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MODEL OF MEDICAL SUPPLY DEMAND AND ASTRONAUT HEALTH
FOR LONG-DURATION HUMAN SPACE FLIGHT

by

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Abstract

The medical care of space crews is the primary limiting factor in the achievement of long-duration
space missions. (Nicogossian 2003) The goal of this thesis was to develop a model of long-
duration human space flight astronaut health and a medical supply demand model in support of
such missions. This model will be integrated into an existing comprehensive interplanetary supply
chain management and logistics architecture simulation and optimization tool, SpaceNet.

The model provides two outputs, Alpha, and Mass, for each set of input variables. Alpha is
an estimate of crew health and is displayed as a percentage. Mass is a measure of medical
consumables expended during the mission and is displayed in kilograms.

We have demonstrated that Alpha is a function of three scaling parameters, the type of mission,
duration of mission, and gender of crew. The type of mission and gender are linked to radiation
fatality data published by NASA and mission duration correlates to predicted incidence of illness
and injury and linked to the model through published US Navy submarine crew medical data.

The mass of medical consumables (MMC) expended increases with the number of crew, the
duration of the mission and the distance of the mission away from the earth. The degree of
medical expertise on-board is not necessarily related to a change in consumption of medical
supplies but perhaps to a better outcome for the individual infirmed crew member. We have
determined that there is no information to incorporate gender into this aspect of the model and
that the ages of the crew members would also have a negligible effect.

Risk was investigated as an additional independent driver in the calculations. This parameter
defined as likelihood of a medical event multiplied by impact to the mission, is in line with current
NASA planning processes. Although the equations don't currently incorporate this parameter,
implementation in subsequent versions of the model would allow for a more granular description
of medical supply mass (i.e. laboratory and diagnostic, imaging, medications, surgical supplies,
telemedicine and expert systems equipment) needed to support long-duration human operations
in space. The framework of SpaceNet does not currently allow for this level of detail but future
version of the software would likely develop and integrate this capability.

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Title: Associate Professor of Aeronautics and Astronautics and of Engineering Systems
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1. Introduction

Importance of crew health and medical supply in space exploration

The rocket science will be the easy part. (Groopman 2000) There are plans in development to send astronauts on long duration space missions to the Moon and eventually to Mars. Planning a safe and productive exploration mission involves needs a dual approach addressing both the vehicle and the crew health. Although the engineering aspects of the vehicle, propulsion, navigation, and communications have been demonstrated with several successful robotic missions, adding humans on these missions adds complexity. The medical care of space crews is the primary limiting factor in the achievement of long-duration space missions. (Nicogossian 2003)

The space environment produces profound changes in the physiology of humans. Astronauts must be prepared to treat accidents and illnesses while they are millions of miles away from the earth. Medical contingencies will occur. In 1997 teams from NASA and NSBRI reviewed the experiences of the two-hundred and seventy-nine men and women who had participated in space missions between 1988 and 1995. They discovered that all but three of them suffered some sort of illness during the trip. (Groopman 2000) An ad hoc committee of the Space Medical Association and the Society of NASA Flight Surgeons reported that morbidity and mortality related to illness and injury have accounted for more failures and delays in the execution of missions than have defective transportation systems. (Ad Hoc Committee 2008)

Although there are many unknowns, there are three areas of special concern; 1 the effects of being exposed to large amounts of space radiation, 2 bone and muscle loss, and the 3 psychological aspects of confinement and isolation. In animal model experiments where rodents were exposed to high energy particles similar to what astronauts would be exposed to on a long duration space mission there were both behavioral changes and the rodent’s brains appeared to have microscopic lesions as if they had been hit with gunfire. (Groopman 2008) The risk of bone fracture on a three-year mission is estimated to be 20-30%. (Groopman 2008)
On such isolated and long-duration missions, there may be difficult choices for the crew to make. Given the finite amounts of resources a commander may have to decide when to offer continued support and when to let an ill or injured astronaut die. (Groopman 2008) Although NASA does not have a policy on this event it does mention the possibility if continued treatment causes undue risk or peril to the remaining crew. (NASA STD- 3001, 2007)

Crew health will require operational planning and appropriate medical supply chain management. The development and execution of long duration human space flight missions will stretch the capabilities of NASA operational planners. (Luciani 1986 AIAA 2337) Although there are a vast number of scientific principles and techniques that have been developed to improve the effectiveness and efficiency of supply chain management on Earth, the potential benefits of this body-of-knowledge are currently only poorly understood in the context of space exploration. Previous space exploration has relied on a combination of carry-along and scheduled resupply. But unlike Gemini, Mercury, Apollo, and Shuttle era exploration programs, future long-duration and long-distance exploration class missions will need to rely on a complex supply network on the ground and in space. This supply chain management may even incorporate prepositioning and utilization of locally available resources.

The goal of this research was to develop a model of long duration human spaceflight astronaut health and medical supply demand requirements.

**Human Experience in Space**

The human experience in space is the work and achievement of many nations. The U.S., Russia, and China have flown humans in space and returned them to Earth. The work of state sponsored programs is also being augmented with private organizations. Scaled Composites a company located in Mojave, California was the first private corporation to design, build, and fly humans into space and return them safely to earth. Other companies are in the planning stages for developing similar capabilities.
Human spaceflight is defined as spaceflight with a human crew and possibly passengers. This makes it unlike robotic space probes or remotely-controlled satellites.

The first human spaceflight was occurred on April 12, 1961, when the former Soviet Union launched cosmonaut Yuri Gagarin aboard the Vostok 1 spacecraft and he made one orbit around the Earth. Valentina Tereshkova became the first woman in space on June 16, 1963. Alexei Leonov made the first spacewalk on March 8, 1965. Svetlana Savitskaya became the first woman to perform a spacewalk on July 25, 1984.

The United States became the second nation to achieve manned spaceflight with the suborbital flight of astronaut Alan Shepard aboard Freedom 7, as part of Project Mercury. The spacecraft was launched on May 5, 1961 on a Redstone rocket. The first U.S. orbital flight was that of John Glenn aboard Friendship 7, which was launched February 20, 1962 on an Atlas rocket. Sally Ride became the first American woman in space in 1983. Eileen Collins was the first female Shuttle pilot, and with Shuttle mission STS-93 in July of 1999 she became the first woman to command a U.S. spacecraft.

The People's Republic of China became the third nation to achieve human spaceflight when astronaut Yang Liwei launched into space on a Chinese-made vehicle, the Shenzhou 5, on October 15, 2003. Previous European and Japanese manned programs were abandoned after years of development. In 1989, Iraq declared its intent to develop manned space facilities, but these plans were soon abandoned. (Wikipedia, Spaceflight, 2007)

The furthest destination for a human spaceflight has been the Moon. The only missions to the Moon have been those conducted by the United States as part of the Apollo program. The first such mission, Apollo 8, orbited the Moon but did not land. The first Moon landing was Apollo 11, on July 20, 1969 during which Neil Armstrong became the first human to set foot on the Moon. Five additional missions landed in total, numbered Apollo 11, 12, 14, 15, 16, and 17. Twelve men reached the Moon's surface and continue to be the only humans to have been on an extraterrestrial body. The Soviet Union discontinued its program for lunar orbiting and landing of human spaceflight missions on June 24, 1974.
The longest human spaceflight of 437 days is that of Valeriy Polyakov from January 8, 1994 until March 22, 1995. Sergei Krikalyov spent the most total time of anyone in space, 803 days, 9 hours, and 39 seconds.

As of 2007, citizens from 33 nations (including space tourists) have flown in space aboard Soviet, American, Russian, and Chinese spacecraft. (Barratt 2008)

Medical Events in Spaceflight

There are sparse published accounts of medical events that have occurred in spaceflight. This may partially be attributed to astronauts being reluctant to talk about medical ailments and NASA is equally reluctant to publish them. Astronauts are concerned about speaking about medical ailments for fear of losing flight status. From the sparse information published we have the following information summarized in figures.

1. Anorexia (loss of appetite)
2. Space motion sickness
3. Fatigue
4. Insomnia
5. Dehydration
6. Dermatitis (skin inflammation)
7. Back pain
8. Upper respiratory infection
9. Conjunctival irritation (eye irritation)
10. Subungual hemorrhage (bruises under fingernails suit gloves)
11. Urinary tract infection
12. Cardiac arrhythmia (abnormal heart beat)
13. Headache
14. Muscle strain
15. Diarrhea
16. Constipation
17. Barotitis (ear problems from atmospheric pressure difference)
18. Bends (decompression-caused limb pains)
19. Chemicals pneumonitis (lung inflammation from EVA)

Figure 1. Medical Problems most encountered in-flight (from the most frequent to the least frequent) (adapted from Fundamentals of Space Medicine, Davis 2008)
<table>
<thead>
<tr>
<th>Condition</th>
<th>Frequency</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facial fullness</td>
<td>226</td>
<td>81.00%</td>
</tr>
<tr>
<td>Headache</td>
<td>212</td>
<td>76.00%</td>
</tr>
<tr>
<td>Sinus congestion</td>
<td>173</td>
<td>62.00%</td>
</tr>
<tr>
<td>Dry skin, irritation, rash</td>
<td>110</td>
<td>39.40%</td>
</tr>
<tr>
<td>Eye irritation, dryness, redness</td>
<td>64</td>
<td>22.90%</td>
</tr>
<tr>
<td>Foreign body in eye</td>
<td>56</td>
<td>20.10%</td>
</tr>
<tr>
<td>Sneezing/coughing</td>
<td>31</td>
<td>11.10%</td>
</tr>
<tr>
<td>Sensory changes (e.g., tingly, numbness)</td>
<td>26</td>
<td>9.30%</td>
</tr>
<tr>
<td>URI (common cold, sore throat, hay fever)</td>
<td>24</td>
<td>8.60%</td>
</tr>
<tr>
<td>Back muscle pain</td>
<td>21</td>
<td>7.50%</td>
</tr>
<tr>
<td>Leg/foot muscle pain</td>
<td>21</td>
<td>7.50%</td>
</tr>
<tr>
<td>Cuts</td>
<td>19</td>
<td>6.80%</td>
</tr>
<tr>
<td>Shoulder/trunk muscle pain</td>
<td>18</td>
<td>6.50%</td>
</tr>
<tr>
<td>Hand/arm muscle pain</td>
<td>15</td>
<td>5.40%</td>
</tr>
<tr>
<td>Anxiety/annoyance</td>
<td>10</td>
<td>3.60%</td>
</tr>
<tr>
<td>Contusions</td>
<td>10</td>
<td>3.60%</td>
</tr>
<tr>
<td>Ear problems (predominantly earaches)</td>
<td>8</td>
<td>2.90%</td>
</tr>
<tr>
<td>Neck muscle pain</td>
<td>8</td>
<td>2.90%</td>
</tr>
<tr>
<td>Stress/tension</td>
<td>8</td>
<td>2.90%</td>
</tr>
<tr>
<td>Muscle cramp</td>
<td>7</td>
<td>2.50%</td>
</tr>
<tr>
<td>Abrasions</td>
<td>6</td>
<td>2.20%</td>
</tr>
<tr>
<td>Fever, chills</td>
<td>6</td>
<td>2.20%</td>
</tr>
<tr>
<td>Nosebleed</td>
<td>6</td>
<td>2.20%</td>
</tr>
<tr>
<td>Psoriasis, folliculitis, seborrhea</td>
<td>6</td>
<td>2.20%</td>
</tr>
<tr>
<td>Low heart rate</td>
<td>5</td>
<td>1.80%</td>
</tr>
<tr>
<td>Myoclonic jerks (associated with sleep)</td>
<td>5</td>
<td>1.80%</td>
</tr>
<tr>
<td>General muscle pain, fatigue</td>
<td>4</td>
<td>1.40%</td>
</tr>
<tr>
<td>Subconjunctival hemorrhage</td>
<td>4</td>
<td>1.40%</td>
</tr>
<tr>
<td>Allergic reaction</td>
<td>3</td>
<td>1.10%</td>
</tr>
<tr>
<td>Fungal infection</td>
<td>3</td>
<td>1.10%</td>
</tr>
<tr>
<td>Hoarseness</td>
<td>3</td>
<td>1.10%</td>
</tr>
<tr>
<td>Concentrated or &quot;dark&quot; urine</td>
<td>2</td>
<td>0.70%</td>
</tr>
<tr>
<td>Decreased concentration</td>
<td>2</td>
<td>0.70%</td>
</tr>
<tr>
<td>Dehydration</td>
<td>2</td>
<td>0.70%</td>
</tr>
<tr>
<td>Inhalation of foreign body</td>
<td>2</td>
<td>0.70%</td>
</tr>
<tr>
<td>Subcutaneous skin infection</td>
<td>2</td>
<td>0.70%</td>
</tr>
<tr>
<td>Chemical in eye (buffer solution)</td>
<td>1</td>
<td>0.40%</td>
</tr>
<tr>
<td>Mood elevation</td>
<td>1</td>
<td>0.40%</td>
</tr>
<tr>
<td>Phlebitis</td>
<td>1</td>
<td>0.40%</td>
</tr>
<tr>
<td>Viral gastrointestinal disease</td>
<td>1</td>
<td>0.40%</td>
</tr>
</tbody>
</table>

Figure 2 Medical events of the Space Shuttle Program reported by frequency from post flight medical debriefings with crewmembers. 1988-1995 (adapted from Fundamentals of Space Medicine, Davis 2008)
<table>
<thead>
<tr>
<th>Medical Event</th>
<th>Initial Events (n=169)</th>
<th>Recurrences (n=135)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial injury</td>
<td>34</td>
<td>2</td>
</tr>
<tr>
<td>Arrhythmia/conduction disorder</td>
<td>30</td>
<td>98</td>
</tr>
<tr>
<td>Musculoskeletal</td>
<td>29</td>
<td>NR</td>
</tr>
<tr>
<td>Headache</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Sleeplessness</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Tiredness</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Conjunctivitis</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Contact dermatitis</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Erythema of face, hands</td>
<td>4</td>
<td>NR</td>
</tr>
<tr>
<td>Stool contents (preflight)</td>
<td>4</td>
<td>NR</td>
</tr>
<tr>
<td>Acute respiratory infection</td>
<td>3</td>
<td>NR</td>
</tr>
<tr>
<td>Asthenia</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Surface burn, hands</td>
<td>3</td>
<td>NR</td>
</tr>
<tr>
<td>Dry nasal mucous</td>
<td>2</td>
<td>NR</td>
</tr>
<tr>
<td>Glossitis</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Heartburn/gas</td>
<td>2</td>
<td>NR</td>
</tr>
<tr>
<td>Foreign body in eye</td>
<td>2</td>
<td>NR</td>
</tr>
<tr>
<td>Constipation</td>
<td>1</td>
<td>NR</td>
</tr>
<tr>
<td>Contusion of eyeball</td>
<td>1</td>
<td>NR</td>
</tr>
<tr>
<td>Dental caries</td>
<td>1</td>
<td>NR</td>
</tr>
<tr>
<td>Dry skin</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Hematoma</td>
<td>1</td>
<td>NR</td>
</tr>
<tr>
<td>Laryngitis</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Wax in ear</td>
<td>1</td>
<td>NR</td>
</tr>
</tbody>
</table>

Figure 3 In-flight medical events for cosmonauts in the Mir program (adapted from Fundamentals of Space Medicine, Davis 2008)

A variety of medical events have occurred in both the recent US and Russian space programs as listed in Figures 2 and 3. The majority of these medical events have been minor and well within the medical capability of the crew medical officers on board and within the level of medical capability of the supplies and equipment on board and the skill levels of the flight surgeons on the ground providing telemedicine support. (Baisden 1999)

**Human Experience in Analog Environments**

As an additional guide for predicting both frequency of medical events and medical supply needs for the isolated and extreme environment of space we looked at medical care delivery in space analog environments, which included nuclear submarines, Antarctic research stations, and polar expeditions.
These analogs involve small groups living and working in isolation. These analogs are helpful also to characterize and quantify the incidence and prevalence of injury and illness. From these environments, extrapolation can be made and procedural guidelines for lunar and planetary expeditions and voyages can be delineated. (Stuster 2005)

**Medical Events in Analog Environments**

*Antarctica*

Medical events that occurred during various studies of personnel in Antarctica are listed in Figure 4. Events are listed in by organ system rather then specific diagnosis. This type of listing will be discussed later in this thesis and was helpful in linking multiple sources of information to the model equations. In addition to he cases of illnesses listed there is a category of poorly defined symptoms. Symptoms that are very common in the South Pole include 1. insomnia, 2. irritability, 3. headache, 4. nightmares, 5. anxiety, 6. mild depression, 7. boredom, 8. fatigue, 9. decline in personal hygiene, 10. reduced motivation combined with impaired concentration, memory, and alertness, 11. increased appetite with weight gain, 12. digestive ailments, 13. rheumatic aches and pains, and 14. increased sensitivity to physical and social stimuli.

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of Cases</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injury and poisoning</td>
<td>3910</td>
<td>42.00%</td>
</tr>
<tr>
<td>Respiratory system</td>
<td>910</td>
<td>9.70%</td>
</tr>
<tr>
<td>Skin and subcutaneous tissue</td>
<td>899</td>
<td>9.60%</td>
</tr>
<tr>
<td>Nervous system and sense organs</td>
<td>702</td>
<td>7.50%</td>
</tr>
<tr>
<td>Digestive system</td>
<td>691</td>
<td>7.40%</td>
</tr>
<tr>
<td>Infections and parasitic disease</td>
<td>682</td>
<td>7.30%</td>
</tr>
<tr>
<td>Muscle, bone, and connective tissue</td>
<td>667</td>
<td>7.10%</td>
</tr>
<tr>
<td>Other illness</td>
<td>335</td>
<td>3.60%</td>
</tr>
<tr>
<td>Mental disorders</td>
<td>217</td>
<td>2.30%</td>
</tr>
</tbody>
</table>

Figure 4. Illness and injury in Antarctica (adapted from Fundamentals of Space Medicine, Davis 2008)
Antarctic Anecdotes

Dr. Jerri Nielsen the sole physician of a 50 member scientific team at an Antarctic research station became seriously ill. Medical supplies were airlifted and parachuted down to her so that she could perform her own biopsy and determine if the lump that she felt in her breast was cancer. Total darkness and extreme cold made landings usually impossible that time of the year. Dr. Nielsen successfully performed her own breast lumpectomy. (New York Times April 13, 2001)

Dr. Leonid Rogozov's had to remove his own appendix, while spending winter at Novolazarevskaya research station in Antarctica on April 30, 1961. Since the incident, that station is always staffed with two doctors. (Information Bulletin of the Soviet Antarctic Expedition)

Submarine

Submarine and spacecraft environments are similar. Both involve isolation, a closed environment with artificial atmosphere, crowded quarters for living and working, limited space for supplies and medical equipment, the occasional use of non-physician health care providers, use of pre-mission health screenings, and the emphasis of mission goals over individual needs. (Thomas 2003) Some potential differences may appear because of the lack of gravity in the space environment. This is a major physiologic stressor in space and will also be discussed later in this thesis.

During the submarine missions, potential mission impacting events were rare. In a study of 1389 officers and 11,952 enlisted crewmembers, served about participating submarines for 215,086 and 1,955,521 person-days at sea respectively during their study period. Among a crew of seven officers, only one medical event would be expected to occur during a 6 month mission and result in ¾ day or less of limited or no duty. Among a crew of enlisted men, about 2 medical events would be expected during a 6 month mission and result in about 1 day of limited or no duty per medical event. (Thomas 2003)
The following table shows NASA’s view of mission risk in relation to the data in the submarine environments. (Thomas 2003) This perception of risk is from the differences in the environment.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental Disorders</td>
<td>2</td>
<td>9</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Sensory</td>
<td>6</td>
<td>5</td>
<td>5-6</td>
<td>6</td>
</tr>
<tr>
<td>Circulatory</td>
<td>9</td>
<td>7</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Respiratory</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Gastrointestinal</td>
<td>8</td>
<td>6</td>
<td>5-6</td>
<td>3</td>
</tr>
<tr>
<td>Genitourinary</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Skin</td>
<td>1</td>
<td>4</td>
<td>3-4</td>
<td>4</td>
</tr>
<tr>
<td>Musculoskeletal</td>
<td>5</td>
<td>3</td>
<td>3-4</td>
<td></td>
</tr>
<tr>
<td>Injury / poisoning</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 5. Comparison of perception of medical risk of space flight for astronauts

82% of submariners had medical complaints (Horn 2003). Most common of these were runny nose, difficulty sleeping, and backache. Despite the availability of medical care, self medication and treatment was common. The authors state that planning for medical care in isolated environments should include consideration of unreported minor medical problems and self-treatment patterns. This underreporting is a major factor among space crews.

**Telemedicine and Presence of Medical expertise**

Telemedicine is a well-developed tool for medical practice whereby telecommunication is used to support health care delivery at a distance. (Merrill 2005) Monitoring and telemedicine support has proven beneficial in remote environments and has also proven its value in space medicine. The delivery of medical care in space at distances of potentially millions of miles will require these tools and principles. (Cermack 2006)

The application of telemedicine to space exploration was driven by necessity. This has often been the only way for space crews to obtain medical care in space. (Barratt 2008)
Time to definitive treatment may vary from between hours in orbital space flight, days for a remote exploratory camp, weeks for polar bases and months to years for interplanetary exploration. Interplanetary flight will make communication with terrestrial support personnel much more difficult than in orbital flight and will require the development of a specialized systems and perhaps the combination of expert systems to increase independence.

The presence of medical expertise may reduce the requirements to carry supplies and reduce the frequency of resupply. NASA has put together a blue print for space medicine providers. The agency has looked at the skills and training requirements for medical officers onboard exploratory class space vehicles. With the longest exploration missions requiring the presence of a surgeon. The skills and training of the CMO (crew medical officer) will require breadth and depth, producing a highly qualified physician for space medical care delivery. (McSwain 2004) An on-board medical crew member will be essential for exploration class missions and two may be necessary in case one medical officer is infirmed or incapacitated. (Doarn 1998, Grigoriev, 2002m and Zuzek 1994)

Available Medical Capability and Facilities in Space

As distance from earth increases there is a need to increased independence and increased capabilities and autonomy. (Hamilton 2007) Since the time required to return an ill or injured crew member to Earth to obtain definitive medical care is prohibitive, future exploration-class missions to the moon or Mars will require sophisticated and complete on-board medical care capabilities and facilities.

At the height of budgeting and planning a fully equipped Health Maintenance Facility (HMF) was planned for the international space station. (Grams 1990) The facility was sophisticated and complete with x-ray equipment and enough supplies to perform surgery and address trauma. (Billica 1991) Due to space station Freedom cost over runs the plans for this facility were canceled.
Plans for on-board medical equipment and resources are currently in flux with changing national and international goals. However, this capability is needed to accomplish any planned exploration missions with success.

**Logistics**

Supply chain management as applied to terrestrial applications is a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system wide costs while satisfying service level requirements (Simchi-Levi). Optimization of supply chains and logistics architectures have been the focus of global industry to increase efficiency and reduce operating costs.

There are a vast number of scientific principles and techniques that have been developed since to improve the effectiveness and efficiency of supply chain management (SCM) on Earth, however, the potential benefits of this body-of-knowledge are currently not well understood in the context of space exploration.

Logistics and supply chain management is a key piece of the exploration picture for NASA. (Galluzzi 2006) Sustainable long-duration space exploration is impossible without appropriate supply chain management. Unlike Gemini, Mercury, Apollo, and Shuttle era exploration programs, future exploration will have to rely on a complex supply network on the ground and in space. This method of supply can be done in three ways: (i) pre-deployment, (ii) carry-along with the crew (iii) scheduled or on-demand resupply.

Lessons can be learned from terrestrial supply logistics and analog environment logistics such as submarines and supplying remote and austere environments such as Antarctica. Submarines pose interesting logistics issues. Submarines are supplied when they are in port and can in extreme situations surface and be supplied by surface vessels or initiate a medical evacuation. This resurfacing although analogous to a return to earth from low earth orbit would not be possible in a distant space mission.
Antarctic environments also teach lessons to logistics planners. There are limits to what and when can be delivered because of operational capabilities.

Up until now, with the farthest mission being the moon and the longest duration stay being on Mir. Medical supply logistics has been limited to what a crew carried with them and what has been pre-supplied to the shuttle or space station. In low earth orbit there is a capability to intermittently replenish stores and consumables with supply ships.

**SpaceNet Modeling Framework**

The SpaceNet software is a simulation and optimization tool that captures the concepts and ideas related to interplanetary supply chain management and logistics architectures. SpaceNet is useful to logisticians, mission architects. The software models interplanetary space logistics as a network, allowing the user to input scenarios, simulate them, and generate measures of effectiveness. Optimization can be used to find the best logistics network for a given set of surface missions, and trade studies can be carried out to evaluate various types of logistics architectures for comparison.

SpaceNet unitizes Building Blocks of Nodes, Supplies, elements, and Network, Orbit Dynamics, and processes (i.e. waiting, transporting, or transferring) and discrete event simulation at the individual mission level (i.e. sortie, resupply) and at the campaign level (i.e. for a set of missions). It provides visualization of the flow of elements and supply items through the interplanetary supply chain and functions as a tool to evaluate manually generated exploration scenarios with respect to measures of effectiveness and feasibility.

**Medical Supply Model**

The primary goal of this thesis was to develop a model of long duration human space flight astronaut health and a medical supply demand model for such missions. This tool will be integrated with the already existing comprehensive space SCM framework, SpaceNet. Future work will incorporate this additional class of supply into SpaceNet.
SpaceNet current classes of supply as well as the addition of medical supply are listed graphically in appendix A.

These goals and deliverables of this thesis are consistent with the new mandate of the Exploration Mission Systems Directorate (EMSD) which are to develop a capability and supporting research to enable sustained and affordable human space exploration and to ensure the health and safety of crew during long-duration space flight. ESMD partially sponsored this research.
2. Classification of Disease

An organ system approach was chosen to classify and categorize medical disorders. This classification facilitated the link from all the published sources of medical event and risk data in the creation of the model. The published event data includes US Navy submarine, US Navy pilot, Antarctic winter-over, US astronauts, and Soviet inflight data.

The International Statistical Classification of Diseases and Related Health Problems (most commonly known by the abbreviation ICD) was chosen. The ICD provides codes to classify diseases and a wide variety of signs, symptoms, abnormal findings, complaints, social circumstances and external causes of injury or disease. Every health condition is assigned to a unique category and given a numeric code. (Wikipedia 2008)

<table>
<thead>
<tr>
<th>ICD-9 Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>001-139: Infectious and parasitic diseases</td>
</tr>
<tr>
<td>140-239: Neoplasms</td>
</tr>
<tr>
<td>240-279: Endocrine, nutritional and metabolic diseases, and immunity disorders</td>
</tr>
<tr>
<td>280-289: Diseases of the blood and blood-forming organs</td>
</tr>
<tr>
<td>290-319: Mental disorders</td>
</tr>
<tr>
<td>320-359: Diseases of the nervous system</td>
</tr>
<tr>
<td>360-389: Diseases of the sense organs</td>
</tr>
<tr>
<td>390-459: Diseases of the circulatory system</td>
</tr>
<tr>
<td>460-519: Diseases of the respiratory system</td>
</tr>
<tr>
<td>520-579: Diseases of the digestive system</td>
</tr>
<tr>
<td>580-629: Diseases of the genitourinary system</td>
</tr>
<tr>
<td>630-676: Complications of pregnancy, childbirth, and the puerperium</td>
</tr>
<tr>
<td>680-709: Diseases of the skin and subcutaneous tissue</td>
</tr>
<tr>
<td>710-739: Diseases of the musculoskeletal system and connective tissue</td>
</tr>
<tr>
<td>740-759: Congenital anomalies</td>
</tr>
<tr>
<td>760-779: Certain conditions originating in the perinatal period</td>
</tr>
<tr>
<td>780-799: Symptoms, signs, and ill-defined conditions</td>
</tr>
<tr>
<td>800-999: Injury and poisoning</td>
</tr>
</tbody>
</table>

Figure 6. ICD-9 codes and their description

The ICD is published by the World Health Organization. The ICD is used world-wide for morbidity and mortality statistics, reimbursement systems and automated decision
support in medicine. This system is designed to promote international comparability in the collection, processing, classification, and presentation of these statistics. (Wikipedia 2008)
3. Model Framework

Two factors were modeled, \( \text{Alpha} \), an estimate of crew health and availability and \( \text{MMC} \) a calculation of the mass of medical consumables.

Assumptions and Justifications

To make the model reliable and accurate, each assumption was based on data and learnings obtained from peer reviewed and published literature. The health and medical supply needs of crews performing missions to remote and austere environments were available for US Navy submarine, US Navy pilot, Antarctic winter-over, US astronauts, and Soviet inflight data.

When available, US astronaut in-flight data from NASA was incorporated over analog environment data. When only analog data was available (i.e. submarine and Antarctic data), submarine data was selected over Antarctic data.

Submarine medical data was chosen to model the space environment since this is more analogous to the crews performing in flight space duties and are similarly medically preselected. Both of these working environments involve isolation, a closed environment with artificial atmosphere, crowded quarters for living and working, limited space for supplies and medical equipment, the occasional use of non-physician health care providers, use of pre-mission health screenings, and the emphasis of mission goals over individual needs. (Thomas 2003) The submarine data different from space environment in that the space environment is much more harsh on human physiology with microgravity, the age and educational status of crews, the ability to communicate outside of the vessel, the size of the crew is much smaller, and the role of the medical providers. In the space environment medical care is provided by a ground based NASA flight surgeons through teleconference and consultation, while on a submarine medical care is dispensed on board the vessel. (Thomas 2003) Data on Officers was chosen over data on enlisted personnel since the health profile of astronauts more similar to Naval Officer than Naval enlisted personnel.
To simplify the model the assumptions was made that there were no reduction in adverse events of the microgravity environment for a lunar gravity of 16% or a Martian gravity of 38% for time spend on those environments during the execution of a mission. This assumption was taken for a lack of data to base a reduction in adverse events on the presence of partial gravity. Assuming this worst case scenario that partial gravity would in no way ameliorate the adverse physiologic effects would in effect increase our estimates for medical interventions and will in the long run result in a more conservative model.

The model does not address countermeasures, just medical intervention.

**Alpha**

Crew health was investigated to determine if there was a relationship between the duration of the expedition, exposure to space radiation and whether there was any impact from the performance of extravehicular activity (EVA) effect. After extensive research, there is no data available at present to assess the health effects of the performance of extravehicular activity on the crew. There did appear to be a positive correlation between the duration of the mission and number of illnesses and injury. This makes sense in that the longer a mission the more likely an illness or injury would occur. This was modeled from published US submarine crew data. (Thomas 2003)

Although, astronauts participating in spaceflight in low earth orbit (LEO) are partly protected by the earth’s magnetic fields and the solid shielding of the planet, this protective effect was not available for missions to the moon or to Mars. Galactic cosmic radiation (GCR) and/or solar flare event (SFE) effect would impart a morbidity and mortality effect that has been modeled. (Cucinotta 2008) A mars mission that would last 3 years for the round trip an astronaut could absorb about 1 Sievert.(Cucinotta 2008) Radiation is predicted to lead to carcinogenesis and degenerative disease and in a certain portion of the spaceflight population, death.(Cucinotta 2008) The health effects can be divided into two classes (acute) and delayed. Acute – GI (diarrhea), CNS (headache and irritability), blood forming organs (decrease in white blood cells and
late - increase the rate of neoplasms and sensory deficits (cataracts) (Davis 1999).

In a recent article, the committee of the Space medical association and the society of NASA flight surgeons called space radiation the “the greatest unknown in interplanetary flight is radiation exposure.” (Ad Hoc Committee 2008)

Countermeasures such as aluminum shielding would only reduce effective GCR dose by 25% and even with more efficient polyethylene by only about 35%. Solar proton events can be protected by solar shielding. With a mission to Mars, every cell in an astronauts body would be hit with a proton or secondary electron every few days and by an High energy heavy ion every month. (Cucinotta 1998) Biological countermeasures could also include radio-protective drugs.

No human data exists on space radiation exposure so published estimates are based on experimental model systems and biophysical calculations. The model used for cancer mortality is based on studies of survivors from atom bombs.

There appears to be a gender related effect on mortality when it comes to space radiation risk. For each type of mission there is a greater number of modeled fatalities when it comes to female crew than when compared to male crew. (Cucinotta Lancet 2006)

Therefore Alphaₐ is a function of three scaling variables, 1. the type of mission whether LEO, lunar, or Martian (fatalities), 2. gender (fatalities), and 3. duration of mission (injury and illness).

**Alpha as a function of duration of mission**

Table 7 shown below lists the rates of medical events of US Navy pilots, US Navy submariners, US Navy sailors, Antarctic personnel, astronauts and cosmonauts. (Billica 1996)
For the model it was preferable not to have zero entries for any ICD codes. This would help in future coding of the software. Therefore we further adapted the proposed rates of medical events by selecting the US inflight data and replacing the zero entries in this set of data with Soviet data when available and the US submarine data when the Soviet data was unavailable. The result is shown in figure 8 below.
Figure 8. Proposed Rates of Medical Events (Adapted from Billica)

The black entries were US spaceflight data, green the Russian spaceflight data and the red, US submarine data. Therefore we have a rate of 27.76 medical events per 100 person-years.

Needed was next to determine a number of days of limited or no duty per medical event we went to the submarine data. This information was available from analog submarine data. (Thomas 2003) When a submarine crew member came into the clinic for evaluation of an illness or injury there were logged as having a recommendation of 1. Full duty – able to assume all regular duties, 2 Limited duty – able to assume some but not all of regular duties, 3. No duty – unable to assume all regular duties, 4. Other – referred for consultation. For officers on submarine missions, 214 medical events resulted in 156 days of limited or no duty 0.73 days lost/ event or 26 days/100 person-years at sea.
Because the space environment is much more severe on human physiology we increased the severity of downtime for each event by a scaling factor for space missions. (Barratt 2008) The scaling factor was incorporated to calibrate the submarine infirmed rate to the space infirmed rate. This space scaling factor was 100.

**Alpha as a function of type of mission**

Space radiation may be less of a factor for LEO missions but will be a factor for long-duration space missions to the moon and Mars. Figure 9 below demonstrates the radiation risks for men and women on missions to the moon and mars. There is a gender difference apparent.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Absorbed dose (Gy)*</th>
<th>Effective dose (Sv)</th>
<th>Fatal risk, % (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar mission (180 days)</td>
<td>0.06</td>
<td>0.17</td>
<td>0.68% (0.20 - 2.4)</td>
</tr>
<tr>
<td>Mars orbit (600 days)</td>
<td>0.37</td>
<td>1.03</td>
<td>4.0% (1.0 - 13.5)</td>
</tr>
<tr>
<td>Mars exploration (1000 days)</td>
<td>0.42</td>
<td>1.07</td>
<td>4.2% (1.3 - 13.6)</td>
</tr>
</tbody>
</table>

Figure 9. Radiation risks for men and women on missions to the moon or Mars (Cucinotta 2006)

These fatal risks were incorporated as part of the calculation of $\text{Alpha}_h$ and these calculations will be described in section 4 of the thesis.

**Mass**

The mass of medical consumables (MMC) was researched as a function of mission duration, age of crew members, crew size, distance from the earth, level of on-board medical expertise, gender of crew, and risk of mission.

After extensive research, there is no available data at present to assess the effects of gender on the expenditure of medical consumables. Risk is the product of the
The governing equations were set as follows:

\[ K_{md} \text{ mission duration scaling factor} \]
\[ K_{ac} \text{ age of crew scaling factor} \]
\[ K_{cs} \text{ crew size scaling factor} \]
\[ K_{de} \text{ distance from the earth scaling factor} \]
\[ K_{me} \text{ medical expertise scaling factor} \]

\[ (1) \text{ MMC = nominal mass for DRM * } K_{md} * K_{ac} * K_{cs} * K_{de} * K_{me} \]

**Effect of mission duration**

The rate of medical events were previously shown in figure 8. From this table it can be determined that the probability of a medical event is related to the duration of the mission. The equations that govern this parameter are:

\[ K_{md} = \text{ scaling factor related to mission duration} \]

\[ k_{md} = (0.278/200) * t \]
\[ t = \text{time in days} \]
\[ k_{md} = 1.39 \times 10^3 \times t \]

**Effect of crew Age**

To determine the effect of crew age on the mass of medical consumables we turned again to the literature. Available and reliable wad data published for submarine crews and missions and is listed in figure 10 below. (Thomas 2003)

<table>
<thead>
<tr>
<th>Category (ICD-9) Codes</th>
<th># of events</th>
<th>Rate/100 Person-Years</th>
<th># of events</th>
<th>Rate/100 Person-Years</th>
<th># of events</th>
<th>Rate/100 Person-Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infectious/Parasitic Diseases (001-139)</td>
<td>19</td>
<td>3.2</td>
<td>8</td>
<td>2.6</td>
<td>11</td>
<td>3.9</td>
</tr>
<tr>
<td>Neoplasms (200-299)</td>
<td>0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Non-Psychotic Mental Disorders (300-316)</td>
<td>0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Nervous System/Sense Organ Disorders (320-389)</td>
<td>15</td>
<td>2.6</td>
<td>6</td>
<td>2.0</td>
<td>9</td>
<td>3.2</td>
</tr>
<tr>
<td>Circulatory System Disorders (390-459)</td>
<td>8</td>
<td>1.4</td>
<td>1</td>
<td>0.3</td>
<td>7</td>
<td>2.5</td>
</tr>
<tr>
<td>Respiratory System Disorders (460-519)</td>
<td>56</td>
<td>9.5</td>
<td>30</td>
<td>9.9</td>
<td>26</td>
<td>8.2</td>
</tr>
<tr>
<td>Digestive System Disorders (520-579)</td>
<td>12</td>
<td>2.0</td>
<td>4</td>
<td>1.3</td>
<td>8</td>
<td>2.8</td>
</tr>
<tr>
<td>Genitourinary System Disorders (580-629)</td>
<td>5</td>
<td>0.8</td>
<td>1</td>
<td>0.3</td>
<td>4</td>
<td>1.4</td>
</tr>
<tr>
<td>Skin &amp; Subcutaneous Tissue Disorders (680-709)</td>
<td>18</td>
<td>3.1</td>
<td>12</td>
<td>3.9</td>
<td>6</td>
<td>2.1</td>
</tr>
<tr>
<td>Musculoskeletal System Disorders (710-739)</td>
<td>19</td>
<td>3.2</td>
<td>9</td>
<td>3.0</td>
<td>10</td>
<td>3.5</td>
</tr>
<tr>
<td>Signs, Symptoms, and Ill-Defined Conditions (780-799)</td>
<td>16</td>
<td>2.7</td>
<td>9</td>
<td>3.0</td>
<td>7</td>
<td>2.5</td>
</tr>
<tr>
<td>Injury (800-899, E800-E899)</td>
<td>33</td>
<td>5.6</td>
<td>15</td>
<td>5.0</td>
<td>18</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Figure 10. Rates of medical events showing relationship to age and duration or mission
Adapted From Thomas 2003

The data for the rates of medical events are divided into incidences in crew that are aged less than 30 and greater than 30. There are some diseased and injuries which are higher in older crew members (i.e. cardiac) and some that are higher in younger crew members (i.e. respiratory disorders). The overall difference between the groups is not clinically significant. If we include this parameter in the model we will rely exclusively on submarine data and not space data. Given these reasons, it was decided to leave this parameter out of the equations (or set to 1.0) in this generation of the software.
Effect of crew size

For each mission there will be a baseline amount of medical consumables and equipment that will be assigned to the mission. This is independent of crew size. With each increase in crew there will be a corresponding increase in the amount of medical consumables and equipment that will be needed to support the mission to successful conclusion. It was modeled that the principle of economy of scale would be evident and that there would be some flattening of the curve.

\[ K_{cs} = 1 \text{ for a crew size of 4} \]

![Graph of K factor values showing "economy of scale" relationship to crew size](image)

Effect of distance from Earth

There are published reports that describe the mass of supply dedicated to medical consumables and medical equipment is related to independence required during the mission and telemedicine limitations. The farther away from the earth the more mass and volume will be needed.
Figure 12. Mass of medical equipment dedicated to various classes of missions
(adapted from Larson 1999)

Figure 12 which is adapted from Larson, lists the mass of medical equipment dedicated to previous missions and lists estimates for a future Mars mission. Apollo 16 carried a medical kit with a mass of 7 kg. It contained a handful of drugs, a radiation dosimeter, tiny amplifiers for ground monitoring of the electrocardiogram, and a few miscellaneous supplies. The Shuttle medical kits are more sophisticated and have a mass of 15 kg and a volume of about 0.15 m³. Given the availability of a quick return to earth and the relative short duration of this mission this amount of mass is all that is needed to successfully support such missions. Despite being a much earlier mission Skylab had a CHS with a mass of 45 kg and a volume of 0.22 m³. Space Station 460kg 1.7 m³ of which 260 kg and 1.1 m³ were consumable supplies. The authors estimate that a distant mission may require from between 1000 kg equipment and 500 kg consumables with a volume 6.5 m³ to 2000 kg with 1000 kg consumables and a volume of 10 m³.

Figure 13 below are our estimates for $K_{de}$ (distance from the earth scaling factor). These were linked to similar masses of medical consumables taken in previous missions.

$$K_{de} = 1 \text{ for LEO}$$

<table>
<thead>
<tr>
<th>Distance from Earth</th>
<th>K Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO</td>
<td>1.00</td>
</tr>
<tr>
<td>Lunar</td>
<td>2.00</td>
</tr>
<tr>
<td>Mars</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Figure 13. Scaling factor for medical supply based on distance from earth
(adapted/calculated from Larson Pranke 1999)
**Effect of on board medical expertise**

Prevention, mitigation, and reduction of medical events can be accomplished with the onboard presence of medical expertise. An on-board medical crew member will be essential for exploration class missions and two may be necessary in case one medical officer is infirmed or incapacitated.

McSwain published a blueprint for space medicine providers. This work was the result of multiple working groups composed of NASA internal and external reviewers and it recommended the knowledge and skill bases needed to proved medical care for various class of mission. They recommended that the levels of providers be categorized in five levels: 1. Crew Medical Officer, 2. Flight Surgeon, 3. Astronaut-Physician, 4. Physician-Astronaut, and 5. Space Surgeon. (McSwain 2004)

Currently, a NASA trained Crew Medical Officer (CMO) would have medical training of about 45 hours. Their terrestrial analog for similar duties has about 300 hours of training. The recommendations for training included skills sets of assessment, ophthalmologic, bag-ventilator-mask (BVM) ventilation and endotracheal intubation, intravenous access, intramuscular and oral medication administration, defibrillation. This crewmember would need very limited sustainment training and some medical simulator sustainment training.

A flight surgeon would provide ground based support through telemedicine. The education would be a medical degree and sustainment of this education would be continuing medical education (CME). There would be no medical simulator training required and some maintenance of clinical patient care.

An astronaut-physician is described by the authors as astronauts who were once physicians who have given up their clinical practices and proficiency for flight proficiency. This describes the current astronauts in the corps with medical degrees. The authors propose a new type of astronaut, a physician-astronaut who would keep their clinical skills proficient, like pilots who are astronauts with their pilot training.
Another new category of space based medical provider is described as a Space Surgeon. The knowledge and skills required would be similar to a general surgeon of about 50 years ago. This person would also be knowledgeable in biomedical equipment maintenance and repair and in psychological counseling.

<table>
<thead>
<tr>
<th>Ground</th>
<th>Flight</th>
<th>Missions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Surgeon</td>
<td>Space Surgeon</td>
<td>Mars</td>
</tr>
<tr>
<td></td>
<td>Physician Astronaut</td>
<td>ISS</td>
</tr>
<tr>
<td></td>
<td>Astronaut Physician</td>
<td>Shuttle</td>
</tr>
<tr>
<td></td>
<td>Crew Medical Officer</td>
<td></td>
</tr>
</tbody>
</table>

Figure 14. Adapted from McSwain: Grand Rounds, UTMB 2004

Figure 14 describes which level of medical provider would be recommended to support which type of mission. With Flight surgeons being ground based only. The higher the level of medical expertise is recommended for exploration class missions to the moon and Mars. The figure is also in line with current standards of a CMO or an astronaut physician being assigned to shuttle class flights.

From these descriptions and from speaking with current NASA physicians and the lead author on this work, we developed a scaling factors related to the on board medical expertise and this is provided in Figure 15. Expertise was estimated to have a small effect on the mass of medical consumables. From the literature however it is clear that the level of medical expertise would have an effect of the outcome for the individual crew member. (Billica 1996)
For the nominal case:

\[ K_{mp} = 1.0 \] for a CMO

<table>
<thead>
<tr>
<th>Level of Medical Expertise</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMO</td>
<td>1.00</td>
</tr>
<tr>
<td>Astronaut Physician</td>
<td>0.98</td>
</tr>
<tr>
<td>Physician Astronaut</td>
<td>0.97</td>
</tr>
<tr>
<td>Space Surgeon</td>
<td>0.95</td>
</tr>
<tr>
<td>Flight Surgeon</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Figure 15 Scaling factor for medical supply based on level of expertise onboard

Risk

Risk was investigated as an additional independent driver in the calculations. This parameter defined as likelihood of a medical event multiplied by impact to the mission, is in line with current NASA planning processes. With increased risk of medical event more resources will be supplied and dedicated to prevent or mitigate that risk. The following ranking scale of medical event risk during spaceflight was developed. (Billica 1996). The results are based on 60 survey responses.
Rating Scale for Medical Events; Perception of the Medical Risk of Space Flight Survey

**Probability:**
1 = not likely to ever occur during a mission
2 = somewhat likely to occur at least once at some time over the course of the program, but will probably be rare
3 = likely to occur occasionally
4 = likely to occur on most missions, but not expected on every mission
5 = expect to occur on each mission

**Effect on health of crewmember:**
1 = quick treatment and recovery, minimal health effect (e.g., bandage, aspirin, decongestants)
2 = acute, self-limiting, with crewmember unable to perform certain tasks or carry-on normal activity, but full recovery expected during mission (e.g., cold, infectious disease process, ear block, sprained ankle)
3 = incomplete recovery during the flight, but complete recovery possible after return to Earth and care provided (e.g., trauma, appendicitis, kidney stone, fracture)
4 = never complete recovery, permanent disability (e.g., hearing loss, loss of limb)
5 = death during mission

**Effect on mission:**
1 = no effect on the mission
2 = some effect on the procedures or time lines, but overall mission objectives not adversely affected
3 = mission effect, loss of certain mission objectives
4 = severe effect on mission objectives
5 = catastrophic effect, mission aborted

The results of the shuttle era NASA flight surgeon survey is listed in figure 17. Mean scores, standard deviations, and rankings, for probability, health effect, and mission effect for disease categories.
<table>
<thead>
<tr>
<th>Disease Category</th>
<th>Mean</th>
<th>SD</th>
<th>Rank</th>
<th>Mean</th>
<th>SD</th>
<th>Rank</th>
<th>RISK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental disorders</td>
<td>2.41</td>
<td>0.124</td>
<td>2</td>
<td>2.66</td>
<td>0.105</td>
<td>5</td>
<td>6.411</td>
</tr>
<tr>
<td>Sensory</td>
<td>2.22</td>
<td>0.055</td>
<td>6</td>
<td>2.37</td>
<td>0.065</td>
<td>8</td>
<td>5.261</td>
</tr>
<tr>
<td>Circulatory</td>
<td>1.83</td>
<td>0.152</td>
<td>9</td>
<td>3.58</td>
<td>0.229</td>
<td>1</td>
<td>6.551</td>
</tr>
<tr>
<td>Respiratory</td>
<td>2.32</td>
<td>0.078</td>
<td>4</td>
<td>2.45</td>
<td>0.045</td>
<td>6</td>
<td>5.684</td>
</tr>
<tr>
<td>Gastrointestinal</td>
<td>2.11</td>
<td>0.074</td>
<td>8</td>
<td>3.04</td>
<td>0.049</td>
<td>3</td>
<td>6.414</td>
</tr>
<tr>
<td>Genitourinary</td>
<td>2.2</td>
<td>0.17</td>
<td>7</td>
<td>2.85</td>
<td>0.13</td>
<td>4</td>
<td>6.270</td>
</tr>
<tr>
<td>Skin</td>
<td>2.46</td>
<td>0.196</td>
<td>1</td>
<td>1.99</td>
<td>0.187</td>
<td>9</td>
<td>4.895</td>
</tr>
<tr>
<td>Musculoskeletal</td>
<td>2.26</td>
<td>0.128</td>
<td>5</td>
<td>2.41</td>
<td>0.121</td>
<td>7</td>
<td>5.447</td>
</tr>
<tr>
<td>Injury/poisoning</td>
<td>2.34</td>
<td>0.132</td>
<td>3</td>
<td>3.09</td>
<td>0.079</td>
<td>2</td>
<td>7.231</td>
</tr>
</tbody>
</table>

**Figure 17. Results of flight surgeon survey**

Because this survey did not assess all the ICD categories, this table was expanded and adapted to make the model more universally applicable to known missions. The ICD categories not surveyed ICD codes were filled in with ones (the lowest probability). This adaptation is listed in Figure 18.

<table>
<thead>
<tr>
<th>Disease Category</th>
<th>Mean</th>
<th>SD</th>
<th>Rank</th>
<th>Mean</th>
<th>SD</th>
<th>Rank</th>
<th>RISK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental disorders</td>
<td>2.41</td>
<td>0.124</td>
<td>2</td>
<td>2.66</td>
<td>0.105</td>
<td>5</td>
<td>6.411</td>
</tr>
<tr>
<td>Sensory</td>
<td>2.22</td>
<td>0.055</td>
<td>6</td>
<td>2.37</td>
<td>0.065</td>
<td>8</td>
<td>5.261</td>
</tr>
<tr>
<td>Circulatory</td>
<td>1.83</td>
<td>0.152</td>
<td>9</td>
<td>3.58</td>
<td>0.229</td>
<td>1</td>
<td>6.551</td>
</tr>
<tr>
<td>Respiratory</td>
<td>2.32</td>
<td>0.078</td>
<td>4</td>
<td>2.45</td>
<td>0.045</td>
<td>6</td>
<td>5.684</td>
</tr>
<tr>
<td>Gastrointestinal</td>
<td>2.11</td>
<td>0.074</td>
<td>8</td>
<td>3.04</td>
<td>0.049</td>
<td>3</td>
<td>6.414</td>
</tr>
<tr>
<td>Genitourinary</td>
<td>2.2</td>
<td>0.17</td>
<td>7</td>
<td>2.85</td>
<td>0.13</td>
<td>4</td>
<td>6.270</td>
</tr>
<tr>
<td>Skin</td>
<td>2.46</td>
<td>0.196</td>
<td>1</td>
<td>1.99</td>
<td>0.187</td>
<td>9</td>
<td>4.895</td>
</tr>
<tr>
<td>Musculoskeletal</td>
<td>2.26</td>
<td>0.128</td>
<td>5</td>
<td>2.41</td>
<td>0.121</td>
<td>7</td>
<td>5.447</td>
</tr>
<tr>
<td>Congential Anomalies</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
</tr>
<tr>
<td>Symptoms, Signs, and I</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
</tr>
<tr>
<td>Injury/poisoning</td>
<td>2.34</td>
<td>0.132</td>
<td>3</td>
<td>3.09</td>
<td>0.079</td>
<td>2</td>
<td>7.231</td>
</tr>
</tbody>
</table>

**Figure 18. Adaptation of NASA Flight surgeon survey**
The survey data was based on shuttle era medical problems and is not representative of currently planned expedition class missions. Figure 19 is a risk matrix plot based on the results of NASA flight surgeon survey. It plots consequences of a medical event occurring against the likelihood of occurrence. The green, yellow, and red portions of the graph are indicative of the level of risk. All of the occurrences appear to be in the green zone so they are not a large risk. It should be noted that these data are only based on shuttle era missions (2 weeks or shorter in low earth orbit that would allow a quick return to the earth in the event of a medical or other contingency).

With an expedition class mission additional unknowns (i.e. solar and galactic radiation exposure) may shift ICD codes to the yellow or red regions of the risk matrix. EVA activity may also shift the risk into the red portions of the matrix.

Figure 19 Risk Matrix plotting results of NASA flight surgeon survey
NASA uses these matrices as a tool to make decisions and to dedicate resources once decisions are made. Resources would fall into two categories; Preventive Control (p): A control, that if successful, will prevent the risk initiator from impacting the mission, reduce the likelihood of risk and Mitigative Control (m): A control, that if successful, will reduce the consequences of the risk (by some fraction, μ) or transfer the consequences to a different dimension.

Although the proposed model equations don’t currently incorporate this parameter, implementation in subsequent versions of the model would allow for a more granular description of medical supply mass (laboratory and diagnostic, imaging, medications, surgical supplies, telemedicine and expert systems equipment) needed to support human operations in space. Figure 20 describes a proposed breakdown of the types of medical supplies and different amounts of supplies could be dedicated to the mission based on risk of medical events to the mission. At the present time, the framework of SpaceNet does not allow for this level of detailed cargo specific information but this may be useful in subsequent versions of the tool.

Prevention and Mitigation (and treatment) will require onboard Laboratory and Diagnostic, Imaging, Medications, Surgical Supplies, Telemedicine supplies. Figure 20 diagrams a proposed breakdown of mass dedicated to the treatment of each ICD code. The red in the figure are zeroed out because these are not expected to occur during a mission (i.e. pregnancy) even during a mission that is 3 years long.
ICD Code | Laboratory and Diagnostics | Imaging | Medication | Surgical Supplies | Teledmedicine | Risk |
--- | --- | --- | --- | --- | --- | --- |
001-139: Infectious and parasitic diseases | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 1.000 |
140-239: Neoplasms | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 1.000 |
240-279: Endocrine, nutritional and metabolic diseases, and immunity disorders | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 1.000 |
280-289: Diseases of the blood and blood-forming organs | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 1.000 |
290-319: Mental disorders | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 6.411 |
320-359: Diseases of the nervous system | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 1.000 |
360-389: Diseases of the sense organs | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 5.261 |
390-459: Diseases of the circulatory system | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 6.551 |
460-519: Diseases of the respiratory system | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 5.684 |
520-579: Diseases of the digestive system | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 6.414 |
580-629: Diseases of the genitourinary system | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 6.270 |
630-676: Complications of pregnancy, childbirth, and the puerperium | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 1.000 |
680-709: Diseases of the skin and subcutaneous tissue | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 4.895 |
710-739: Diseases of the musculoskeletal system and connective tissue | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 5.447 |
740-759: Congenital anomalies | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 1.000 |
760-779: Certain conditions originating in the perinatal period | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 1.000 |
780-799: Symptoms, signs, and ill-defined conditions | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 1.000 |
800-999: Injury and poisoning | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 0.0667 | 7.231 |

Nominal Supply weight (Kg) | 50 | 100 | 150 | 150 | 50 | 500 |

Total (Kg) | 7.231 |

Figure 20. Classes of medical supply by ICD code

One possibility for the incorporation of this table into the model is to multiply risk by the individual masses of the classes of medical supplies for each ICD code. For example:

1. \( \text{risk} = \text{probability of a medical event} \times \text{impact to the mission} \)
2. \( \text{uncorrected mass} = f(\text{function of risk}) \times \sum \text{masses (K*supply category)} \)
3. \( \text{mass of (ICD)} = \text{Risk (ICD)} \times \sum \text{masses (K*supply category)} \)

mass (001-139: Infectious and parasitic diseases) = Risk (ICD) \times \sum \text{masses (K*Laboratory, K*Imaging, K*Medications, K*Surgical Supplies, K*Teledmedicine)}
mass (140-239: Neoplasms) = Risk (ICD) \times \sum \text{masses (K*Laboratory, K*Imaging, K*Medications, K*Surgical Supplies, K*Teledmedicine)}
mass (240-279: Endocrine, nutritional and metabolic diseases, and immunity disorders) = Risk (ICD) \times \sum \text{masses (K*Laboratory, K*Imaging, K*Medications, K*Surgical Supplies, K*Teledmedicine)}
mass (280-289: Diseases of the blood and blood-forming organs) = Risk (ICD) \times \sum \text{masses (K*Laboratory, K*Imaging, K*Medications, K*Surgical Supplies, K*Teledmedicine)}
mass (290-319: Mental disorders)
Adding all the component masses would also provide another way of calculating overall mass.

Another perspective can be taken in terms of risk to the individual and not risk to the mission. This could also be applied to the dedication of the MMC that is needed to support a human crew. Figure 21 below incorporated health effect on the individual crew members.
<table>
<thead>
<tr>
<th>Disease Category</th>
<th>Probability</th>
<th>Mean</th>
<th>SD</th>
<th>Rank</th>
<th>Health Effect</th>
<th>Probability</th>
<th>Mean</th>
<th>SD</th>
<th>Rank</th>
<th>Mission Effect</th>
<th>Probability</th>
<th>Mean</th>
<th>SD</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infectious and Parasitic</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Neoplasms</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Endocrine, nutritional and metabolic</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Diseases of the blood</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Mental disorders</td>
<td>2.41</td>
<td>0.124</td>
<td>2</td>
<td>2.47</td>
<td>0.35</td>
<td>5</td>
<td>2.66</td>
<td>0.35</td>
<td>5</td>
<td>6.411</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Nervous System</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Sensory</td>
<td>2.22</td>
<td>0.055</td>
<td>6</td>
<td>2.41</td>
<td>0.34</td>
<td>7</td>
<td>2.37</td>
<td>0.065</td>
<td>8</td>
<td>5.261</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Circulatory</td>
<td>1.83</td>
<td>0.152</td>
<td>9</td>
<td>3.12</td>
<td>0.982</td>
<td>1</td>
<td>3.58</td>
<td>0.229</td>
<td>1</td>
<td>6.551</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Respiratory</td>
<td>2.32</td>
<td>0.078</td>
<td>4</td>
<td>2.17</td>
<td>0.174</td>
<td>9</td>
<td>2.45</td>
<td>0.045</td>
<td>6</td>
<td>5.684</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Gastrointestinal</td>
<td>2.11</td>
<td>0.074</td>
<td>8</td>
<td>2.69</td>
<td>0.341</td>
<td>3</td>
<td>3.04</td>
<td>0.049</td>
<td>3</td>
<td>6.414</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Genitourinary</td>
<td>2.20</td>
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<td>7</td>
<td>2.45</td>
<td>0.5</td>
<td>6</td>
<td>2.85</td>
<td>0.13</td>
<td>4</td>
<td>6.270</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Complications of Pregnancy</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Skin</td>
<td>2.46</td>
<td>0.196</td>
<td>1</td>
<td>2.23</td>
<td>0.728</td>
<td>8</td>
<td>1.99</td>
<td>0.187</td>
<td>9</td>
<td>4.895</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Musculoskeletal</td>
<td>2.26</td>
<td>0.128</td>
<td>5</td>
<td>2.74</td>
<td>0.527</td>
<td>2</td>
<td>2.41</td>
<td>0.121</td>
<td>7</td>
<td>5.447</td>
<td>1.00</td>
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<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Congenital Anomalies</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>1.00</td>
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<td>N/A</td>
</tr>
<tr>
<td>Symptoms, Signs, and Illness</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Figure 21. NASA survey data with health effect included
4. Applications of model to Design Reference Missions (DRM)

Using the proposed model and applying to three scenarios we have:

**Scenario #1**

Duration: 30 days  
Mission: LEO  
Crew Size: 4  
Crew Ages: 25M 28F 35M 40F  
Medical Expertise on board: Physician-Astronaut

**Alpha Calculation**

*Injury and Illness (mission duration effect)*

\[
100 \times \frac{156}{214} \times \frac{27.76}{100} \times \frac{30}{365} \times 4 = 6.65
\]

6.65 days out of a possible 120 person-day mission (4 persons * 30 days) indicates an availability decrease to 94.5% due to illness or injury.

*Fatalities (type of mission effect and gender effect)*

For LEO there is no increased fatality risk due to the protective magnetic field of the earth.

\[
\text{Alpha} = 94.5\ \%
\]

**Mass Calculation**

\[
K_{md} = 1.39 \times 10^{-3} \times 30\ 	ext{days}
\]

\[
K_{cs} = 1.0
\]

\[
K_{de} = 1.0
\]

\[
K_{me} = 0.97
\]

\[
\text{MMC} = \text{nominal mass for DRM} \times K_{de} \times K_{me} \times K_{cs} \times K_{md}
\]

\[
\text{MMC} = 500\ 	ext{kg} \times 1.0 \times 0.97 \times 1.0 \times (1.39 \times 10^{-3} \times 30)
\]

\[
\text{MMC} = 20.2\ \text{kg}
\]
Scenario #2

Duration: 180 days  
Mission: Lunar  
Crew: 5  
Crew Ages: 25M 28F 35M 40F 45M  
Medical Expertise on board: Crew Medical Officer

Alpha Calculation

\textit{Injury and Illness (mission duration effect)}

\[ 100 \times \frac{156}{214} \times \frac{27.76}{100} \times \frac{180}{365} \times 5 = 49.84 \]

\text{(space scaling factor) \ day /medical events /events/person-years /years /crew /days}

49.84 days out of a possible 900 person-day mission (5 persons \times 180 days) indicates an availability decrease to 94.5\% due to illness or injury

\textit{Fatalities (type of mission effect and gender effect)}

For a Lunar Mission of 180 days fatal risk for a male is 0.86\% and for a female 0.82\% \text{(ref #)}

Taking an average for \((3 \text{ males} \times 0.68) + 2 \text{ females} (0.82) \) / 5 = 0.74\%

\[ \text{Alpha} = 100 - 5.53 - 0.74 = \%
\]

\[ \text{Alpha} = 93.71 \%
\]

Mass Calculation

\[ K_{md} = 1.39 \times 10^{-3} \times (180 \text{ days}) \]

\[ K_{cs} = 1.1 \]

\[ K_{de} = 2.0 \]

\[ K_{me} = 1.0 \]

\[ MMC = \text{nominal mass for DRM} \times K_{de} \times K_{me} \times K_{cs} \times K_{md} \]

\[ MMC = 500 \text{ kg} \times 2.0 \times 1.0 \times 1.1 \times (1.39 \times 10^{-3} \times 180) \]

\[ MMC = 275.2 \text{ kg} \]
Scenario #3
Duration: 600 days
Mission: Mars
Crew: 6
Crew Ages: 25M 28F 35M 40F 45M 55F
Medical Expertise on board: Astronaut Physician

Alpha Calculation

Injury and Illness (mission duration effect)

\[
100 \times \frac{156}{214} \times \frac{27.76}{100} \times \frac{600}{365} \times 6 = 199.37
\]

(space scaling factor) day/medical events events/person-years years crew days

199.37 days out of a possible 3600 person-day mission (6 persons * 600 days) indicates an availability decrease to 94.5% due to illness or injury.

Fatalities (type of mission effect and gender effect)

For a Lunar Mission of 600 days fatal risk for a male is 0.86% and for a female 0.82% (ref #)

Taking an average for \((3 \text{ males} \times 4.0 + 3 \text{ females} \times 4.9) / 6 = 4.45\%\)

\[
\text{Alpha} = 100 - 5.53 - 4.45 = \%
\]

\[
\text{Alpha} = 90.01\%
\]

Mass Calculation

\[
K_{md} = 1.39 \times 10^{-3} \times 600 \\
K_{cs} = 1.3 \\
K_{de} = 4.0 \\
K_{me} = 0.98 \\
\text{MMC} = \text{nominal mass for DRM} \times K_{de} \times K_{me} \times K_{cs} \times K_{md}
\]

\[
\text{MMC} = 500 \text{ kg} \times 4.0 \times 0.98 \times 1.3 \times (1.39 \times 10^{-3} \times 600)
\]

\[
\text{MMC} = 2125.0 \text{ kg}
\]
5. Conclusions and Recommendations

Conclusions

The proposed model has two outputs, $\alpha_h$ and MMC, for each set of input variables. $\alpha_h$ is representation of crew health and is displayed as a percentage. Mass of medical consumables calculated from the demand model and is delivered in kilograms.

We have demonstrated that $\alpha_h$ is a function of three scaling variables, the type of mission, gender, and duration of mission. The gender and type of mission are linked to radiation fatality data modeled by NASA and the duration of the mission is related to illness and injury and linked through submarine data.

For Mass we have determined that there is no published information available to integrate gender into the model. Age of the crewmembers was seen to have a negligible effect as available analog data indicates that although some coded medical events do increase with increased age, some events actually go down with increased age. The mass of medical consumables increases with the number of crew, the duration of the mission and the distance of the mission away from the earth. The degree of medical expertise on-board is not necessarily related to a decrease or increase in consumption of medical supplies but perhaps related better outcome for the individual infirmed crew member.

Risk was investigated as an additional independent factor in the calculations as a potential driver for the amount of medical supplies needed or potentially consumed during a mission. This parameter is in line with current NASA planning processes and would make the model and subsequent incorporation into SpaceNet more useful to future operational planners. Although the equations don’t currently have this level of granularity (it is not needed for the current SpaceNet tool) it may be a more subtle driver for the duration of the mission increasing the amount of MMC needed in that farther missions are riskier and the MMC is related to risk. This factor would also provide a breakdown in the type of medical supplies allocated to the mission (laboratory and diagnostic, imaging, medications, surgical and trauma supplies, and telemedicine and
expert system equipment). This would be useful in all forms of supply chain management whether it is carry along, pre-positioning, or scheduled resupply.

**Mockup of GUI**

The proposed mockup of the input GUI will involve entry and selection of mission duration (in days), the type of mission (low earth orbit, lunar, or Martian) via tick boxes, crew size, crew age and gender, and the level of medical expertise on board (crew medical officer, astronaut physician, physician astronaut, space surgeon) via tick boxes. (See appendix B) The proposed mockup of the output GUI will deliver model based calculations of mass (in kilograms) and alpha (expressed as a percentage).

**Recommendations**

Since future development and enhancement of SpaceNet is planned will be a web based application, the code should optimally be written in Java. This will allow for a systems approach interface to the existing and future upgradeability of SpaceNet. Although currently, some of the equations do not incorporate all variables (for lack of existing data) implementation of the equations in code should include these as yet unused variables (i.e. age of crewmembers).

It is recommended that the data for the scaling factors in the model be updated to reflect a larger pool of potentially available human spaceflight medical data. This data is potentially available through the NASA Database: The Longitudinal Study of Astronaut Health (LSAH).

The Longitudinal Study of Astronaut Health (LSAH) is an ongoing NASA research study which began in 1992 to examine the long-term physiological effects of space flight on astronauts. The primary goal of the LSAH is to investigate and describe the incidence of acute and chronic morbidity and mortality of space travelers and to determine whether the unique occupational exposures encountered are associated with increased risks of
cause-specific morbidity or mortality. The study includes medical data on men and women who have been selected as NASA astronauts since the space program began in 1959. All NASA astronauts participate in the study and are followed from selection throughout their lifetime or until the end of the study. The study also collects health and medical data from a ground-based comparator group of Johnson Space Center (JSC) employees matched to the astronauts at a 3:1 ratio. This comparator group is matched by sex, age, and body mass index. This group is followed in the same manner as astronauts. (NASA LSAH 2008)

It is recommended that the following questions be queried from the database: For all completed missions to date (Gemini, Mercury, Apollo, Skylab, Shuttle, Shuttle-MIR, ISS, et al): 1. what are the medical events that have occurred during each mission (by mission)? 2. How much time was the crew member unavailable to fulfill his/her duties in conjunction with this medical event? 3. What intervention was needed to correct or prevent a medical occurrence? 4. During each mission with a medical event, what are the following descriptors; number of crew, ages of crewmembers, gender of crewmembers, duration of expedition, distance from Earth (i.e. LEO or moon), and type of medical expertise on mission. 5. What are the medical consumables (medical supplies other than pharmaceuticals) that have been consumed during each mission (by missions)? 6. What pharmaceuticals have been consumed during each mission (by mission)? 7. What medical capital equipment (lab diagnosis equipment, scanners, blood testing etc...) was carried on each mission? Was the equipment considered part of the installation of the spacecraft itself, or was it part of loosely carried logistics items?

Risk was investigated as an additional independent driver in the calculations. This parameter defined as likelihood of a medical event multiplied by impact to the mission, is in line with current NASA planning processes. Although the equations don't currently incorporate this parameter, implementation in subsequent versions of the model would allow for a more granular description of medical supply mass (laboratory and diagnostic, imaging, medications, surgical supplies, telemedicine and expert systems equipment) needed to support human operations in space. Figure 20 describes a proposed breakdown of the types of medical supplies and different amounts of supplies could be dedicated to the mission based on risk of medical events to the mission. At the present
time, the framework of SpaceNet does not allow for this level of detailed cargo specific information but this may be useful in subsequent versions of the tool.
## Classes of Supply

1. Propellants and Fuels
3. Crew Operations
4. Maintenance and Upkeep
5. Stowage and Restraint
6. Exploration and Research
7. Waste and Disposal
8. Habitation and Infrastructure
9. Transportation and Carriers
10. Miscellaneous
11. Medical
Appendix B

Input GUI

SpaceNet Medical GUI

INPUT

Mission Duration (days): 60
Mission: (tick boxes) LEO, LUNAR, MARS
Crew Size: 4
Crew Age and Gender: 25M 35F 45M 55F
Medical Expertise Onboard: (tick boxes) CNO, ASTRONAUT PHYSICIAN, PHYSICIAN ASTRONAUT, SPACE SURGEON
<table>
<thead>
<tr>
<th>Category</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Duration (days)</td>
<td>180</td>
</tr>
<tr>
<td>Mission</td>
<td>LEO</td>
</tr>
<tr>
<td>Crew Size</td>
<td>4</td>
</tr>
<tr>
<td>Crew Age and Gender</td>
<td>25M 35F 45M 55F</td>
</tr>
<tr>
<td>Medical Expertise Onboard</td>
<td>CAN</td>
</tr>
<tr>
<td>Laboratory and Diagnostics (kg)</td>
<td>28</td>
</tr>
<tr>
<td>Imaging (kg)</td>
<td>128</td>
</tr>
<tr>
<td>Medications (kg)</td>
<td>88</td>
</tr>
<tr>
<td>Surgical Supplies (kg)</td>
<td>21</td>
</tr>
<tr>
<td>Telemedicine supplies (kg)</td>
<td>123</td>
</tr>
</tbody>
</table>

\[ \text{Mass (kg)} = 1893 \]
\[ \text{Alpha (\%)} = 94 \]
Acronyms and Abbreviations

$K_{md}$ scaling parameter mission duration

$K_{ac}$ scaling parameter age of crew

$K_{cs}$ scaling parameter crew size

$K_{de}$ scaling parameter distance from the earth

$K_{me}$ scaling parameter medical expertise

MMC mass of medical consumables

$\alpha_h$ crew health and availability factor

GUI graphic user interface
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**Terrestrial Supply Logistics**


**Interplanetary Space Logistics**


