second and third of which will begin in 2012. Costs will also go to procuring and installing replacement hardware if the existing equipment is found to be unfit for re-certification.

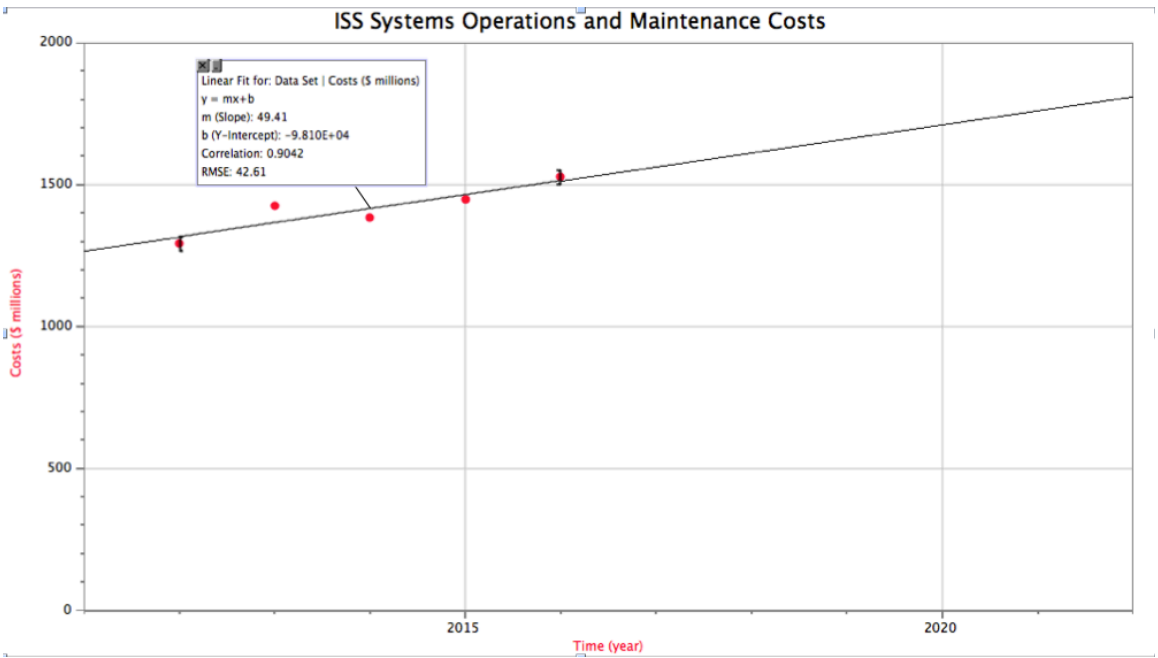
Table 2.1: NASA 2012 Total Budget Request Breakdown

FY 2012 Budget Request

Budget Authority ($ millions)	FY 2010	Ann CR. FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016
FY 2012 President's Budget Request	**2,312.7**	**-**	**2,667.0**	**2,775.8**	**2,818.0**	**2,847.3**	**2,883.8**
ISS Systems Operations and Maintenance	1,555.2	-	1,291.4	1,425.3	1,385.1	1,449.6	1,526.3
ISS Research	129.5	-	189.8	176.9	178.8	186.1	189.1
ISS Crew and Cargo Transportation	628.0	-	1,185.7	1,173.6	1,254.1	1,211.6	1,168.5

With this data, we extrapolated and created a model that will project the costs of maintenance and operations costs to the year 2021, the final year of our ten-year program. The model was created by plotting the given points from the NASA's extrapolations from 2012 to 2016. The linear regression feature was then employed to find a best-fit line between all of these points. The equation of the best-fit line is what we will use to predict the maintenance costs of the future.

Graph 2.1: ISS Systems Operations and Maintenance Costs per Year



The equation obtained from this extrapolation is:

$M = 49.41t - 98000$

Where M is the total maintenance cost in dollars and t is the time in years. From this equation, we can create a table of the costs from 2012 to 2021. (Only the points that were not included in the NASA's original extrapolation were extrapolated. NASA's original extrapolations are included in the data set created below).

Table 2.2: Predicted Maintenance Costs From 2012 to 2021

Year	Maintenance Cost: $49.41t - 98000$ ($ millions)
2012	1291.4
2013	1425.3
2014	1385.1
2015	1449.6
2016	1526.3
2017	1659.97
2018	1709.38
2019	1758.79
2020	1808.2
2021	1857.61

Equipment Failures

Over time, the International Space Station has had to deal with maintenance issues, malfunctions, and equipment failures. The incidents have disrupted the flight schedules and assembly timeline, reduced the ISS's capabilities, and have jeopardized the ISS's ability to sustain astronauts and research. Since the ISS's development, these incidents have had a major impact on the total maintenance cost.

Our group initially thought accounting for these technical failures would be useful because they can greatly affect the total maintenance costs. We attempted to determine the frequency of major malfunctions on the ISS to predict how many equipment failures will occur in the future. We also hoped to find the average cost of each technical failure so that--

coupled with the average frequency of incidents--a prediction of how much equipment failure repairs would cost.

Table 2.3: Past Accidents on the ISS

Date	**Accident**
February 1, 2003	Waste accumulation in ISS toiletry systems
January 2, 2004	Air leak
September 18, 2006	Venting of gas
June 14, 2007	Computer failure
September 25, 2007	Damaged starboard Solar Alpha Rotary Joint
October 30, 2007	Torn solar panel
January 14, 2009	Excessive vibration during reboost
May 15, 2009	Potential ammonia leak from S1
August 1, 2010	Failure in cooling loop A
June 28, 2011	Near collision with space debris
August 24, 2011	Progress resupply failure

However, we discovered that trying to account for costs of technical failures is impractical. This is because the data for the costs for specific failures is difficult to obtain and even if the costs for each specific failure could be found, the range of the costs between the failures is very large. Because there many different types of malfunctions, an average cost of failures would not be a good indicator of how much future incidents may cost to fix. Because malfunctions and technical failures are hard to predict, and the large range of the cost to repair and replace, these costs were removed from the ten-year plan.

III. Research

The third section considered in our ten-year plan aims to allow NASA to continue performing scientific research on the ISS by replacing the transport of research equipment and personnel previously done by the US Space Shuttles with commercial spacecrafts, currently the Dragon and the Cygnus.

The exact cost of sending research equipment and personnel to the International Space Station cannot be accurately determined due to the uncertainty of the research programs and experiments that are going to be approved and sent by NASA and the mass of the equipment they will need. However, our ten-year plan uses a prediction of the cost per kilogram payload of the Dragon spacecraft in the period modeled on existing developmental data so that when the mass of the research materials is determined, the cost to send it up to the ISS can be determined easily as well.

To create this prediction, we found the cost per kilogram payload of the three consecutively tested versions of the Falcon rocket (used to launch the Dragon spacecraft), then modeled the rate at which the cost per kilogram changes over time. The table below shows the calculation of these values:

Table 3.1: Payload of the Falcon Rocket and Price per Kilogram

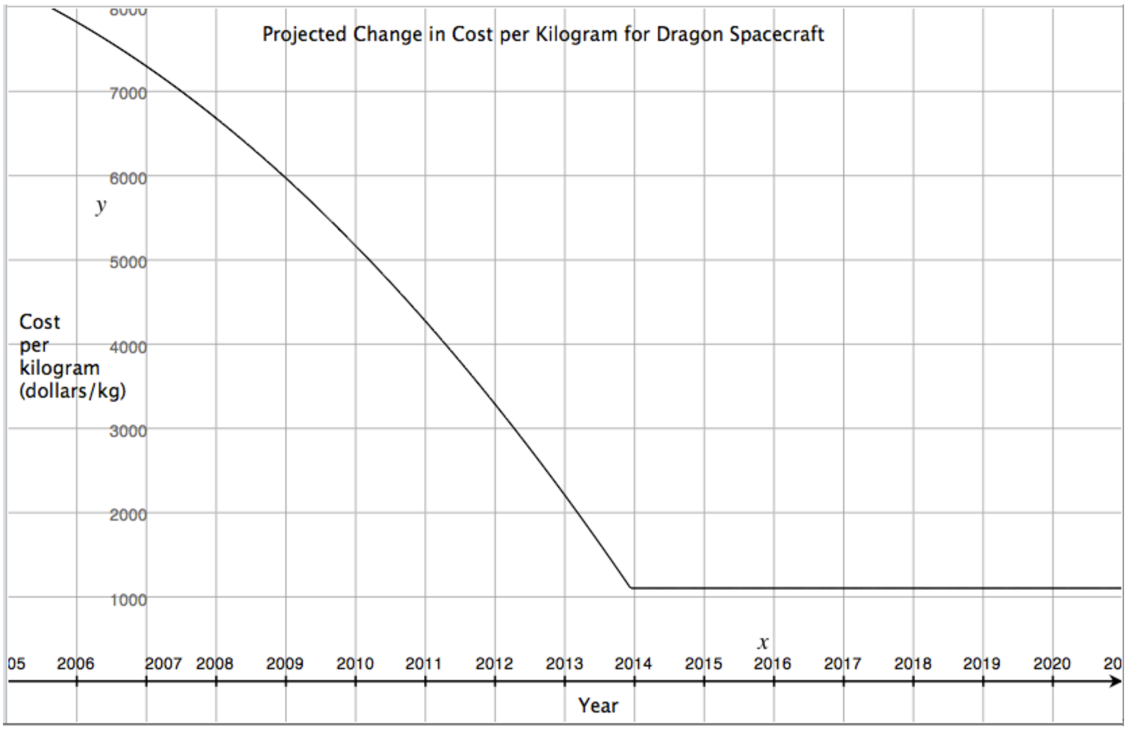
2006	Falcon 1	1,010 kg payload	$7.9 million/flight	$72,822/kg
2010	Falcon 9	10,450 kg payload	$54 million/flight	$5,167/kg
2013	Falcon Heavy	53,000 kg payload	N/A (cost/kg provided by SpaceX)	$2,205/kg

However, if this data were to be modeled as is, there would be a time where the cost/kg would decrease to an unrealistic rate. Thus we must determine a ‘lower limit’ at which the growth slows to a constant or near constant rate. In a Senate testimony on 5 May 2004, Elon Musk--founder of SpaceX--stated, ‘ultimately, I believe $500 per pound or less is very achievable’. As a result, in this model the lower limit is $500 per pound or around $1102 per kilogram, the final viable cost that future versions of the Falcon rocket will achieve. We recognize that it is possible the price may drop lower with further technological advances and competition. These developments, however, are unpredictable, and so for the 10-year plan we will not take them into account.

After plotting the data in the table above, the best-fit line was found to be a quadratic equation, with a correlation of coefficient value of 1.

$$Q = \begin{cases} -46.226t^2 + 184980.63t - 185047469.071 & 2012 \le x < 2014 \\ 1102 & 2014 \le x < 2022 \end{cases}$$

Graph 3.1: Projected Change in Cost per Kilogram for the Dragon Spacecraft



The Cygnus spacecraft being developed by Orbital Sciences Corporation will also be used to transport equipment and personnel in the same way as the Dragon. The Cygnus and the Taurus II rocket that is to propel the craft, however, are in earlier stages of testing and development than the Dragon and Falcon. As of now, the highest published price of a Taurus II rocket launch is \$80 million, and it is able to lift a payload of 5,100 kg. This translates to around \$15,686 per kg. But as of 26 May 2011, Orbital has already completed 15 out of 19 of the COTS development milestones set with NASA (Chaplain). By this progress speed, we estimate that by 2016 the Cygnus will have reached the $1102 per kilogram mark. From 2016 on, both the Dragon and Cygnus will be $1102 per kilogram.

From this an equation can be written to model the total cost of the transporting a specific mass of research equipment and/or personnel:

$E = m * Q$

With E representing the total cost in USD, m representing the total mass transported, and Q the cost per kilogram payload for that year.

Table 3.2: NASA 2012 Budget Estimates for International Space Station Expenses

FY 2012 Budget Request

Budget Authority ($ millions)	FY 2010	Ann CR. FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016
FY 2012 President's Budget Request	**2,312.7**	**-**	**2,667.0**	**2,775.8**	**2,818.0**	**2,847.3**	**2,883.8**
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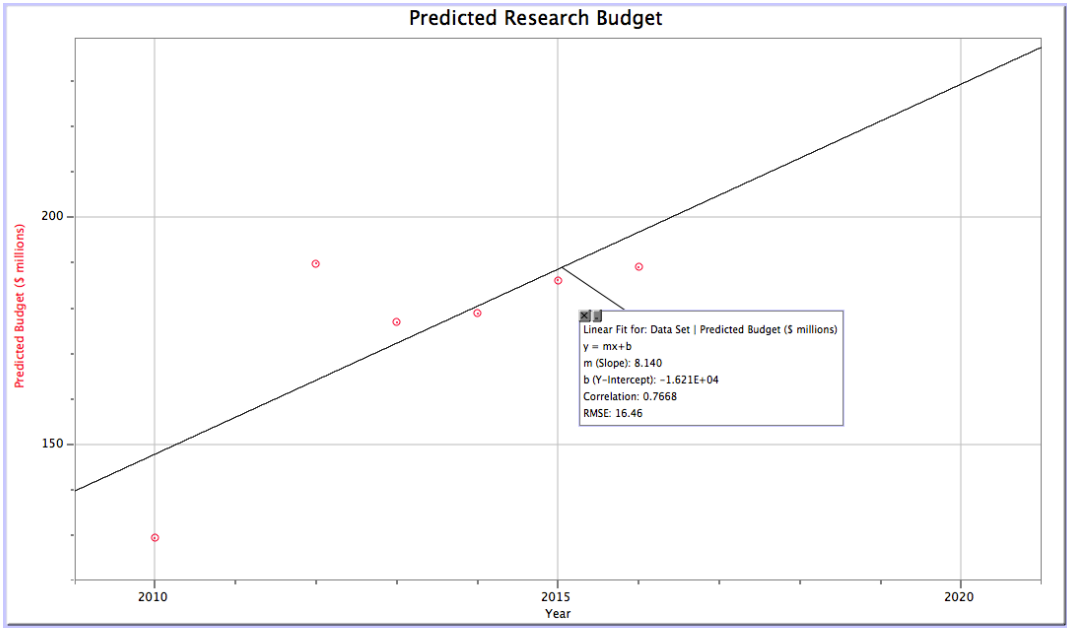
ISS Crew and Cargo Transportation	628.0	-	1,185.7	1,173.6	1,254.1	1,211.6	1,168.5

In addition to the cost of transporting research equipment and personnel, costs under the research section also include the cost of the research equipment itself (the cost of salary accounted for previously). According to NASA's '2012 Complete Budget Estimates' above, the cost of the research experiments, materials, and equipment itself was $129.5 million in 2010 ('FY 2012 Complete Budget Estimates').

These costs are made up of the equipment and materials needed for NASA's own research programs on board the International Space Station, and the funding of the Centre for the Advancement of Science in Space Inc. (CASIS) – the non-profit research organization selected by NASA this July to manage around 50% of the research facilities on board the ISS.

At least \$15 million will be given to CASIS to fund their management of research. NASA will also help with transporting research material and crew to the ISS as needed. Using data from the estimates a linear model was made projecting the potential costs of research funding through to 2021.

<u>Graph 3.2: Predicted Research Budget with Outliers</u>

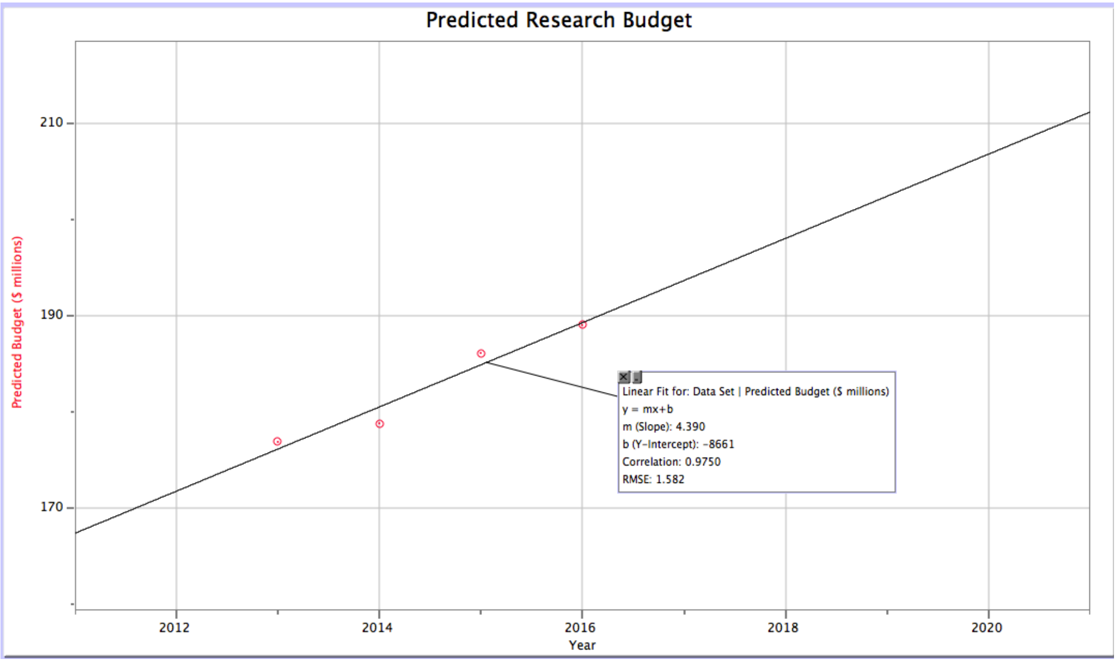


The model yielded was:

$R = 8.140t - 16200$

It was found that accounting for the actual 2010 research expenses and the predicted 2012 budget yields an unreasonable linear model for predicting future budgets, as the model would have predicted values that are too high. A second model was made with the first two values removed. This improved the 0.7668 coefficient of correlation to 0.9750, indicating that the second model was a better fit for the data.

Graph 3.3: Predicted Research Budget without Outliers



The revised linear fit is:

$R = 4.390t - 8661$

Table 3.3: Predicted Research Budget From 2017 to 2021

Year	Predicted Research Budget ($ millions)
2017	193.70
2018	198.09
2019	202.48
2020	206.87
2021	211.26

The two equations generated above for E, the total cost of transporting a specific mass of research equipment and/or personnel and R, the total predicted research budget can be combined to find the total cost of the plan related to research for any year in the 10 year period:

$Z = E + R$

$Z = mQ + 4.390t - 8661$

IV. Resupply

The second area that needs to be addressed concerns how NASA will fulfill its responsibilities towards resupplying the ISS with the station's daily necessities.

To avoid relying on foreign cargo vehicles, and to encourage the development of the domestic spacecraft transportation industry, our ten-year plan calls for NASA to use commercial unmanned spacecrafts to cover its missions to resupply the ISS, specifically the Dragon Cargo and the Cygnus available in the period of the ten-year plan.

To determine the amount of supplies NASA will be required to transport, we gathered and organized into a chart data regarding all resupply missions – from the Russian Federal Space Agency (RKA), the European Space Agency (ESA), and the Japan Aerospace Exploration Agency (JAXA) – from 2008 to 2011. As detailed in assumptions 2 and 3, the ISS will require 26,776 kg of supplies per year, with the break down from each major ISS contributor as detailed in Table 2, recalled below:

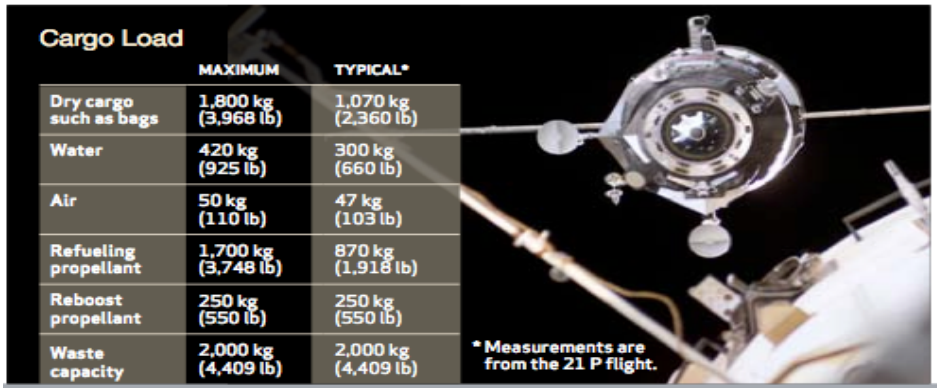
Table 2: Projected Future Supply Values (kg) of Contributing Entities

	2008	**2009**	**2010**	**2011**	**Future Supply per Year**
Russia:	10,704	9,352	10,203	10,348	**10,152**
Europe:	2297	0	0	7084	**7,084**
Japan:	0	4082	0	4808	**4,445**

By subtracting the yearly contribution from Russia, Europe and Japan from the required 26,776 kg per year, we can determine that NASA must transport the remaining 5,095 kg of supplies per year.

After researching previous resupply missions, we determined that the contents of regular resupplying can be divided into water, air, and dry cargo, including food. The amounts of each carried by the typical resupply mission can be seen through this chart of the Russian Progress spacecraft on one of its regular resupply missions:

Figure 4.1: Cargo Load of Progress Space Shuttle



Cargo Load

	MAXIMUM	TYPICAL*
Dry cargo such as bags	1,800 kg (3,968 lb)	1,070 kg (2,360 lb)
Water	420 kg (925 lb)	300 kg (660 lb)
Air	50 kg (110 lb)	47 kg (103 lb)
Refueling propellant	1,700 kg (3,748 lb)	870 kg (1,918 lb)
Reboost propellant	250 kg (550 lb)	250 kg (550 lb)
Waste capacity	2,000 kg (4,409 lb)	2,000 kg (4,409 lb)

*Measurements are from the 21 P flight.

As can be seen, in addition to the dry cargo, water and air, the resupply vehicle also carries refueling propellant and re-boost propellant. The latter can be excluded from the planned cargo of the Dragon Cargo and Cygnus as the goal of these commercial spacecrafts will be merely to resupply the ISS and will not play a role in re-boosting the ISS to higher altitudes periodically to counteract atmospheric drag.

The number of resupply missions NASA must fund each year can be found by comparing the capacity of the Dragon Cargo and Cygnus with the total amount of supplies to be transported, keeping in mind the spacecraft’s need to carry a proportionate amount of refueling propellant. The maximum capacity of the Dragon Cargo according to the fact sheet by SpaceX is 3318 kg. Orbital’s Cygnus is contracted by NASA to transport a minimum of 20,000 kg over 8 flights, to equal a minimum capacity of 2500 kg per flight. A bit of experimentation revealed that **3 missions per year** would require 5,095 kg/3 or about 1698 kg of supplies to be transported per mission, the most feasible number.

To find the cost of transporting the required amount of supplies per flight, the total cargo mass must first be determined. Using the cargo breakdown from the Progress spacecraft resupply mission, the approximate amounts of dry cargo, water, and air can be found by multiplying the ratios of the Progress supplies by the total mass of supplies of 1698 kg. For example, to calculate the mass of the dry cargo:

(Mass of dry cargo, Progress)/(Total mass of dry cargo, water, air) x (1698 kg)

There is, however, still the refueling propellant to consider. The amount of refueling propellant to be carried can be determined by multiplying the ratio of dry cargo and propellant carried by Progress by the mass of dry cargo that will be transported by Dragon Cargo and Cygnus.

(Mass of Refueling Propellant) = (870 kg/1070 kg) x (1282 kg) = 1042 kg

The resultant amounts would be as follows:

Table 4.1: Planned Breakdown of Dragon/Cygnus Resupply Space Shuttle

Item	Mass
Dry Cargo	1282 kg
Water	359 kg
Air	56 kg
Refueling Propellant	1024 kg
Total	**2739 kg**

SpaceX has a contract for 12 resupplying missions for a total of $1.6 billion. At the same time, Orbital is under contract with NASA to make 8 resupplying missions to the ISS for a total of $1.9 billion before 2016. As a result, 8 Cygnus missions must be scheduled prior to 2016, for the fixed cost of $1.9 billion or 237,500,000 per mission. The first 12 Dragon Cargo missions will be for the fixed cost of $1.6 billion or 133,333,333 per mission. After these pre-contracted missions, the costs for Dragon Cargo missions will follow the model detailed in the third section above concerning research.

$E = m * Q$

The total mass transported, m, as calculated above, is 2739 kg.

$E = 2739Q$

With Q representing the cost per kilogram payload at the time.

Although the starting costs for Cygnus is higher, with the pressures of competition pushing development, we consider the likelihood of the costs for Cygnus falling to the level of Dragon Cargo by the end of 2016 very high, and thus starting from 2017 will treat the costs of transporting an equal mass of supplies on Dragon Cargo and Cygnus to be the same.

Below is a chart of the proposed resupply missions to be scheduled for each type of spacecraft over the 10 years of the plan in accordance with the conditions and conclusions formed above.

Table 4.2: Resupply Missions by Dragon and Cygnus per Year, 2012 – 2021

Year	Resupply Missions	Total
2012	1 Dragon Cargo, 2 Cygnus	3
2013	1 Dragon Cargo, 2 Cygnus	3
2014	1 Dragon Cargo, 2 Cygnus	3
2015	1 Dragon Cargo, 2 Cygnus	3
2016	1 Dragon Cargo, 2 Cygnus	3
2017	2 Dragon Cargo, 1 Cygnus	3
2018	2 Dragon Cargo, 1 Cygnus	3
2019	2 Dragon Cargo, 1 Cygnus	3
2020	1 Dragon Cargo, 1 Cygnus, 1 X missions	3
2021	1 Dragon Cargo, 1 Cygnus, 1 X missions	3

As can be seen, from 2017 the recommended breakdown of missions between Dragon Cargo and Cygnus changes after the contracted 8 Cygnus flights are fulfilled, but 7 pre-contracted Dragon Cargo flights remain. The plan recommends that NASA maintain one yearly usage of both companies – though from 2017 to 2019 still aiming to fulfill the SpaceX contract – in the interest of both security, and preventing a monopoly of the budding industry. Once these considerations are satisfied, however, NASA should proportion the remaining missions at their discretion according to the situation at the time, whether granting them to Orbital, SpaceX, or a separate developer.

Returning to the cost of the missions, starting from 2017 the cost of all Cygnus missions will be calculated according to the weight of the supplies, as will all Dragon Cargo missions beginning 2021, though unspecified missions with new developers in 2020 and 2021 may be under contract.

Proposed Solution

Overview

Our plan for maintaining the International Space Station from 2012 until 2021 is a four-pronged approach, including personnel, operation, research, and resupply. The solution below includes a flight schedule for all manned and unmanned flights suggested based on ISS flight schedules for 2012, as well as equations to model the total cost of the operations.

Personnel

From 2012 to 2021, the most cost effective method of transporting astronauts to the ISS would be for NASA to continue transporting them via the Russian Soyuz spacecrafts. This will cost $62.75 million per crewmember, and since 4 US crewmembers are sent to the ISS per year, this will cost a total of $251 million per year, or a total of $2.51 billion over the ten-year period.

The average salary of an astronaut ($82,920) multiplied by the number of astronauts involved with the ISS (64) gives the cost of paying the astronauts per year: $5,306,880. Over the ten-year period, this will amount to a total of around $53 million per year.

Lastly, the cost of maintaining the ISS ground crew is best modeled by the following equation:

$G = 90.65t\text{-}180000$

Ground operation costs will range from $840.6 million in 2012 to $1.8 billion in 2021, with a total of $14 billion over the ten-year period.

In total, personnel costs will cost $16.6 billion over the ten-year period.

Operation

Operation includes 2 major parts: operation & maintenance costs and equipment failure costs. Based on extrapolations from NASA's original projected data on the ISS's operation and maintenance costs, NASA should use the following equation to project its change in operation and maintenance costs from 2012 to 2021.

$M = 49.41t - 98000$

The cost for accidents was neglected because there was insufficient data on costs for specific accidents and the concept of predicting accidents itself is implausible.

The total cost over the 10 years for operation will be determined by the total sum of each operation cost from 2012 to 2021. The total cost is \$15.87165 billion.

Research

Calculating the precise cost of how much it will cost to transport as yet undetermined research equipment is difficult, so the equation for projected change in cost per kilogram for Dragon spacecraft over time is instead developed:

$$Q = \begin{cases} -46.226t^2 + 184980.63t - 185047469.071 & 2012 \le x < 2014 \\ 1102 & 2014 \le x < 2022 \end{cases}$$

When in 2014 the predicted cost per kilogram of the Dragon reaches \$1102 per kilogram, the price is estimated to remain at that price.

To determine the total cost of a mass of research equipment and personnel:

$E = m * Q$

The estimated research costs taken from NASA budgetary projections was used to model an equation for research expenses from 2017 through to 2021. These costs include funding CASIS and NASA's own research in the remaining ISS facilities:

$R = 4.390t - 8661$

The combined cost related to research:

$Z = mQ + 4.390t - 8661$

Resupply

In order for the ISS to be adequately supplied, NASA needs to resupply the ISS through unmanned commercial spacecrafts - currently either Cygnus or Dragon - 3 times a year, each time carrying 1698 kg of supplies and a total cargo of 2739 kg.

From there, this chart of resupply missions by year was formulated according to contractual obligations, as well as concerns of security and the development of the market:

Table 4.2: Resupply Missions by Dragon and Cygnus per Year, 2012 – 2021

Year	Resupply Missions	Total
2012	1 Dragon Cargo, 2 Cygnus	3
2013	1 Dragon Cargo, 2 Cygnus	3
2014	1 Dragon Cargo, 2 Cygnus	3
2015	1 Dragon Cargo, 2 Cygnus	3
2016	1 Dragon Cargo, 2 Cygnus	3
2017	2 Dragon Cargo, 1 Cygnus	3
2018	2 Dragon Cargo, 1 Cygnus	3
2019	2 Dragon Cargo, 1 Cygnus	3
2020	1 Dragon Cargo, 1 Cygnus, 1 X missions	3
2021	1 Dragon Cargo, 1 Cygnus, 1 X missions	3

Flight Schedule: Crew

Flight Schedule 2012

Date: March
Mission: Expedition 31/32
Launch Vehicle: Soyuz
Launch Site: Baikonur Cosmodrome, Kazakhstan

Date: May
Mission: Expedition 32/33
Launch Vehicle: Soyuz
Launch Site: Baikonur Cosmodrome, Kazakhstan

Date: October
Mission: Expedition 33/34
Launch Vehicle: Soyuz
Launch Site: Baikonur Cosmodrome, Kazakhstan

Date: November
Mission: Expedition 34/35
Launch Vehicle: Soyuz
Launch Site: Baikonur Cosmodrome, Kazakhstan

Note: the Soyuz missions will take off in the same months every year for the duration of the ten-year plan, so the launch schedule is the same for all years.

Flight Schedule: Resupply

Date: April
Mission: Resupply

Launch Vehicle: Dragon **Launch Site:** Cape Canaveral, USA
Date: July **Mission:** Resupply **Launch Vehicle:** Cygnus **Launch Site:** Mid-Atlantic Regional Spaceport, USA
Date: December **Mission:** Resupply **Launch Vehicle:** Cygnus **Launch Site:** Mid-Atlantic Regional Spaceport, USA

Note: The supply spacecraft will take off in the same months every year for the duration of the ten-year plan, so the launch schedule is the same for all years, excepting the launch sites and launch vehicle.

Strengths & Weaknesses

One of the strengths of our model is that it is much of it is based on and extrapolated from primary source data published by NASA. All of the figures that we worked with came from sources such as NASA's 2010 Budget Report and reports from NASA's plan of projected growth. We conducted in-depth research and gathered a large amount of information on NASA's existing flight schedules, its relationship with private companies, its relationship with other countries, its costs for certain practices etc. All of our extrapolations and equations were based on at least one of these legitimate sources.

Another strength of our model is that it we considered many factors. Our model was divided into four parts – personnel, resupply, operation, and research – and each part had sub-parts within them. We considered everything from the salaries of the astronauts and the ground operations crew to the weight capacities of the different commercial orbital transportation services to the maintenance costs of the ISS. Having all of these factors greatly contributes to the accuracy of the model.

One of the main weaknesses of our model is the lack of data of commercial orbital transportation services. The information regarding the different commercial orbital transportation services, such as Dragon, Cygnus, and Progress was very limited. This was partially due to the fact that many of these commercial orbital transportation services are still in development.

Another weakness of our model is that we extrapolated from projected data. Much of the data that we worked with were projected costs of the next 5 years. We used these extrapolations to extrapolate for the next 10 years, thus our model could be subject to

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