Analysis of Historical International Space Station Logistical Mass Delivery

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Abstract— **Crewed space exploration missions are extremely logistics dependent, as cargo requirements shape numerous program elements such as vehicle and habitat size. Logistics mass is the mass of items like food and clothing that are not a part of the vehicle or habitat, yet are required by the crew to complete the mission. Numerous studies, such as the Human Exploration Research Analog (HERA) and the Human Exploration Spacecraft Testbed for Integration and Advancement (HESTIA) 20-foot chamber analog, have been conceived to research the rates at which crews consume logistics mass. These analogs can simulate many aspects of life in space, including confinement, isolation, limited supplies, and, in certain experiments, the habitat pressure. However, some aspects of space exploration, such as the effects of low gravity and the use of space-based amenities, cannot currently be tested on the ground. In this paper, International Space Station (ISS) manifest data obtained through the National Aeronautics and Space Administration's (NASA's) Mission Integration Database Application System (MIDAS) portal is used as a precursor to space-based analogs. The objective of the analysis is determining the breakdown of logistics mass used in space exploration. This identifies potential areas of improvement and highlights the rates at which significant items are supplied, aiding in the weighing of alternative options such as utilizing in space manufacturing for supplies vs. manifesting spares, or cleaning clothing in flight vs. discarding it. Official flight manifests ranging a span of 878 days, just short of the three-year length of a potential human mission to Mars, were analyzed to find the rates at which astronauts consumed various logistics supplies.**

From this analysis we have found that contrary to our own hypothesis, 'food' was not the largest portion of the supplied mass. Instead, 'Environmental Control and Life Support Systems' (ECLSS) contributed 34% of the overall supplied mass, followed by 'Science and Outfitting,' which contributed 29%. Food totaled less than a quarter (21% of the resupplied mass, while other items of focus in mass reduction efforts such as 'Hygiene' (6%), 'Clothing' (3%), and 'Operational Supplies' (4%) each contributed less than a tenth of the supplied mass. This data suggests that by categorizing and analyzing the data based on an alternative taxonomy and analyzing the full supply manifests rather than handpicked items, we have revealed unexpectedly significant items which had not been previously tracked by exploration logistics efforts. For example, toilet hardware made up 4% of ECLSS mass, and laptop hardware and multi-tools each made up 10% of operational supplies mass. Additionally, the 'Specialized Clothing' subcategory containing fire protective equipment, coveralls, and penguin suits made up 15% of the overall clothing mass. By identifying these newly found significant items, we can create more realistic mass estimates for exploration missions and direct mass reduction efforts to new areas, potentially leading to lower future mission masses.

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1. INTRODUCTION

The International Space Station (ISS) program already has methods in place to track everything that reaches the station. Required quantities of consumable and logistics items such as wipes and food are calculated weeks or months ahead of their launch date. This has been an acceptable method of logistical planning due to the modern availability of delivering supplies to low Earth orbit, which continues to advance with the progression of commercial cargo options.

In planning for exploration farther than Earth orbit, it becomes increasingly more important to predict mission logistics further in advance. For example, there is a 26-month gap between optimum Earth-Mars planetary alignment. In addition to the alignment period, it would take many more months for the supplies to transit to Mars. In order to pre-position supplies on Mars, we would need to be capable of planning two or more years in advance [1].

There have been numerous efforts to develop models and progress our understanding of resource consumption in exploration scenarios. Analog studies such as the Human Exploration Research Analog (HERA) [2] and the Human Exploration Spacecraft Testbed for Integration and Advancement (HESTIA) [3] 20-foot chamber analog have simulated both land and space exploration environments, allowing researchers to find the rates of consumption across various logistics supplies as well as study other aspects of confinement. While these studies have replicated exploration environments to incredible detail, there are elements that cannot currently be replicated on Earth such as the lack of gravity and use of purely space-based facilities.

Fortunately, ISS has a long history of crewed space flight dating back more than 20 years at the time of writing this document. While a dedicated experiment measuring logistical use on the ISS would require many resources and crew hours to track supply usage, we know that aside from the ejection of some garbage the ISS is a closed system. We have very accurate information regarding what is supplied to the ISS. By analyzing this data over time we can find the rates of supply for reoccurring items. In this paper, ISS manifest data obtained through the National Aeronautics and Space Administration's (NASA's) Mission Integration Database Application System (MIDAS) portal is used as a precursor to space-based analogs.

While a mission to another planet will look different than current missions to the ISS, there will likely be many commonalities. Modelling and analyzing logistics use of food, water, wipes, clothing, etc. on the ISS will help us develop better prediction capabilities for future missions.

The objective of the analysis is determining the breakdown of logistics mass used in space exploration. This identifies potential areas of improvement and highlights the rates at which significant items are supplied, aiding in the weighing of alternative options such as utilizing in space manufacturing (ISM) for supplies vs. manifesting spares, or cleaning clothing in flight vs. discarding it. This analysis is meant to be a first pass at such a product, to be used to aid the development of predicted logistical requirements for a range of deep space missions.

2. METHOD AND SELECTION OF DATA

The optimal data set for this analysis consists of a large amount of data points, over a large time frame, covering a range of crew complements (different numbers and types of crew for varying mission durations), in an environment as close to space exploration travel as possible. The ISS is a spacecraft that has been occupied by humans for more than 20 years as of the writing of this paper. It follows that such an environment is as close to a perfect analog for deep space exploration as humanity has ever been able to achieve. Unfortunately, no study has yet been conducted in tracking the exact daily consumption of each astronaut and each system on a broad scale. Such a study would be either extremely labor intensive for the astronauts or technologically complex in creating an automated system to track all consumption. Fortunately, outside of all ejected waste products, the ISS is a closed system. By analyzing every item that is sent to the ISS, we can determine what was used by the crew per unit time. One noteworthy exception to this is that some supplies may have been thrown out before use, such as food which the astronauts do not prefer; however, we will not try to deduce the amount of wasted supplies in this paper. Averaging the supply delivery data over a long period of time allows us to develop a model of the crew's consumption without using a direct study. The data used to create the analysis which is the subject of this paper was provided by MIDAS and consists of a complete set of manifests and cargo lists containing all items shipped to the ISS from October 2017 through February 2020. It encompasses the following missions shown in Table 1. While all missions are included in this table, items that were not successfully delivered to the ISS were not included in the model.

Table 1. Missions Included in The Analysis

Mission Name	Launch Date
Progress 68	10/14/2017
OA-8	11/12/2017
SpaceX 13	12/15/2017
Soyuz 53	12/17/2017
Progress 69	2/13/2018
Soyuz 54	3/21/2018
SpaceX 14	4/02/2018
OA-9	5/21/2018
Soyuz 55	6/06/2018
SpaceX 15	6/29/2018
Progress 70	7/09/2018
HTV7	9/22/2018
Soyuz 56	10/11/2018 – Booster failure
Progress 71	11/16/2018
Northrup-Grumman 10	11/17/2018
Soyuz 57	12/03/2018
SpaceX 16	12/05/2018
SpaceX Demo 1	3/02/2019
Soyuz 58	3/14/2019
Progress 72	4/04/2019
Northrup-Grumman 11	4/17/2019
SpaceX 17	5/04/2019
Soyuz 59	7/20/2019
SpaceX 18	7/25/2019
Progress 73	7/31/2019
Soyuz 60	8/22/2019
HTV8	9/24/2019
Soyuz 61	9/25/2019
Northrup-Grumman 12	11/02/2019
SpaceX 19	12/05/2019
Progress 74	12/06/2019
Boeing Orbital Flight Test	12/20/2019 – Did not arrive
Northrup-Grumman 13	2/15/2020

All 'Official Reports' data from this source dating up to the present was used. Prior data was organized differently and contained similar items under different names. The analysis is meant to simulate modern space exploration, therefore the most recently available data set was utilized.

3. Categorizations and Data Screening

All the 23,947 item instances included in the data set were screened equally to make the model as useful as possible. The process began by analyzing previous exploration-based logistics models [4]. A list of common items was created from these models as a reference to ensure the new model was not missing elements previously deemed important. To allow the new model to be used for analyzing the mass of potential exploration missions with differing payloads, payload data has been removed from the original data set. All items which were manifested as a payload were not considered logistics mass.

Table 2. Rules for Inclusion in The Model

Rule	Rationale
I. Items manifested as payloads shall not be included	Payloads change based on mission, future exploration missions will not have the same payload as missions to the ISS
II. Items with more than five occurrences across the data set shall be included	Items which seldomly occur are not consumables by definition
III. Items with masses greater than 100 kg shall be included	Rarely occurring items of large mass contribute significantly to the overall manifested mass and understanding their use is important towards mass reduction efforts
IV. Consumable items essential to sustaining life shall be included	The analysis must at a minimum contain all consumables required to sustain life in order to be useful in mission planning applications

The analysis is focused on consumable logistics items. To remove non-consumable items, all items were given counts with the value of the number of times they appeared across all manifests. Any items which did not occur at least five times across the three-year span of data were cut from the data set. The logic behind this is that rarely-occurring or single use items are not deemed consumables. The analysis was originally conducted by removing items which had not occurred ten times in the data set, ten being a magnitude greater than a single item, yet when manually searching through the data we discovered that not all items on our list of common items were included. To remedy this problem, the cutoff for inclusion was halved.

Upon further review we noted that large essential items such as treadmills and exercise equipment were not included. To include such items another rule was created that items with masses greater than 100 kilograms would be included. 100 kilograms acting as a magnitude for inclusion. Additionally, resupplies of gases such as nitrogen had not been included. To solve that issue, another rule was created permitting any consumable item essential to life. This rule was applied minimally and the only affected item was nitrogen recharge assemblies. The rules were applied as shown in Table 2 and the resulting breakdown of the dataset is shown in Figure 1.

The official flight reports came in spreadsheet format. Due to the large size of the data set, it could not be sorted by hand within a reasonable time frame. Instead, a computer program was used.

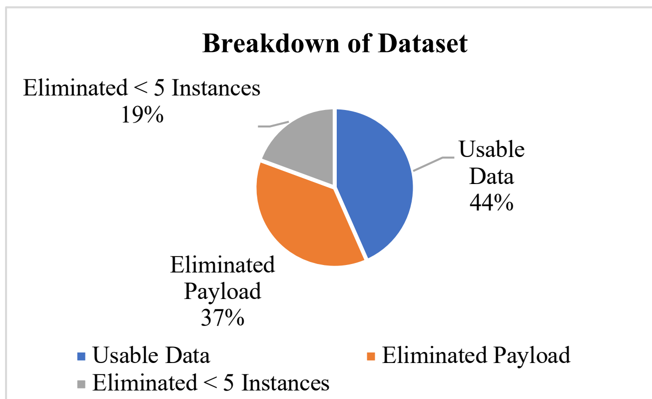

Fig. 1. Breakdown of the Dataset.

The manifests were re-formatted simply by copying all data into a single spreadsheet file. This file was then converted into a Comma Separated Values (.csv) format to be easily manipulated. A script of code was then written in Python to screen the .csv file and apply all rules except for rule IV, which was applied manually. The script output a sorted .csv file from which all data was taken and manually input into the spreadsheet-based analysis in categories according to our own taxonomy, which included the following groups:

- Food
- Environmental Control and Life Support Systems (ECLSS)
- Clothing

- Hygiene
- Health Care Consumables
- Operational Supplies
- Personal and Recreational
- Science and Outfitting

In total, 1066 types of items were categorized. The "Food" category contains all edible items, nutritional supplements, and their packaging, excluding water. Water is placed within the "Environmental Control and Life Support Systems" (ECLSS) category alongside oxygen, filters, station monitoring hardware, plumbing, and waste management. The clothing category contains all items that are worn by astronauts including harnesses and tool belts. Space Suits are not included in clothing but instead belong to the "Extra-Vehicular Activities (EVA) Consumables" category with all the other items such as tapes, thermal control garments, and protective covers that are used to assist the astronauts in their work outside of the spacecraft. Items used to maintain personal health such as washcloths, wipes, shampoo, and toothpaste are included in the "Hygiene" category. Any items used to treat patients or test the medical health of patients are included in the "Health Care Consumables" category. Office supplies, cables, small bags, batteries, cameras and more are included in the "Operational Supplies" category. Headphones, iPods, personal items and other materials used for leisure are included in the "Personal and Recreational" category. Lastly, items related to scientific experimentation or outfitting such as test setups, animal transport gear, and lab supplies are included in the 'Science and Outfitting' category. After the initial categorization, items were grouped and placed into subcategories such as 'Shirts,' 'Pens,' or 'Packaged Food.' The spreadsheet was used to determine the average mass of each item across all instances as well as the total quantity of the item supplied to the ISS within the designated time frame.

To find the rates of use, the average mass was multiplied by the total quantity and divided by the range of data in days multiplied by the average amount of crew on-board throughout that time frame. This results in the rate of use for each item in the format of kilograms per crew member day (1) - the average mass of the item consumed by a single crew member each day.

$$\frac{(Avg.Mass)*(Quantity)}{(Days)*(Avg.Crew)} = \frac{kg}{(Crew\ Member)*(Day)} \qquad (1)$$

All item rates in each category were then added to find categorical rates which were once more combined to find the total breakdown of logistics by category.

4. ANALYSIS AND FINDINGS

The general results of the model are that the largest portion (34%) of the logistics mass delivered to the ISS belongs to the Environmental Control and Life Support Systems category. The next largest portion is Science and Outfitting (S&O, 29%), followed by Food (21%), Hygiene (6%), Operational Supplies (Supplies, 4%), Clothing (3%), EVA Consumables (EVA, 2%), Health Care Consumables (Health, 1%) and Personal items (Personal, <1%), as shown in Figure 2.

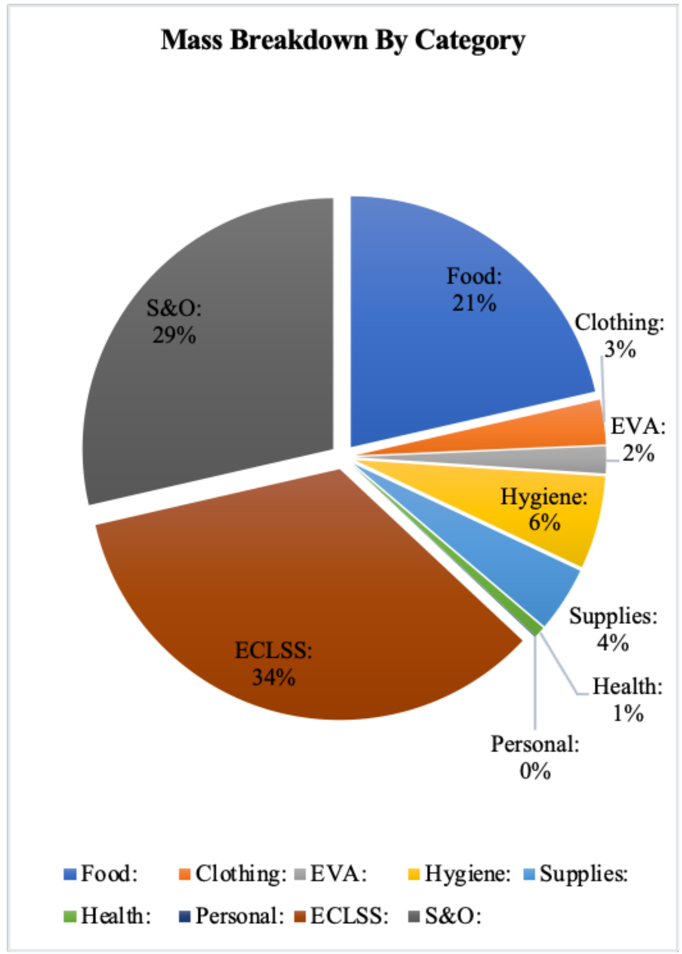

Fig. 2. Mass Breakdown By Category.

Further breaking the data down, we produce charts for each subcategory allowing for a discussion about the breakdown of each category. Note that not all items and subcategories will be mentioned, as doing so would dramatically increase the length of this paper.

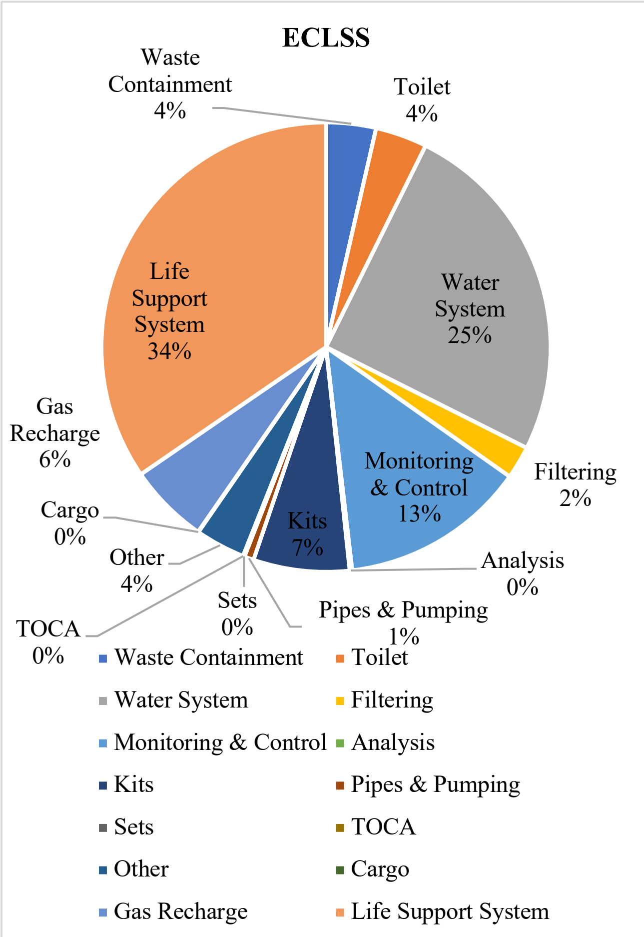

Fig. 3. ECLSS Subcategory Breakdown.

The largest portion of ECLSS is the Life Support System subcategory which contains only the Russian supplied item manifested as Life Support Systems (LSS). This item name is vague as given from the manifests and appears to cover general life support supplies. Information on the exact breakdown of the system was not readily available. The next largest portion is the 'Water System' which contains water containers, the water supply system, resupply water tanks and improved water resupply tanks, water sample collection packets and all other water-based consumables. Next, the Monitoring and Control category contains items used to maintain a steady station environment such as air revitalization and atmospheric monitoring, the thermal control system, the power supply subsystem, acoustic monitors, and coliform detection packets. Aelita kits (Russian cleanliness supplies), Ekosfera kits (biological testing), and NORS (Nitrous/Oxygen Recharge System) maintenance kits lie within the kits category. Waste Containment and Toilet Hardware each make up 4% of ECLSS mass. Waste Containment contains water waste bags and solid waste containers. Toilet Hardware includes toilet replacement hardware as well as urine receptacles.

The Science and Outfitting category does not have a sub categorical breakdown as it contains one hundred eleven items used in outfitting or experimentation with little commonality aside from their use. The largest contributors to S&O are Lithium-Ion Battery orbital replacement units, the 'as packed mass adjustments' which contains all of the corrected mass estimates from each launch, 800A storage units (storage batteries), in-flight maintenance, and structural components. Examples of smaller items include double cold insulated sample bags, and incubation bags.

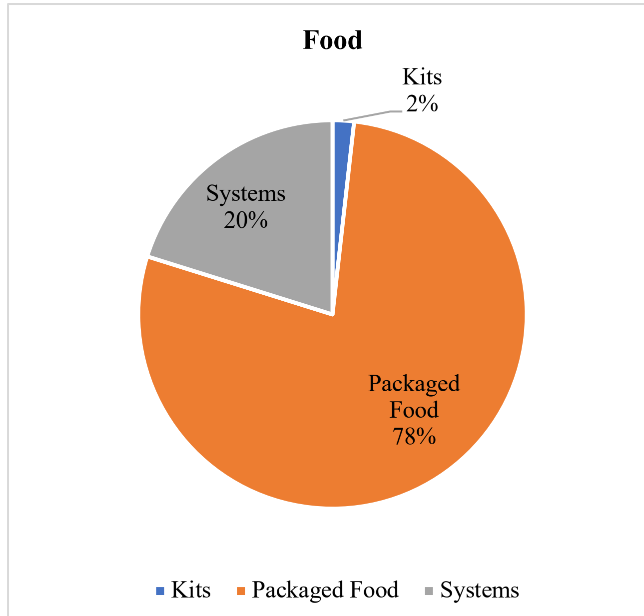

Fig. 4. Food Subcategory Breakdown.

Food is broken down into three simple subcategories. The largest is packaged food. This subcategory contains Bulk Overwrap Bags (BOBs) that are the most common form of American food distribution, food rations containers which contain Russian food, Cargo Transfer Bags (CTBs) labeled as containing food, and fresh produce selections. The systems subcategory contains the food supply system which is another Russian food source. Kits includes nutritional supplement kits, small food kits, and chewing gum kits.

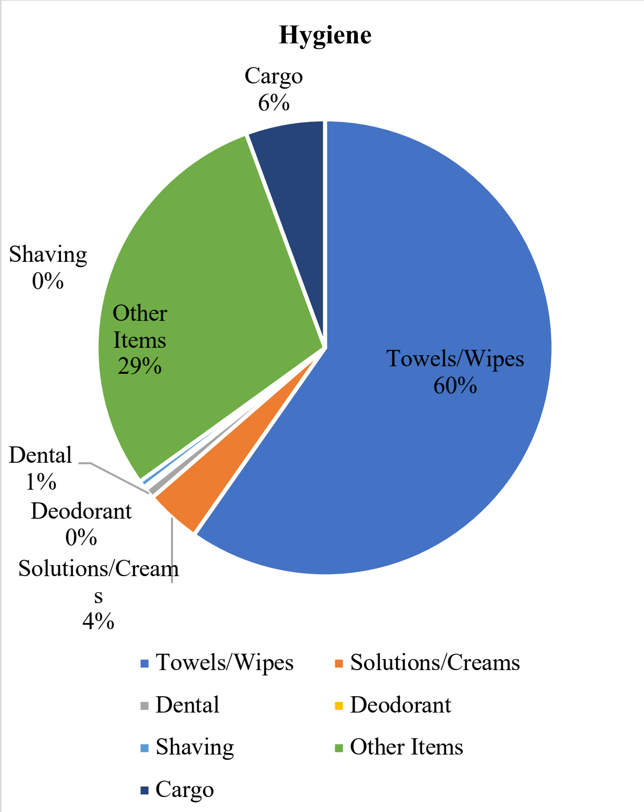

Fig. 5. Hygiene Subcategory Breakdown.

The Hygiene category contains items used to maintain personal cleanliness. Its largest subcategory is Towels/Wipes which contains various forms of towels, washcloths, wipes and napkins both wet and dry. The Other Items subcategory contains items that were miscellaneous and did not easily fit within other subcategories such as sleeping bag liners, nail clippers, hair combs, tweezers, and generalized hygiene kits. The Cargo category contains all CTBs designated for hygiene use. Solutions and Creams contains lotion, body bath, makeup, and hand cream. Toothpaste, floss and toothbrushes are in the Dental category.

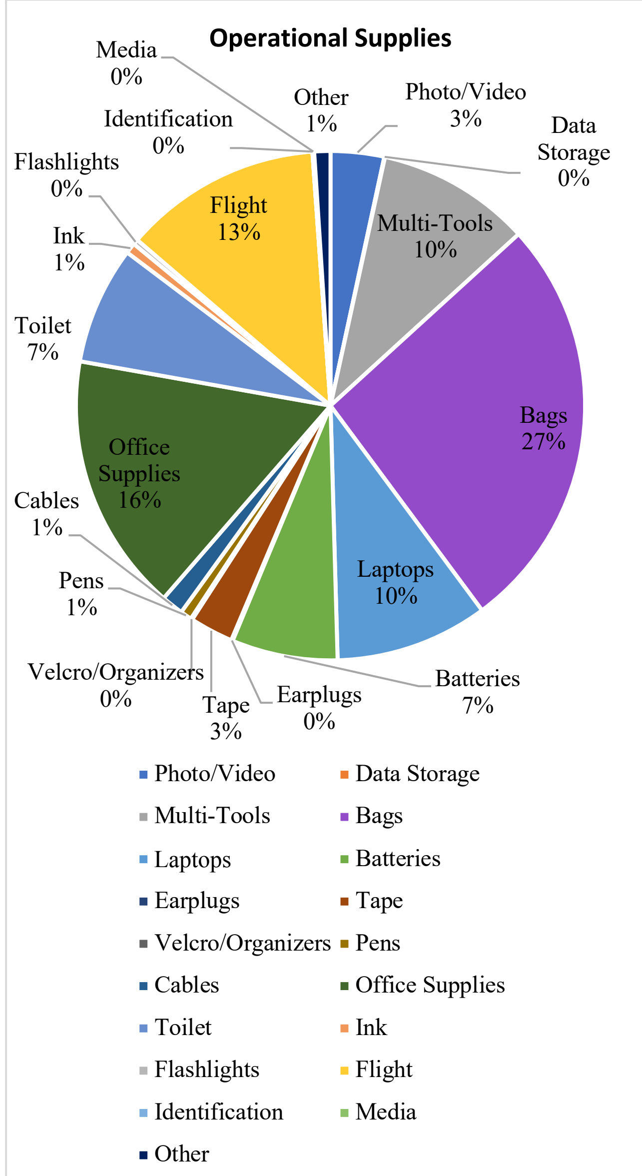

Fig. 6. Operational Supplies Subcategory Breakdown.

Operational Supplies contains the most subcategories. Starting from the most significant, the bags subcategory contains plastic bags, mesh laundry bags, freezer bags, containment bags, and trash bags. The next largest category is office supplies which contains note pads, sticky notes, printer paper, scissors, and binder clips. The flight category contains materials used for flight such as flight kits, copies of flight procedures, kneeboards and post flight analysis packets. Next, the laptops category contains all laptop computers and their components such as hard drives, power cables, batteries and adapters. The multi-tools subcategory includes the handheld multitools used by the crew as well as their sheaths.

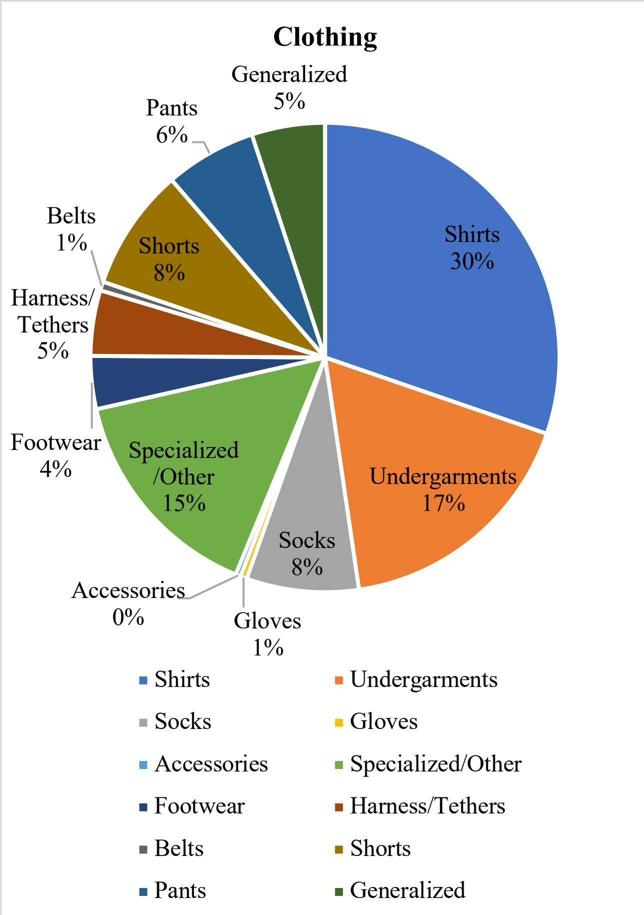

Fig. 7. Clothing Subcategory Breakdown.

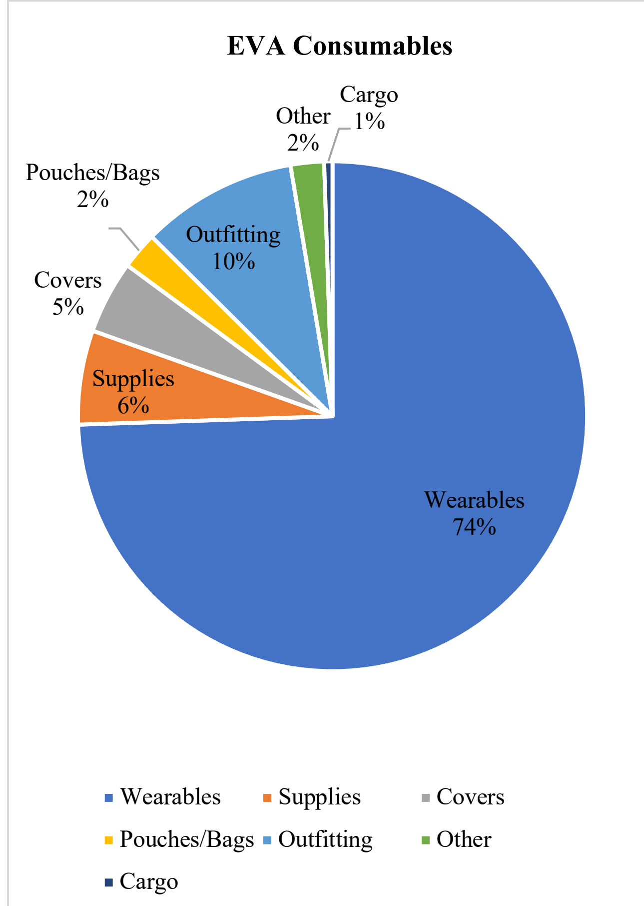

Fig. 8. EVA Consumables Subcategory Breakdown.

Clothing consists of all items worn by the crew inside of the vehicle. The largest subcategory is Shirts, which includes excercise shirts, T-shirts, crew preference shirts, and sleepwear tops. Undergarments contains all underwear worn by the crew. Specialized/Other includes coveralls, training/loading suits, fire protection equipment (FPE), and penguin suits which have a series of elastic bands and are used to compress the body to simulate gravity and counteract the physical effects of spending time in space. The socks subcategory contains all socks worn by the crew including ankle socks, exercise socks, and crew preference socks. Generalized contains bags such as CTBs designated to hold clothing.

Any clothing and other materials used outside of the spacecraft are included in the EVA consumables category. Wearables, the largest category, includes replacement space suit parts such as gloves, Maximum Absorption Garments (MAGs), liquid cooling vests and thermal comfort garments. The outfitting subcategory includes the EV crew options kit, attachments, and moisture barriers. Supplies covers various types of tapes, EVA wire ties, stericide wipes, and absorbent paper. The covers category contains protective covers for arm disconnects, rings, and battery cartridges. In EVA consumables the Other category includes crew identifiers, suit patches, foam sheets, and Valsalva devices which allow astronauts to equalize the pressure in their ears without using their hands to block their nose.

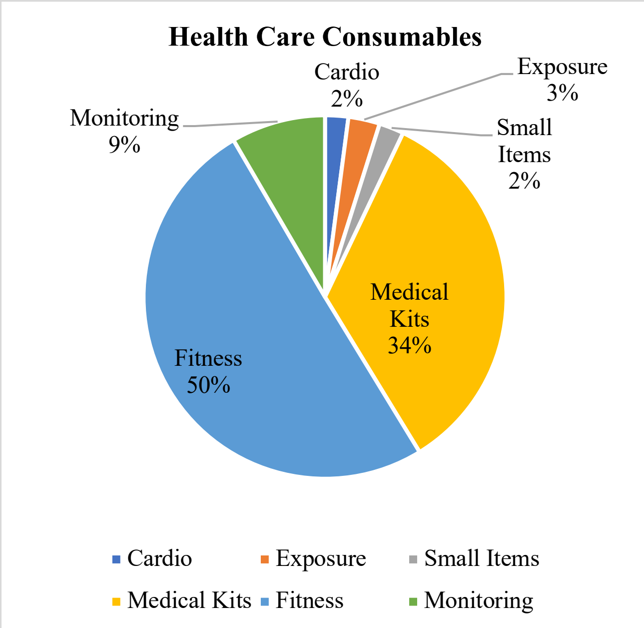

Fig. 9. Health Care Consumables Subcategory Breakdown.

The health care consumables category contains items used to maintain health, treat or diagnose crew members. The largest subcategory, fitness, contains parts for the treadmills and cycle ergometers. The medical kits subcategory contains the ISS Medical Accessory Kit, urisys sets, and other generalized medical kits. The monitoring subcategory includes items manifested as medical monitoring equipment. Exposure contains dosimeters and harmful exposure protection equipment. The small items subcategory contains sterile gauze, batteries specifically designated for medical equipment, cotton swabs, and emesis bags. 'Cardio' contains the cardiomed system and cardiocasset sets.

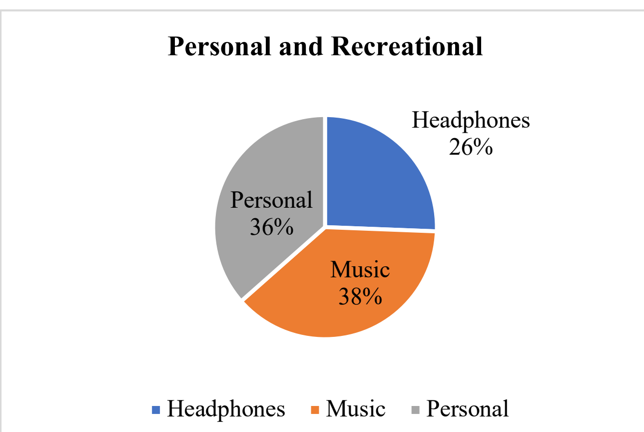

Fig. 10. Personal And Recreational Subcategory Breakdown.

The personal and recreational category is the smallest category and contains items used by the crew for leisure or entertainment. The Music subcategory contains mp3 players and the cables that come with them. 'Personal' contains Comfort 1M cases and items manifested as personal items both of which which consist of small crew picked items like books, CDs, small instruments, or foods. The headphones category consists of various forms of headphones including bluetooth headphones, portable players with headphones, and the headphones that come with the mp3 players.

5. CONCLUSIONS

An analysis of all items appearing on ISS flight manifests from October of 2017 to February of 2020 suggests that there are 1066 unique item types which occur regularly throughout the data set. In analyzing all of the items rather than handpicking items of importance, it is found that items not typically accounted for in previous logistics studies make up a large portion of the overall mass. This model can help identify these unexpected contributors and prime targets for mass reduction opportunity.

Most surprisingly, when all items are accounted for, Food mass made up only 21% of the overall launched mass. From studying previous models, this value was expected to be closer to 38% for long duration missions. The lower percentage found here is due to the increase in mass by the other categories rather than the reduction of mass in food. In fact, the rate of food usage found by our analysis of 2.77 kg/crew member day is larger than the value of 1.86 kg/crew member day in [4]. Part of the rate difference is likely due to the inclusion of items such as chewing gum kits and differences in packaging efficiencies between different suppliers.

Another surprise was the mass of Science and Outfitting, composing 29% of overall mass, even though "payloads" were screened out of the data set. The items in this category are not typically studied in logistics reduction efforts. There are a large number of experiments being conducted on the ISS and if an exploration mission plans on conducting a similar amount of research then it will be important to consider the mass of experimentation equipment in logistics estimates.

Specialized/Other clothing was a major contributor to clothing mass (15%). Therefore, reducing the quantity of heavy clothing items such as coveralls and loading suits for long duration missions may be able to reduce contributions to overall mass from clothing. Additionally, shirts, undergarments, socks, and shorts combined contributes 63% of clothing mass. Devices enabling astronauts to wash their cloths in flight may allow for mass savings in this area.

Towels and Wipes is another subcategory of interest as it contributes 60% of Hygiene mass. Proposed solutions to this include the development of equipment which can produce sanitizing solution onboard a spacecraft. The inclusion of such a system could reduce the mass of items like wet wipes and wet towels overall, reducing the mass of the hygiene category.

In operational supplies, the Bags subcategory contributes 27% of the categorical mass. This is a complex issue as some of these manifested bags may have contained items therefore driving their mass up. Nevertheless, the majority of the sub categorical mass comes from more than a thousand plastic bags which were manifested over the nearly three-year data range. A study into the use of plastic bags in space exploration may yield results allowing the replacement of disposable bags with reusable bags. Reusable bags could lower the mass contribution of Bags and therefore the categorical mass contribution of Operational supplies. Or perhaps the emptied bags can be reformed into something else in a 3D printer.

While the Health Care Consumables category is relatively small, making up only 1% of overall mass, Fitness items make up 50% of this categorical mass. Efforts to make treadmills and cycle ergometers more reliable or to reduce the weight of the hardware would decrease the mass of the Health Care Consumables. The data shows many areas of potential improvement which should be addressed in the future analyses. The development of technologies such as in space sanitizing solution production, reusable or lighter weight bags, and more reliable ECLSS and exercise equipment, as well as reductions in heavy clothing and science items, may decrease overall mass of future exploration missions allowing for more efficient space travel.

Lastly, due to the large number of items and inconsistencies we found, we would recommend that future programs use a more consistent and refined taxonomy for their manifesting to make the data easier to analyze. Ensuring that all similar items are manifested under the same name and that items have clear categorizations for their use would simplify the work required to conduct a similar study in the future.

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BIOGRAPHY

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