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A Method to Predict Component Life and Inform System Design

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The commercialization of space is reshaping the traditional methods of designing and sustaining a system in the emerging Commercial Low Earth Orbit (LEO) Destinations (CLD) market. To enable a successful program over the life of a product, it is critical to know the non-recurring, recurring, and sustaining engineering efforts required to meet performance needs at the onset of the program. One of the key drivers in all three of these aspects is hardware reliability and predicted life. Collins Aerospace, an RTX business, has worked to develop an analysis method and associated model that can be used to predict component life and the impact of life values on a program. Using this method, operation and hardware information informs component life, sub-assembly life, and system life. The outputs of this model include the aforementioned life data as well as the impacts of that data on key design metrics such as initial and lifetime mass. This paper will discuss the analysis methodology and how the results can be used to inform the initial design of a system, the sustaining engineering plan, and the initial assumptions for Collins' Leto™, an Artificial Intelligence (AI) powered spaceflight intelligence system. To demonstrate the value of the approach, a case study is described on the Water Processor Assembly (WPA).

Nomenclature

AI = Artificial Intelligence
CLD = Commercial Low Earth Orbit (LEO) Destinations
CRU = Crew Replaceable Unit
ECLSS = Environmental Control Life Support Systems
ESM = Equivalent System Mass
FMEA = Failure Mode and Effects Analysis
GS = Gas Separator
Hr = Hour
ISS = International Space Station
lb = Pound
LEO = Low Earth Orbit
MU = Maintenance Unit
NASA = National Aeronautics and Space Administration
NextSTEP= NASA's Next Space Technologies for Exploration Partnerships
ORU = Orbital Replacement Unit
QD = Quick Disconnect
SWaP = Size Weight and Power
UWMS = Universal Waste Management System
WPA = Water Processor Assembly

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I. Introduction

THE commercialization of space is redefining the most important considerations for designing and sustaining a system. This is especially true in the emerging Commercial Low Earth Orbit (LEO) Destinations (CLD) market. To enable a successful program over the life of a product, it is critical to know the non-recurring, recurring, and sustaining engineering efforts required to support the entire life of the product at the onset of the program. One of the key drivers in all three of these aspects is hardware reliability and predicted life.

Collins Aerospace, an RTX business, has developed and supplied systems to the International Space Station (ISS) for over 20 years. Some of these include Environmental Control and Life Support Systems (ECLSS) essential to human habitation such as carbon dioxide removal, thermal control, and waste collection. Collins is also responsible for the water processing and oxygen generation onboard the station; technologies that reduce the required consumable launch mass. As the space frontier commercializes, Collins has continued to improve these key technologies through investment in our NextGen systems line. These NextGen systems place a focus on decreasing cost while maintaining and improving upon the robust technologies scientists and explorers depend on.

The NextGen systems address hardware obsolescence, incorporate lessons learned from years of operation on the ISS, and implement design guidelines developed to meet the changing priorities of the commercial market. One important design feature that was challenged was the boundaries for maintenance units commonly referred to as Orbital Replacement Units (ORU). In an effort to consider the lifetime impact of these design decision, Collins has worked to develop an analysis method and associated model that can be used to predict life and the impact of life values on a program. Using this method, operation and hardware information informs component life, sub-assembly life, and system life. The life predictions are then used to determine the lifetime mass, cost, crew-time, or other metrics of interest. These outputs can be used in trade studies to enable data-based decision making when choosing components, defining maintenance units, or comparing system alternatives. The outputs can similarly be used to inform the sustaining engineering plan and the initial assumptions for Collins' Leto™, an artificial intelligence (AI) powered spaceflight intelligence system.[1] This paper will discuss the development of the analysis method, the outputs and uses for the method, a case study of the Water Processor Assembly (WPA) to demonstrate use of the method, and the opportunities for continued development.

II. Development of the Analysis Method

A. Historical Models

During the development of a space platform, recurring trade studies must be conducted to arrive at an optimal design. At the core of these trade studies, there is often a comparison of size, weight, and power (SWaP). Tools such as National Aeronautics and Space Administration's (NASA) "Advanced Life Support Equivalent System Mass Guidelines[2]" document provide direct comparison of SWaP and other factors by enabling normalization to a mass value, called the Equivalent System Mass (ESM). Break-even plots expand the trade by comparing the lifetime launch mass of a system or set of systems. Basic break-even plots will oftentimes include the mass of consumables as a recurring mass cost. Programs intended for long duration habitation or deep space exploration may be motivated to further increase the complexity of the model to account for reliability and the resulting mass of spares over the life of the program. Lange and Anderson discuss this in their paper, "Reliability Impacts in Life Support Architecture and Technology Selection."[3] Here, a detailed representation of ESM was generated that accounted for spares to compare reliability approaches, with one of the conclusions being that "achieving necessary reliabilities for deep-space missions will add substantially to the life support ESM and could influence the optimal degree of life support closure."[3] The work completed by Owens and Weck expands upon that by developing break-even plots that incorporate initial system, consumable, and maintenance considerations.[4]

Over time, these models have evolved in accuracy by incorporating data gathered on ISS and accounting for an increasing number of model-informative variables. Still, many of these studies focus on using the results for high level decisions such as the degree of loop closure, determination of the reliability requirements for a system, or program logistics planning. The common trend is that many of the existing models begin with the assumption that only existing systems can be selected from, and therefore, the existing systems cannot be changed in their design, and that there is some degree of known performance.

The analysis method presented in this paper builds off these decades of work, but instead looks to inform the early development of systems and the program to influence lower-level design decisions and create a bottoms-up foundation for initial program logistics planning. The sum of the results of these lower-level decisions can have significant impacts on the platform level trades and logistics. By accounting for these considerations in initial design, there can be significant program level impact that is unachievable after system design is completed.

B. Method Considerations

Building on the models discussed above, the analysis method developed by Collins accomplishes two primary tasks: (1) predicting the life of each component within the system and (2) using that life prediction to generate lifetime projections in the form of replacement hardware launch mass, fiscal cost, and other metrics of importance.

Task 1: Defining the Life of a Component

Having a clear understanding of what defines the life of a component is critical to building an accurate model that can predict the need for spares, and therefore predict the lifetime cost of a system. This definition is reached by the completion of five steps.

1. Define a life cycle model.
2. Develop an operational model of the system.
3. Identify the life limiting factors of each component.
4. Define the life of the component associated with each life limiting factor.
5. Calculate the instances of required replacement using the life cycle of the system to simulate consumption of a component over time.

To begin, the preliminary life cycle model for the system is defined. Once each of the primary stages of systems' life cycle are identified, including on ground testing, storage, and operation on orbit, the duration of each is defined. Within each of these durations, an operational model for the stage is developed.

When creating a model, one must consider questions regarding the operation and use of the system, for example: Is the system expected to operate continuously or in a batch fashion? Is a valve expected to cycle during operation and how often? An example of why these considerations are important can be seen when completing an analysis to determine the life of a component where life is defined as number of cycles. Here, it is necessary to account for how the number of crewmembers and intended operation of the system affects the number of cycles experienced by the component per day. If a user increases the number of crewmembers, a water processor may need to be operated more than the assumed baseline operation to meet the water processing load. More frequent operation can contribute to higher wear on components and therefore, a shorter life or shorter maintenance timeframe than a baseline estimate. Identifying these requirements provides higher fidelity inputs to inform the model. In Collins' current state of the model, the operational model information is input as an average value per year via a user interface page. This means the model can account for a crew of four in year one growing to a crew of eight in year five of system operation and reflect how the change in operation impacts the lifetime system performance.

After definition of the operational model and life cycle, the life limiting factors of the individual components within a system must be determined. Pump life is typically dependent upon operating hours and number of on/off cycles. Pressure sensor life is dependent upon operating hours and pressure cycles. Expendable bed size, and therefore its life, is a function of throughput, inlet fluid quality, and required outlet fluid quality. During the definition of life limiting factors, the Collins model allows for the user to label a component as consumable or non-consumable. The former label indicates that an item would have planned maintenance versus the latter label which may or may not have unplanned maintenance.

Once the life limiting factors for each component are identified, the limit associated with each factor must be defined. This will create a realistic expectation of component life developed within the bounds of the targeted total system life. The information sources to consider include:

- *Historical ISS Performance* – Performance from comparable components on ISS can be used as a guide for life. For the ECLSS systems, much of the hardware is operated as a run to failure, providing good insight into actual life.
- *Advertised Commercial Life* – For the commercialization effort, components will be procured from new commercial vendors. Many of these vendors have a database of component performance that can be used to guide component life.
- *Ground Test Performance Data* – In the absence of complete and quality historical or advertised life data, ground testing can be completed to fill in information gaps.
- *Applicable Safety Factor* – Traditional ISS programs apply a 4x safety factor on cycle life. Based upon the pedigree of the data for cycle life, this factor can be adjusted.

It is important to note that this method and associated model are intended to assist with system design and design decisions. Because of this, there are times where a component may not yet have been selected or sized. In these cases, it is necessary to make predictions and be critical of the results. Pulling data from similar components with known performance, capturing that assumption, and completing a sensitivity analysis around the unknowns can be strategies to allow for successful modelling in spite of unknowns.

Finally, the collected information on system operation and life limiting factors are combined to predict the life of the component and when the component will require replacement. This is completed using a life consumption calculation. When a component's life is entirely consumed, it is noted that a spare is required. In its current state, the model created by Collins assumes that spares are always immediately available when required.

This five-step process can be demonstrated with an example from the NextGen WPA inlet valve. A block diagram of the system with the location of the valve marked with a red X is shown in Figure 1. This NextGen system differs from the current ISS system in that it does not include the waste and potable water storage. Because of this design change, the inlet valve used to modulate flow into the water separator from the wastewater supply is required to cycle a large number of times, approximately once per minute, to provide semi-steady flow into the system. Because of the high quantity of required cycles, it was one of the components that benefitted from undergoing this analysis.

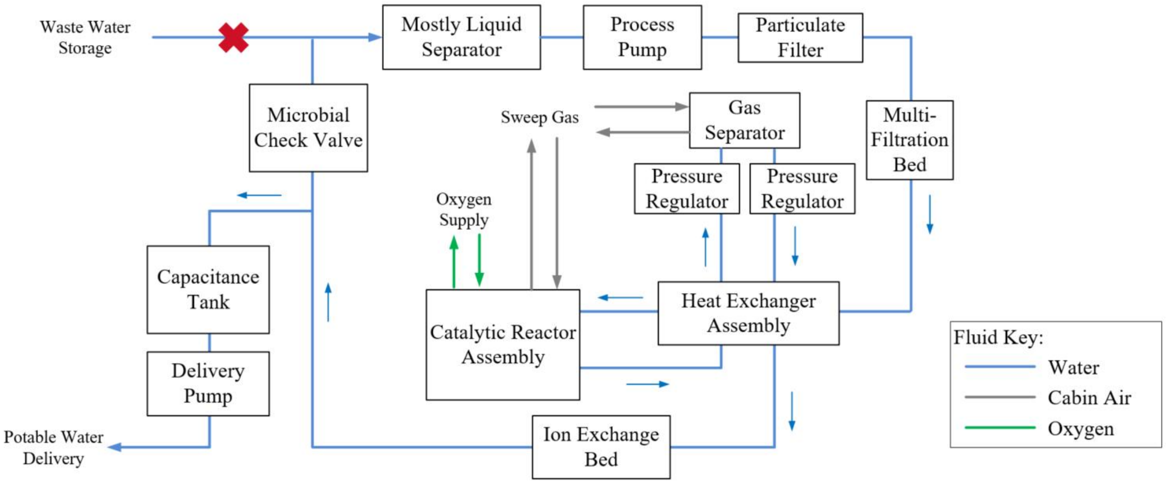


Figure 1. Block Diagram of the Water Processor Assembly with Example Valve Marked by a Red X.

The first and second steps, respectively, in the process are defining preliminary life cycle and associated operational model of the water processor assembly. It is assumed that the WPA will undergo two years of testing before being launch, followed by 10 years of operation on station.

The WPA operation is a batch process, defined by on/off cycles as well as operating duration while active. The WPA is designed to process wastewater from condensate and urine distillate. For a crew of six, 48 lb/day of the wastewater must be processed. At a nominal system flowrate of 10-13 lb/hr, a process cycle would last approximately 4-6 hours with one hour in recycle mode added for every process cycle. Because of the nature of the recycle mode, the valve is cycled an average of once per minute during this operation mode. For this example, the testing on the ground for 2 years would include 100 processing cycles at 4-6 hours of operation per cycle. Following this, the WPA is launched to orbit and processes the wastewater generated by 4 crew members for the first 5 years, then 8 crew members for the following 5 years. This is a total of 32 lb/day or 3-4 hours of operation per day for 5 years, followed by 64 lb/day or 6-7 hours of operation per day for another 5 years. Additional assumptions on operational conditions, such as interface pressure, may need to be made. Specific to the valve, changes in the interface pressure can influence how often the valve will cycle.

Third, the life limiting factors of the valve must be identified. In this case, the life of the valve is limited by total operational life and experienced cycles. Other life limiting factors, such as total flow through, launch/re-entry cycles, and thermal cycles could be considered if critical to a given component's life. The translation of the previous definition for system operation into life impact for the valve is shown in Table 1.

Table 1. Life Consumption Rate for Example Valve.

Life Cycle Period	**Cycles [cycle/year]**	**Total Life – Time Passage [year/year]**
Ground Testing	15,000	1
Launch	0	0
Operation – 4 crew	76,650	1
Operation – 8 crew	142,350	1

Fourth, the life of the component with respect to each life limiting factor must be defined. For the valve considered, these values exist in Table 2.

Table 2. Life Limit for Each Life Limiting Factor.

Life Limiting Factor	Life Limit
Cycles	360,000 cycles
Total Life	10 Years

The life limit associated with each factor is critical to the accuracy of the analysis and can be a challenging piece of information to obtain. As discussed above, this information can come from a variety of sources, each varying in fidelity and statistical significance. In the current model, accounting for the uncertainty with respect to true life of a component is completed by setting a threshold for life consumption at which point maintenance will occur, and the completion of a sensitivity analysis. Future work for the Collins model could be modifying the percent life consumed calculation to a probability of failure calculation. For Collins heritage systems, a safety factor of 4x was typically used to account for a statistically small data sample of component performance. Then in operation, components were often run to the point of failure, resulting in a component seeing much more operation in reality than as was defined in the requirements. This allows for a conservative but not accurate representation of the spares demand of a system. By completing an analysis with and without safety factors, worst case and average results can be attained, respectively. For commercial hardware, this safety factor may be lowered if sufficient industry data is available.

Finally, the compiled information is processed to monitor life consumption over the life of the valve. The developed model accounts for life consumption against all provided factors when predicting end of life. For example, if a material bed has a life of 5 years or 100 lb. water processed, the model will monitor the consumption of both over the defined operating cycle and capture a bed replacement whenever the first limit is hit. In the valve example, the model will compare usage and crew scaling rates to see what limiting factor is hit first, cycles or total life.

At the beginning of use, life consumed is set to 0%. Based on mission milestones, system operation, or the passage of time, life is consumed. Using the valve example, if the WPA operates for a year with four crew members, approximately 81,000 cycles will occur and 22% of the valve's life is considered consumed. When life consumption reaches the defined threshold, the component is assumed to be replaced. When this occurs, the consumed life is reset to 0% and the occurrence of a spare being required is tracked by the model. The threshold of consumed life is selected by the user and should be based on the component and the consequences of failure. The threshold in this example was set to 80%. Figure 2 shows a plot of the percent life consumed over time with key milestones identified. It can be seen that a replacement is required when consumed life reaches 80%. Figure 3 shows the tracked instances of replacement over the life of the system.

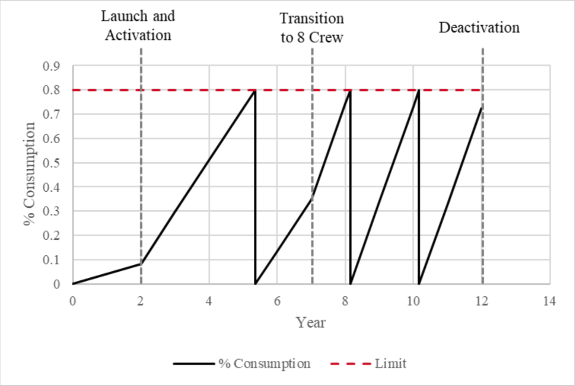


Figure 2. Consumption of Component Life for Example Valve Over Life.

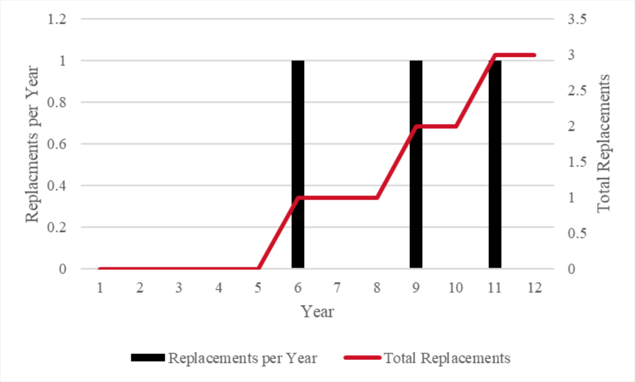


Figure 3. Component Replacement for Example Valve Over Life.

This example demonstrates the completion of the first task in the methodology on the WPA inlet valve. At the completion of this task, each component's anticipated life over the life of the system or area of interest should exist. Additionally, the occurrences of failure or required replacement should be predicted.

Task 2: Addition of Inputs to Generate Life Impacts

Once predictions of the various component lives and instances of required replacement are derived, this information is combined with mass estimates, reliability factors, and cost factors to determine the programmatic cost over the lives of the components. These outputs can then be used for trade studies to select component technology and define boundaries of maintenance units. The additional inputs required for this include component and system level information.

1. Component Level Inputs

At the component level, cost, mass, maintenance considerations, and any other factors of interest are added to the model to be processed into outputs. As was also seen when sourcing information on component life, the availability of information can vary. For heritage components, factors such as cost and mass are often known. For commercial components, these data points may be known, or can be estimated if a component had not yet been sized or selected. The impact parameters are inputs to feed the projections for recurring cost based on planned maintenance. Building on the WPA valve example discussed in the previous section, the mass of the valve can be added to the model to generate the total mass associated with valve maintenance, rather than total number of maintenance occurrences. This is shown in Figure 4.

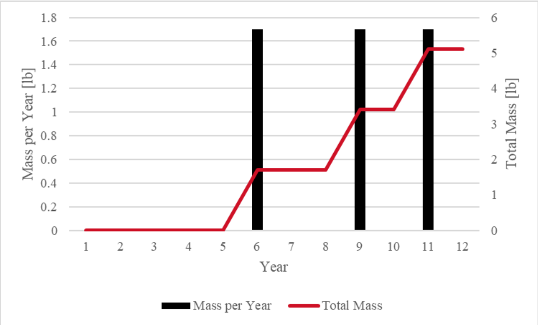


Figure 4. Component Replacement Mass for Example Valve Over Life.

Similarly, cost, size, or any other metric could be tracked. As mentioned in Section IIB, Task 1, the life of a component can be labelled as a consumable or a non-consumable item. This label allows the model to sort activities by consumable or preventative maintenance. Because a consumable's life is a more consistent calculation than an electromechanical component's preventative maintenance cycle, this separation can aid in planning efforts. Additionally, this can be useful in the case of commercial components or components with unknown life, as this can highlight areas with more uncertainty.

2. System Level Inputs

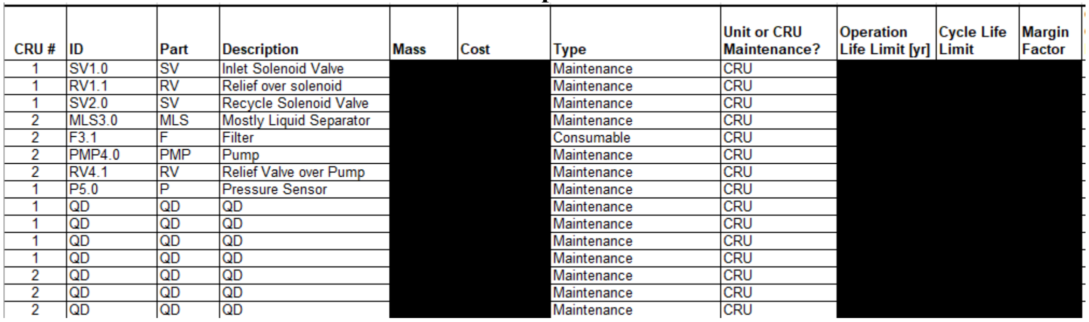
To complete system level assessments, additional inputs are required including system architecture, maintenance division lines, and the maintenance approach. The system architecture is the sum of all components that comprise the full system and some additional factors to account for features not shown at a schematic level. Because the method is intended for initial use and development on systems that are not yet designed, the mass, cost, volume, or other metrics associated with the hardware not shown on a schematic level are oftentimes unknown. These unknowns can include structure, tubing, fittings, insulation, labels, and other supporting hardware required for a system to function. To account for these significant contributors, factors are applied at a component or sub-assembly level. For mass, Collins typically assumes a factor of 1.5 to 2.5. This is based on heritage total mass versus schematic component mass data but varies based on the number of components in the sub-assembly, the type of component in the sub-assembly, and other variables. As the system develops, these factors can be removed and replaced with actuals for the supporting hardware.

The output becomes more accurate if components within the system are grouped by maintenance division lines. Historically, systems have often been divided are into Orbital Replacement Units (ORUs). These maintenance units have typically been defined by functionality within the system and can consist of one or multiple components. The expected life of the ORU is defined by the component with the lowest expected life. If one component in a given ORU fails, the entire ORU is replaced. When redesigning systems for new applications, it can be beneficial to redefine these ORU boundaries to optimize groupings. Collins is doing this through the definition of Crew Replaceable Unit (CRU) in NextGen systems. This re-definition aims to group together components in a way that minimizes lifetime cost metrics such as mass or crew time. This often means grouping components that have the same expected life and will require maintenance at the same time, thus saving both supplier and customer time and money through undesirable replacement of components that still have significant remaining life. By completing the analysis using this methodology on multiple CRU division alternatives, the impact on cost, mass, maintenance, and other metrics over the life of the system for different alternatives can be compared. It is in this way which the model informs the system architects of the optimal CRU boundaries to achieve the aforementioned goal of cost and time savings.

Finally, the level at which maintenance occurs can also be assessed, whether at or below the ORU/CRU level. To do this, the user can denote whether the sub-assembly or the component is replaced in the case of a failure. If the CRU is replaced, all life consumption states are reset to zero for the hardware in the CRU and the full cost of the CRU is accounted for in the lifetime cost. If the component within the CRU is replaced, the remaining components in the CRU continue at their current life consumption state and only the cost of the replaced component is incurred.

An example of the system design and component inputs page of the Collins developed model that follows the described methodology is shown in Table 4. Here, the components and their associated information of interest are shown for the WPA inlet. Note that some column inputs have been redacted to protect proprietary information.

Table 4. Inputs for WPA Inlet.



CRU #	ID	Part	Description	Mass	Cost	Type	Unit or CRU Maintenance?	Operation Life Limit [yr]	Cycle Life Limit	Margin Factor
1	SV1.0	SV	Inlet Solenoid Valve	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
1	RV1.1	RV	Relief over solenoid	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
1	SV2.0	SV	Recycle Solenoid Valve	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
2	MLS3.0	MLS	Mostly Liquid Separator	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
2	F3.1	F	Filter	[redacted]	[redacted]	Consumable	CRU	[redacted]	[redacted]	[redacted]
2	PMP4.0	PMP	Pump	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
2	RV4.1	RV	Relief Valve over Pump	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
1	P5.0	P	Pressure Sensor	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
1	QD	QD	QD	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
1	QD	QD	QD	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
1	QD	QD	QD	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
1	QD	QD	QD	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
2	QD	QD	QD	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
2	QD	QD	QD	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]
2	QD	QD	QD	[redacted]	[redacted]	Maintenance	CRU	[redacted]	[redacted]	[redacted]

III. Model Outputs and Use

The goal of developing this method and the associated model was to create a tool that enabled more informed system and program design from the beginning of a project. The direct outputs of are an anticipated commercial life with a projection of when failures and/or planned maintenance will occur. This summary is available at the component level, the ORU/sub-assembly level, or the system level, all of which are important views to consider when defining the system. The current state of the Collins developed model allows for output by year, and future work could increase the granularity of outputs to enable monthly or weekly reports. Because the current model is intended for use in the early stages of development of a system, the benefit of increased granularity at the early stages may not be large due to the limited accuracy. The indirect outputs can include hardware cost, mass, or other variables of interest for the initial system and over the operational life of the system. Completing the system level analysis for different configurations allows direct comparison of the variables of interest and selection of the optimal design for a given application.

A. Impact on Initial Design

The outputs of this analysis can inform the initial component selection, ORU/sub-assembly division, and system architecture design. By comparing the outputs of alternate configurations, the optimized configuration can be selected.

i. Informing Component Selection

A current discussion point for many trades in commercial space is where traditional space hardware can be replaced with lower cost, commercial alternatives. Depending on the priorities of a platform, this decision may require the trade to be considered over the life of a system, rather than only the initial cost of a component. By completing the activity discussed in Section IIA for multiple components, this analysis method allows for comparison of lifetime ownership between alternatives. For example, two sample valves can be compared over the 12-year operation of the system for the application in the example of Section IIB, Task 1. The space grade valve has a cycle life of 360,000 cycles and an assumed cost of 5x the commercial alternative. The commercial valve is assumed to have a cycle life of 100,000 cycles and a 1x cost. Both valves are assumed to have equal crew time per replacement and mass per valve. When completing the analysis, the plots in Figure 6 can be generated to show the replacements over life, with those numbers translated to the variables of interest in Table 5.

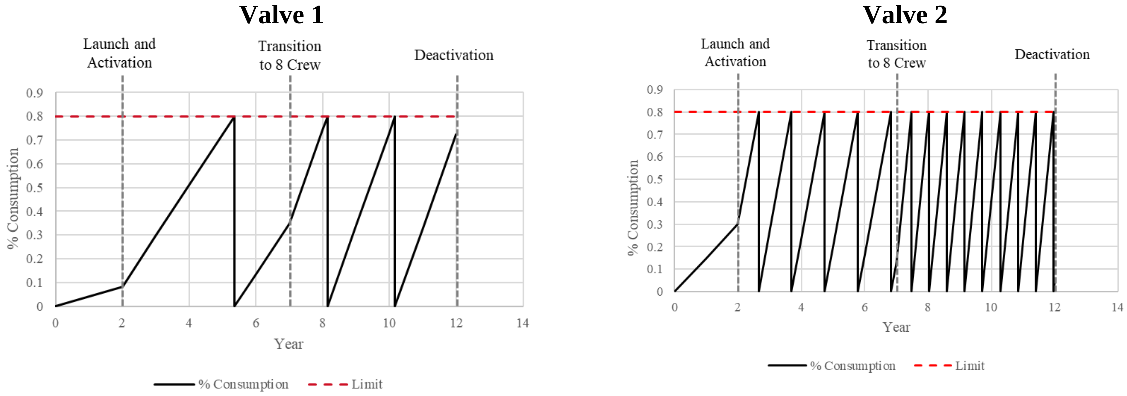


Figure 6. Comparison of Consumption of Component Life for Two Example Valves.

Table 5. Impact of Component Selection for Variables of Interest.

Metric	**Valve 1 – Space Grade**	**Valve 2 - Commercial**
Total Spares Anticipated	3	14
Mass	5 lb	24 lb
Hardware Cost – Initial	5x	1x
Hardware Cost – Lifetime	15x	14x
Crew Time for Maintenance	3 hr	14 hr

For the space grade valve, there are 3 valve replacements required, resulting in a total mass of approximately 5 lb, a total estimated crew time of 2.25 hours, and a total cost that is 1.07x the total cost of the commercial valve. In contrast, the commercial valve has over 4 times the required launch mass and crew time.

The results of this analysis show that although the commercial valve is a vast reduction in initial cost, the lifetime impact of the valve is greater than the space grade alternative. However, it must be noted that there are many assumptions made in this analysis. First, the advertised life of a commercial component may be lower than the actual achievable performance. This drives the need for life testing and increased data collection for a more accurate view. Second, as is discussed further in ICES-2024-174 “Case Study of the Benefits of Collaboration Between Aviation and Space”[5], there are many additional considerations that must be accounted for when considering the true cost of a commercial component. This can include the ability for a commercial component to meet the necessary quality, design and construction, material, electrical, or other requirements for a space system and the added cost of any required non-recurring efforts or recurring modifications.

It is also important to note that the results are not consistent for every trade between commercial and space grade hardware. Different applications or products can hugely sway the trade in one way or another. The final decision based on these outputs could vary across applications, products, or platform. Extrapolated across an entire system, the difference in initial cost may justify the increased lifetime impact, delaying those impacts until a steady income stream is created. Additionally, there are other considerations that must be accounted for such as the safety critical nature of a component.

There are two major takeaways from this example:

- The developed method cannot make a final decision in isolation but can provide valuable data for a more complete trade.
- This analysis should be completed for each instance on a case-by-case basis, as the results vary more than trends hold. Traditionally, this could take a large amount of time, but the tool enables a thorough analysis in seconds.

ii. ORU Division

It is clear that the components selected for use in a system are large drivers of the system’s lifetime program impact. When considering the impact of spares and consumables, the division of maintenance units and level at which maintenance will occur also influence the system’s lifetime cost.

Redefinition of heritage ORU boundaries was first investigated by Collins Aerospace as part of NASA’s Next Space Technologies for Exploration Partnerships (NextSTEP), with the vision of an ECLSS capable of supporting in-flight maintenance and repair. These new division lines defined Maintenance Units (MU), which were designed to be removed from the system, taken to a workbench, and repaired by fixing or replacing smaller subcomponents. During this work, Collins was able to develop design principles for maintainability, showcase how the ECLSS can be designed for in-flight maintenance, and identify factors to consider when defining the boundaries of MUs. Although MUs were specifically designed with the considerations necessary for deep space, there are still valuable lessons to consider when designing for LEO.

Boundary definition for MUs is influenced by a number of factors, some of which are listed below in Table 6. It should be noted that this list is not exhaustive because each MU is unique in its operation and environment, therefore each MU requires individual consideration; however, the following factors occurred most prevalently when defining MU boundaries. These factors include necessary considerations for safety and accessibility, but do not include qualitative metrics that can be used to select between multiple safe or generally acceptable configurations.

Table 6. Common factors that influence the definition of MU boundaries.[1]

Simplicity	Is the MU boundary defined intuitively/simply?
Safety	As defined, is the MU safely removed from the system or is a higher-level definition of the assembly required?
Working Fluids	How many working fluids are interrupted by MU removal? (Fewer is better)
	What kind of working fluid is interrupted? Is it hazardous?
Acceptance Testing & Verification	What testing (Ex. bench testing) can be done to verify that a repair or rework has resulted in an acceptable fix? Can acceptance testing be performed?
Accessibility	How accessible is the hardware? Is the MU as defined easily removed? (e.g. are Quick Disconnects (QDs) used?)
Failure Modes	What type of failure is being addressed? (e.g. electrical vs. mechanical)
	Is it possible to avoid exposing the working fluid to the cabin environment?

The Collins model can assist in developing sub-assembly division decisions by allowing for the comparison of lifetime impacts of systems with alternate designs. This can be shown by walking through an example boundary definition activity for the inlet of the WPA. The inlet includes two valves, a rotary separator, and a pump work together to provide gas free wastewater to the system for processing. A block diagram of this portion of the system is shown in Figure 7.

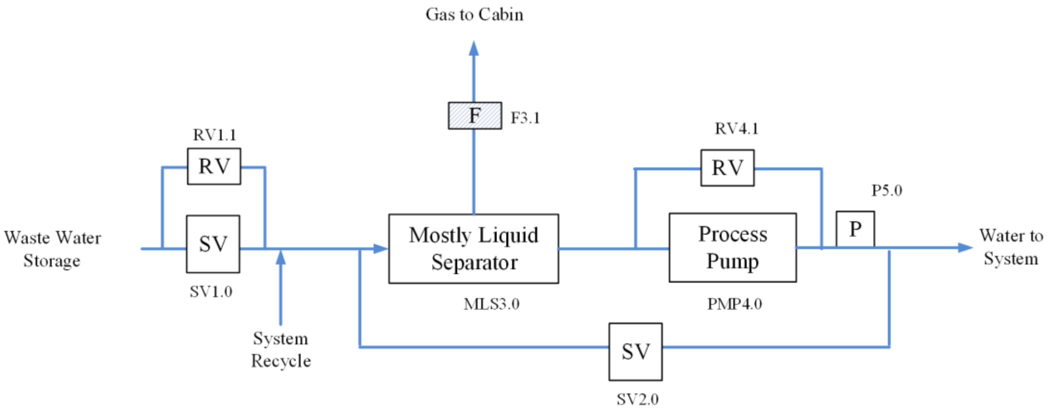


Figure 7. Block Diagram of the Inlet of the WPA.

For this example, the model can first be run assuming each component is individually maintainable. This is the same as completing the component level analysis described in Section II above and allows us to observe the anticipated life of each component. The results of this are shown in Figure 8.

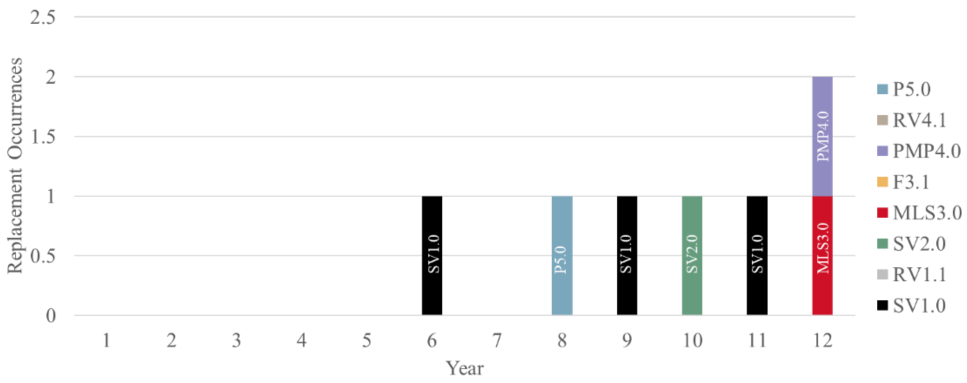


Figure 8. Replacement Occurrences for Each Component in WPA Inlet.

Then, the factors described in Table 6 and the initial results in Figure 8 can be used to group components based on expected life. Defining CRUs at the individual component level may at first seem like the logical choice, as this would enable each component to reach its full life before requiring replacement. However, several factors may drive the need to group components. First, the physical limitations like the fluid in a line may make maintenance where that line is required to be broken impossible or costly. Second, quick disconnects are often times added to the inlets and outlets of a maintenance unit. Each additional QD in a system adds cost, mass, volume, and another item where reliability must be tracked. QDs also decrease the packing density because of the added hardware and increased required access points. Ultimately, there is no priority when weighing these factors and final CRU boundaries should be chosen based on final application/customer need.

Assuming that each component will not be individually serviced without QDs, the user must then tell the model how to group components. For this example, two configurations will be compared. In the first, valve SV1.0 and the relief valve around it will be placed in an independent CRU due to the frequency of maintenance. The mostly liquid separator and pump will be placed into a CRU together, as their anticipated life is approximately equal. This CRU will include the accompanying hardware. Finally, valve SV2.0 and pressure sensor 5.0 will be placed in a CRU together. For configuration 2, CRUs 1 and 3 will be combined. The CRU divisions are summarized in Table 7. It is assumed that every broken fluid connection would have a QD on each side of the break, that there are no hazards that would limit the discretization of components into CRUs, and that both configurations would allow for accessibility for maintenance.

Table 7. CRU Division Definition.

CRU	**Configuration 1 Components**	**Configuration 2 Components**
CRU 1	SV1.0 RV1.1 QD Qty 2	SV1.0 RV1.1 SV2.0 P5.0 QD Qty 4
CRU 2	MLS3.0 F3.1 PMP4.0 RV4.1 QD Qty 4	MLS3.0 F3.1 PMP4.0 RV4.1 QD Qty 3
CRU 3	SV2.0 P5.0 QD Qty 3	N/A

When the analysis is completed, the CRU required maintenance occurrences and mass can be compared. Other factors like cost or maintenance time could also be compared but are not considered in this example. The results are shown in Figure 9.

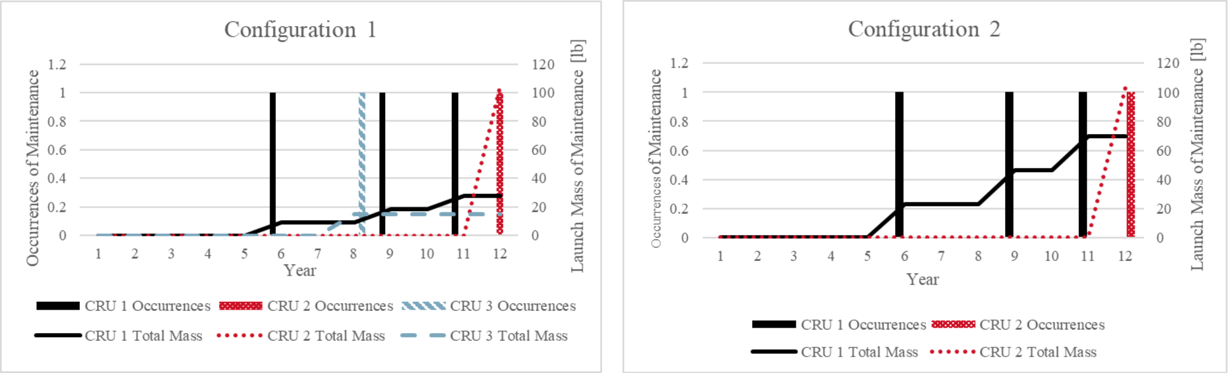


Figure 9. Configuration 1 and Configuration 2.

Table 8 contains a summary of the impact output. From this analysis, it can be seen that Configuration 1 has a has an increased number of required maintenance activities but a reduced mass of maintenance hardware over the life of the system. Although the differences between these configurations may seem small, completing a similar analysis over an entire system, or multiple systems, can have large impacts on platform lifetime metrics.

Table 8. Summary of Impact for Two Alternate Configurations.

	Configuration 1	**Configuration 2**
Maintenance Occurrences	5	4
Mass of Hardware	148 lb	173 lb

One final note on CRU division is that the methodology can inform division lines that optimize interest variables, but the realities of mechanical design may limit the extent to which creating CRUs with the optimized divisions are possible. Because of this, the model must be used while considering the factors in Table 6 as well as the limit of possibilities for mechanical design. As the system develops, the dynamic nature of the model allows for the analysis to be rerun as more data is available.

iii. System Architecture

The developed model can also assist by providing system level data for alternate systems or system configurations. By completing the exercise described above, the system level impact of the decision can be compared. An example of an application where this system level architecture can be informed is the work being completed by Collins in redesigning the Oxygen Generator Assembly to include an anode rather than cathode fed cell stack to increase the reliability and reduce cost of the system. However, changing the technology of the cell stack required changes to the larger system design, such as the inclusion of an additional microgravity phase separator. By applying this analysis method, the key metrics of the two alternate system designs can be compared. This design change is further discussed in the paper ICES-2024-2018 “NextGen Oxygen Generating Assembly (OGA) for Commercial Aerospace”[6]. In addition to this, an example of the system level outputs of the method with respect to the WPA can be found in Section IV.

B. Impact on Sustaining Engineering Plan and Leto™

The outputs described above can assist in generating estimates or an initial sustaining engineering plan for the program. After the final design is determined, the required occurrences of maintenance and the cost, mass, or other impacts of that maintenance can be used to anticipate occurrences of required component or CRU replacement. In doing so, the outputs of the model can be used as preliminary inputs to a traditional Traffic Model. However, this model is not intended to act as a Traffic or Life Limiting Component analysis, as those analyses require large amounts of additional inputs and considerations.

In addition to the impact on sustaining engineering operations, the results of this model accelerate the development of Leto™, Collins’ AI-powered spaceflight intelligence system, and decrease the time-to-value of its implementation for the next generation of commercial ECLSS. Leto™, discussed further in ICES-2024-210[7], is a full-stack system that uses physics-based models and AI-powered algorithms to continuously monitor and inform ground support personnel and onboard crew about the performance of their vehicle's ECLSS.

Leto™ is trained and verified on decades of spaceflight telemetry, but like other modern AI systems it requires an initial ‘understanding’ of how different ECLSS subsystems should behave when operating nominally. More importantly, it needs to understand the factors that can lead to off-nominal operation. For example, to predict when the Multi-filtration Bed in the Water Processor will degrade to the point of needing replacement, Leto™ is taught to monitor the conductivity of the water, among other parameters. The patterns in the conductivity of the water contribute to the leading indicator ‘signature’ that suggests when a filter change is required. The outputs of this method, including identification of data sources, component replacement histories, and aggregation of event rationale (e.g. SME knowledge) can all be used as starting inputs to Leto™ to begin learning and adding value to current and future life support systems.

IV. Large Scale Study – ISS Water Processor Assembly

To show the value and shortcomings of creating and applying this model, a study on the WPA from activation to 2015 was conducted. To complete the study, several WPA models were created following the steps defined above. The first model created was a baseline model of the ISS WPA. Table 9 contains the predicted instances of maintenance by the model and the actual instances of maintenance reported.[8]

Table 9: Comparison of the Model Mass and Maintenance Against Actual Values

ORU	Reported Instances of Maintenance[8]	Predicted Instances of Maintenance
Waste Water Tank	0	0
Pump Separator	2	0
Separator Filter	1	1
Particulate Filter	1	1
Multi-Filtration Bed	4	3
Sensor	0	0
Catalytic Reactor	3	1
Gas Liquid Separator	0	2
Reactor Health Sensor	0	0
Ion Exchanger Bed	1	2
Microbial Check Valve	2	1
Water Storage	0	0
Water Delivery	0	0
Process Controller	0	0
Oxygen Filter	0	0
External Filter Assembly*	4	4

* Assumed that the existence of the External Filter Assembly was known at the beginning of the program.

From the table, it can be seen that there is a discrepancy in the predicted and reported instances of maintenance. This highlights a shortcoming of the model in that it, like any model, will not be able to predict unexpected causes of failure. For example, the Pump Separator ORU was replaced twice, and the model does not predict either instance of failure. The actual failures were a pump failure that was unpredictable using cycle life analysis and a valve failure caused by blockage due to bacterial growth and shedding in the wastewater storage tank.[9] Modifications made to the system design and operation have improved this failure case. Moving forward with this example, the corrections were applied to the component lives to better represent actual performance on station.

Using the information gained through operation, the boundaries of the ORUs can be redrawn to reduce the mass impact of the failures experienced. A second model of the WPA was created with the ORU boundaries redrawn. In this model, the Pump Separator ORU was redesigned to move the separator to an independent ORU and the Catalytic Reactor ORU was redesigned to move much of the oxygen hardware into the oxygen filter ORU and several sensors and a pressure regulator into the Gas Liquid Separator ORU. Figure 10 compares the occurrences and mass of maintenance reported for the WPA in operation, the maintenance for the ISS WPA as predicted by the model, and the maintenance for a WPA with redesigned ORUs as predicted by the model. Both model predictions incorporate the component life corrections based on ISS performance. By considering ORU definition based on component life, the maintenance mass of the system predicted by the model was able to be reduced by over 150 lb during the 6 years of operation. This can be seen comparing the red and blue lines in Figure 10.

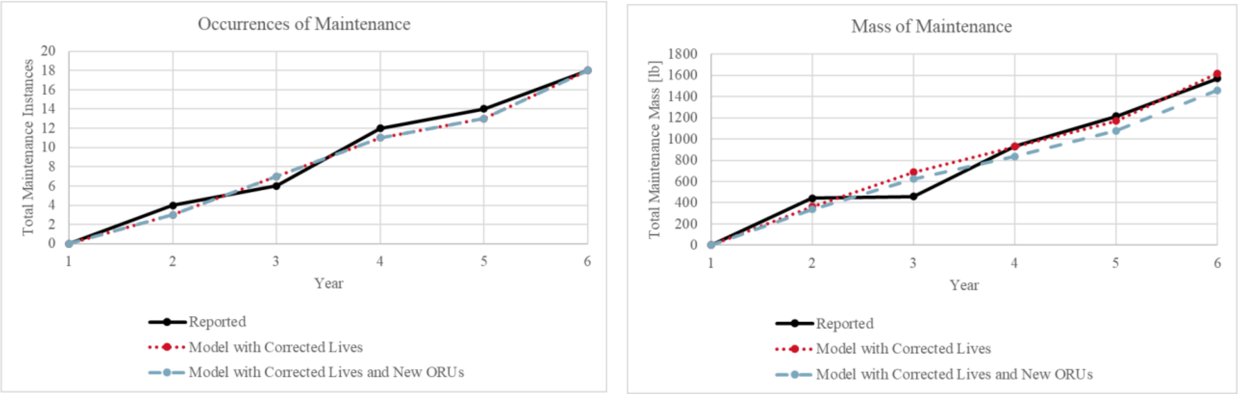


Figure 10. Maintenance Instances and Mass as a Function of ORU Division.

From Figure 10, it can also be seen that the mass predictions for the model do not exactly align with the reported mass for maintenance over the life of the system. This is due to an average absolute percent error of approximately 10% between the actual mass of the WPA ORUs and the mass calculated by the model. The discrepancies are primarily due to the differences in the actual mass of miscellaneous hardware such as manifolds compared to the mass calculated through the application of the miscellaneous mass factor. Although the exact mass of each ORU within the WPA could be input into the model to remove this error, this still would not result in an entirely accurate result after redefinition of the ORUs.

The next portion of the study looked at how replacing space grade components with commercial components would impact the maintenance mass over the life of the system. To assess this, all valves in the system were assumed to be replaced with commercial valves having a very conservative cycle life of only 7,000 cycles. Table 10 displays the predicted failures for each ORU before and after making the switch to commercial valves. Note that this table does not assume the actual lives of components seen on station, but rather the lives that would have been predicted at the onset of the WPA program. From this table, it can be seen that the valve life reduction impacts the Pump Separator ORU, the Water Storage ORU, and the Water Delivery ORU.

Table 10. Maintenance Instances With and Without the Inclusion of Commercial Valves.

ORU	**Predicted Instances of Maintenance *Space Grade Valves***	**Predicted Instances of Maintenance *Commercial Valves***
Waste Water	0	0
Pump Separator	0	5
Separator Filter	1	1
Particulate Filter	1	1
Multi-Filtration Bed	2	2
Sensor	0	0
Catalytic Reactor	1	1
Gas Liquid Separator	2	2
Reactor Health Sensor	0	0
Ion Exchanger Bed	2	2
Microbial Check Valve	1	1
Water Storage	0	1
Water Delivery	0	1
Process Controller	0	0
Oxygen Filter	0	0
External Filter Assembly	4	4

To reduce the impact on the system, the failing valves could be returned to their heritage equivalent, moved into an independent ORU, or moved into an ORU with a more similar life, if that is an available option. Figure 11 shows the instances and mass of maintenance for the model with the heritage hardware and heritage ORU configuration, the model with all commercial valves and heritage ORU configuration, and the model with selective commercial valve usage and a redesigned ORU configuration. In this third configuration, the valve in the Pump Separator ORU was replaced with the heritage valve and the valves in the Water Storage and Water Delivery ORUs were separated into independent ORUs.

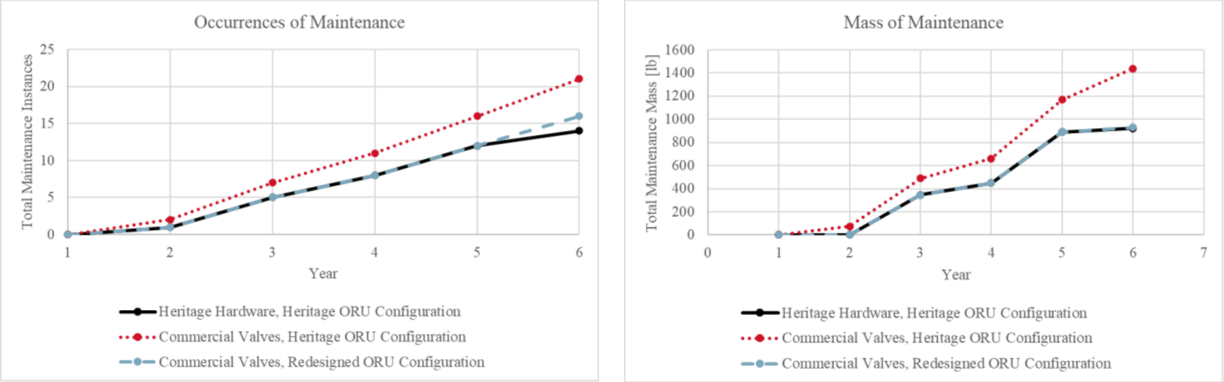


Figure 11. Maintenance Instances and Mass With and Without the Inclusion of Commercial Valves.

By overarchingly applying commercial hardware, the predicted system maintenance mass over life increased from 920 lb to 1440 lb. However, by redesigning the ORUs according to the considerations discussed in this paper, the commercial valves can be implemented in all cases except one with a net mass impact of only 930 lb. This is a 10 lb increase over the life of the system.

From this study, there were three primary takeaways:

1. Models are limited in their ability to accurately predict all sources of failure, but a well-built model can be updated and continue to be used as more information becomes available.
2. Models that account for component life can be beneficial in assessing where commercial hardware is more or less beneficial.
3. Redrawing ORU lines with component life in mind can significantly reduce the launch mass of maintenance items.

VI. Future Work and Short Comings

Completion of this method provides quantitative ways to assess alternate design decisions and inform program plans. ICES-2024-173 “Development of a Model for Quantifying Technical Trades Using Cost in Commercial Space”[10] discusses how these outputs can undergo further processing to complete a trade considering additional factors such as engineering efforts, the passage of time with resulting fiscal impacts, and launch cost normalized to a total cost. However, the model in its current state does have opportunities for future work. Such opportunities include expanding the accuracy and quantity of the input data, incorporating statistical analyses to improve the life estimations, and enabling real-time feedback to compare model predictions to real-life operation. As previously mentioned, the current state of the model allows for output by year, but future work could enable monthly or weekly reports to provide a more refined predictive maintenance outlook for our customers.

It is known that the accuracy of any model is limited by the accuracy of the data used in the model. The life limit associated with each factor is critical to the accuracy of the analysis and can be a challenging piece of information to obtain. As discussed above, this information can come from a variety of sources, each varying in credibility and statistical significance. One area where there is opportunity for more accurate data is system operation. While Collins can predict current WPA processing time, recycle, and downtime, there is no direct pipeline to seeing exactly how the astronauts utilize the current on-orbit system each day. Additionally, on-orbit usage will most likely vary from customer to customer depending on the platform. This input is subject to human factors- making it only predictable if the system is operated as suggested by Collins. The input becomes even more complicated with systems that have less predictable uses such as the UWMS. However, it is expected that as the commercial space industry grows, data and the credibility of data will increase.

Future work on this model also includes the incorporation of more detailed failure mode considerations. In addition to “when”, it is also important to understand “how” and “why” a component reaches end of life, as different causes may have different impacts. For instance, unplanned maintenance for a never-before-seen quality defect may not have the same statistical occurrence as an unplanned maintenance for a known failure mode. An example of this would be the Gas Separator (GS) in the current WPA. Two GS have failed after 68,000 lbs throughput of water. This will likely be the failure mode if the heritage component is used in the NextGen system but may or may not change if a commercial alternative is selected.

The model also does not account for cascading failures. This is discussed in ICES-2019-14 “High Reliability Requires More Than Providing Spares”[11] and represents an opportunity for future work. It is desired by the model creators to conduct FMEA with Safety and Reliability teams to get more detail on the likelihood of certain unplanned failures.

Finally, an area of future work that will be critical to refining future models is to alongside engineers during the system’s development and the system owners over its life to assess prediction accuracy, improve future models, and inform Leto™.

VII. Conclusion

As the space industry continues to change, it is essential to reevaluate the tools, approaches, and data used in decision making. The analysis method described in this paper provides a means to assess the impact of low-level design decisions on lifetime system performance. It was shown that considering component lives and maintenance unit division lines during system design can significantly reduce the maintenance frequency, mass, crew time, cost, and other metrics of a given system. By considering these factors at the onset of a program, design decisions can be made that better align with platform owner needs. The development of the model can also be used to inform the sustaining engineering plan and be used as initial inputs to predictive maintenance AI tools such as Leto™. Through this model and the development of Leto™, Collins is well on its way to the goal of providing life support systems that are technically robust while easing the maintenance burden on the customer.

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