Maintenance Support for the

Reusable Launch Vehicle Program:

The RLV Repair Cycle Simulator*

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INTRODUCTION

The reliable and successful operation of the next Reusable Launch Vehicle (RLV) program will depend fundamentally on the efficiency of the vehicle maintenance process that is established. In turn, the efficiency of the vehicle maintenance process will depend fundamentally on the resource strategies that are put in place to support it. Recognizing these facts, NASA has engaged Cornell University in developing analytical tools for determining and evaluating resource strategies for the Reusable Launch Vehicle (RLV) program. As part of this effort, we have developed the RLV Repair Cycle Simulator (RRCS), a simulation tool designed specifically for the evaluation of alternative resource strategies for the Reusable Launch Vehicle (RLV) program. The purpose of this document is to describe the RRCS and provide a guide for its use.

This remainder of this document is organized as follows:

➢ *RRCS Modeling Framework*: This section outlines the basic framework upon which the simulation model is based, including descriptions of the part types that undergo regular maintenance (LRUs and SRUs), the RLV ground maintenance process, the LRU repair process, and the SRU repair process.

➢ *RRCS User Reference Guide*: This section describes the programming model for the RRCS and gives detailed instructions on how to use the simulator.

➢ *RRCS Workcenter Scheduling Rules*: This section describes the rules embedded in the scheduling logic components of the RRCS for selecting parts to service.

RRCS MODELING FRAMEWORK

This section outlines the basic framework upon which the simulation model is based. It is divided into five subsections:

- Part Descriptions

- The RLV Maintenance Process

- The LRU Repair Process

- The SRU Repair Process

- Additional Assumptions

Part Descriptions

The RRCS model considers two classes of RLV parts that undergo regular maintenance: line replaceable units (LRUs), and shop replaceable units (SRUs).

- LRUs

  LRUs are modular parts (or subsystems) that are tested in-place on an RLV during the vehicle maintenance cycle. If an LRU fails its test, the part is removed from the vehicle and replaced with a spare LRU (if one is available). Meanwhile, the failed LRU enters a repair process in which the cause of its failure is identified and remedied.

- SRUs

  SRUs are modular components of LRUs. An LRU failure may be due to a failure in one or more of its SRU components. During the LRU repair process, if an LRU failure is determined to be the result of one or more SRU failures, then the failed SRUs are removed from the LRU and replaced with spare SRUs (if available). Each failed SRU then enters its own repair process in which the cause of its failure is identified and remedied. Components needed to repair SRUs are presumed to be readily available and are not considered in the RRCS model.

The RLV Maintenance Process

The RLV maintenance process modeled in this project includes two basic components: the ground maintenance cycle pattern, and the ground maintenance schedule.

- Ground Maintenance Cycle Pattern

  RLV ground maintenance takes place between the time an RLV lands and the time of its subsequent launch. RLV landings and subsequent launches are presumed to follow a fixed, cyclic pattern, and the time windows in which ground maintenance is scheduled to take place are presumed to follow the same cyclic pattern. In this model, the ground maintenance pattern is fully defined by the length of the maintenance window and the time between the start of consecutive RLV maintenance cycles.

- Ground Maintenance Schedule

  The ground maintenance schedule specifies the times within a maintenance cycle at which each LRU type is checked for soundness. Regardless of when the LRUs are checked during the maintenance cycle, all failed LRUs must be replaced by the end of the scheduled maintenance window in order to avoid a delay.

The LRU Repair Process

When an LRU fails, it is either sent away for repair, or it enters an in-house repair process. In this subsection we describe the process for in-house repairs. The in-house repair process begins as the failed LRU is removed from the vehicle. The LRU is transported to a repair site where it is queued for service at an appropriate LRU workcenter or group of workcenters. The LRU service process has two phases, failure diagnosis and repair.

During the failure diagnosis phase, the cause of the LRU failure is determined. The failure may be the result of one or more failed SRU components, or it may be the result of conditions not related to the SRU components. In addition, the LRU failure may be repairable or irreparable. If the failure is repairable, the LRU continues on to the repair phase. If the failure is irreparable, the LRU and its constituent SRUs are condemned. Depending on the condemnation policy for the LRU in question, an order may be placed for a replacement LRU upon condemnation.

During the repair phase, any faulty SRU components are replaced with available serviceable spares, and the LRU is prepared for subsequent use on a vehicle. A failed LRU that has just been diagnosed will have its repair begin immediately on the same workcenter if all of the needed SRU components are available in serviceable SRU stock at that time or if the failure is the result of conditions not related to the SRU components. However, if one or more of the needed SRU components are not available, the LRU is placed back in the repair queue and must wait to be repaired until all of the needed SRU components are available.   Once an LRU has been repaired, it is transported to a stock location where it is then available for use.

The drawing below depicts the LRU repair process:

LRU Repair Process

LRU Removed from RLV		Possible Condemnation		LRU Available for Use	
Transport-In	Repair Queue	Diagnosis	Possible Wait for SRU's and Repair Queue	Repair	Transport-Out

TImeline
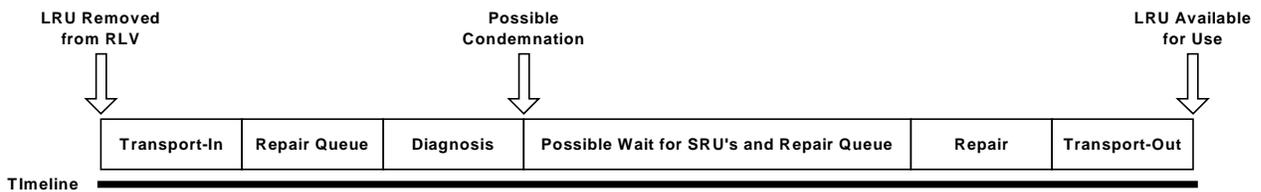
The SRU Repair Process

As described above, SRU failures are detected during the LRU failure diagnosis phase. When an SRU failure is detected, the failed SRU is removed from the LRU and is transported to a repair site where it is queued for service at an appropriate SRU workcenter or group of workcenters.

Once selected for repair, the SRU undergoes a service process similar to the LRU service process, except that there is no waiting time for components in the SRU service process if the failure is deemed repairable. Once an SRU has been repaired, it is transported to a stock location where it is then available for use.

The drawing below depicts the SRU repair cycle:

<u>SRU Repair Process</u>
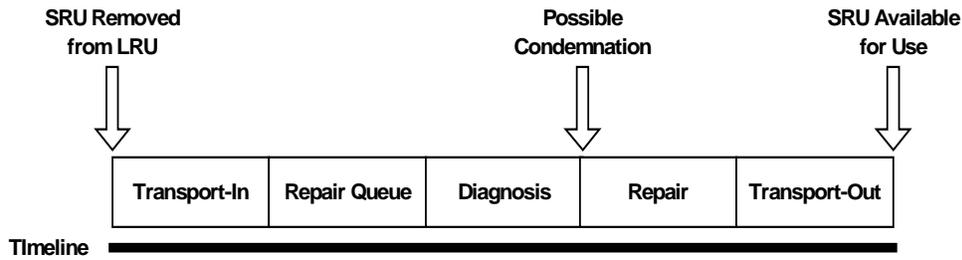
Additional Assumptions

RLV

1. Each RLV contains exactly one LRU of each type.

2. RLVs are serviced in a fixed cyclic pattern, and the times at which LRU types are tested for soundness are fixed within the maintenance cycle.

LRU

3. Each LRU contains at most one SRU of each type.

4. LRU failures are independent of one another and are identically distributed within LRU type.

5. Each LRU type is either repaired in-house or sent away for repair.

6. If an LRU is sent away for repair, its constituent SRUs are assumed to be repaired in the process.

7. If multiple backorders exist for the same LRU type, the oldest backorder will be filled first when an LRU of this type becomes available.

8. Each LRU type repaired in-house requires a single, specific type of workcenter upon which all diagnosis and repair tasks are completed. Different LRU types may require the same type of workcenter.

SRU

9. Each SRU type is either repaired in-house or sent away for repair.

10. SRU types belonging to different LRU types fail independently of one another.

11. SRU types belonging to the same LRU type fail independently of one another across maintenance cycles, but failure dependencies can exist within a maintenance cycle.

12. Each SRU type repaired in-house requires a single, specific type of workcenter upon which all repair tasks are completed. Different SRU types may require the same type of workcenter.

Workcenters

13. Each workcenter can service at most one part at a time.

14. The LRU and SRU workcenters are distinct, so the two classes of parts to do not compete for the same repair capacity.

15. The LRU workcenters are devoted to servicing the failed LRUs that enter the service queue. That is, there is no outside competition for LRU repair capacity.

16. The SRU workcenters are devoted to servicing the failed SRUs that arise from the LRU repair process. That is, there is no outside competition for SRU repair capacity.

17. A workcenter will not be kept idle if there is work waiting for that type of station. Thus, stations will not remain idle to accommodate anticipated arrivals or completions.

18. Service at the LRU and SRU workcenters is not interrupted for higher priority work. Once a service is initiated, it is completed before service on another part begins on the same station.

Other

19. Once repaired, an LRU or SRU does not fail until used again.

20. Cannibalization is not allowed.

RRCS USER REFERENCE GUIDE

This section provides details on how to use the RLV Repair Cycle Simulator. It is divided into four subsections:

- Programming Model: This subsection describes the entities used to capture the processes within the RRCS framework.

- Operating the Simulator: This subsection includes general instructions for using the RRCS, such as those related to screen navigation, initializing data, and starting the simulation.

- Entering Data: This subsection describes the input screen for the RRCS and each individual input field.

- Viewing Output: This subsection describes the output screen for the RRCS and each individual output field.

Programming Model

The previous section illustrated the high-level modeling framework upon which the RRCS is based. Recall that this framework included three primary processes: the RLV maintenance process, the LRU repair process, and the SRU repair process. The programming model for the RRCS uses four types of interconnected entities to capture these processes: events, activities, scheduling logic, and inventories.

Events

Events are significant occurrences that happen instantaneously and trigger an activity within the RLV maintenance process. In the diagrams that follow, events are represented by rounded rectangular objects. The following diagram illustrates the 14 events addressed by the RRCS:
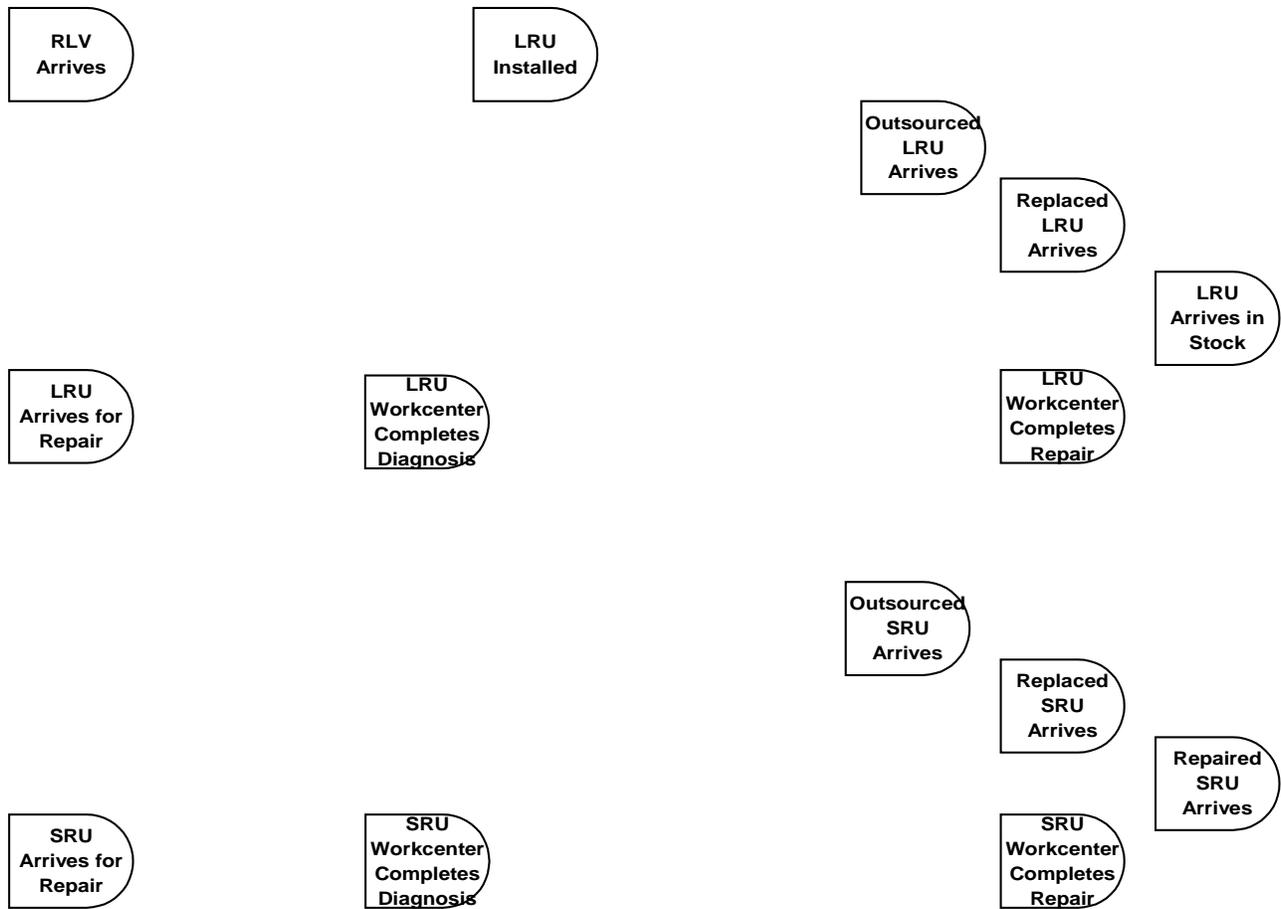
Figure 1: Events in the RRCS Programming Model

The 14 events captured in the RRCS can be grouped into three categories:

- RLV Maintenance Events: The entire RLV maintenance process is initiated by an RLV arriving to begin ground repair and ends with the last LRU for that RLV being installed.

- LRU Repair and Replacement Events: Four events describe critical moments in the LRU repair process: LRU Arrives for Repair, LRU Workcenter Completes Diagnosis, LRU Workcenter Completes Repair, and Repaired LRU Arrives (in stock). For the outsourcing process there is only one event: Outsourced LRU Arrives (in stock). LRUs that are condemned after diagnosis must be replaced. The replacement process has one event: Replaced LRU Arrives (in stock).

- SRU Repair and Replacement Events: Four events describe critical moments in the SRU repair process: SRU Arrives for Repair, SRU Workcenter Completes Diagnosis, SRU Workcenter Completes Repair, and Repaired SRU Arrives (in stock). For the outsourcing process there is only one event: Outsourced SRU Arrives (in stock). SRUs

that are condemned after diagnosis must be replaced. The replacement process has one event: Replaced SRU Arrives (in stock).

Activities

Activities are significant actions that take place within the RLV maintenance process. They are denoted by rectangular objects. Activities typically are triggered by events and require time and resources (workcenters and inventory) in order to complete. The simulation program uses these activities to generate the time of some completion event. The following diagram illustrates the 10 activities performed by the RRCS:
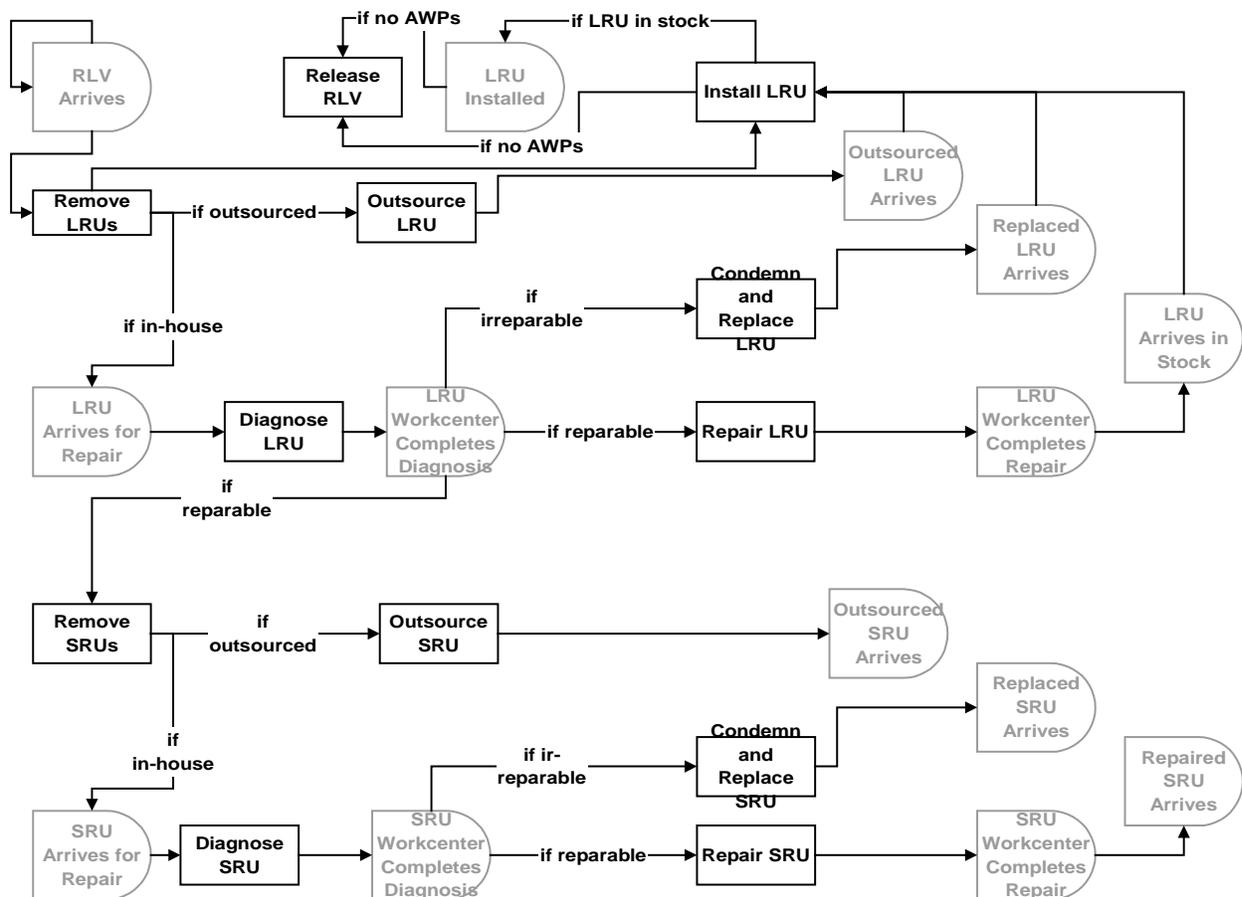

Figure 2: Activities in the RRCS Programming Model

The 10 activities that define the RLV maintenance process for the RRCS can be placed into one of three categories, corresponding to the three linked processes described in the overall modeling framework:

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- RLV-related: Because an event initiates the RLV maintenance process, there is just one activity, "Release RLV", contained in the RLV maintenance process for the programming model.

- LRU-related: Six activities describe the LRU repair process. After an RLV arrives for maintenance, one or more LRUs are removed (Remove LRUs). If the LRU is to be repaired by a supplier, the LRU is sent to the outsourcing repair facility and eventually returns to be placed in the serviceable inventory (Outsource LRU). Otherwise, the LRU arrives for repair and is scheduled to be serviced by a particular workcenter. When the workstation is scheduled to serve that LRU, the reason for failure is diagnosed for the LRU, and the LRU is deemed either repairable or irreparable (Diagnose LRU). If irreparable, the defective LRU is condemned and replaced by a functioning one (Condemn and Replace LRU). Once the replacement arrives for the condemned LRU, it is placed in stock for installation on a grounded RLV. When a needed SRU becomes available, a defective LRU is repaired (Repair LRU), and the functioning LRU is placed into stock.

- SRU-related: Three activities define the SRU repair process. If the LRU is repairable, the defective SRUs for that LRU are removed and each is designated to be serviced internally or externally (Remove SRUs). If the SRU is to be serviced by a supplier, the SRU is sent to the outsourcing repair facility and eventually returns to be placed into the serviceable inventory (Outsource SRU). Otherwise, the SRU arrives for repair and is scheduled to be serviced by a particular workcenter. When the workstation is scheduled to serve that SRU, the reason for failure is diagnosed for the SRU, and the SRU is deemed either repairable or irreparable (Diagnose SRU). If irreparable, the defective SRU is condemned and replaced by a functioning one (Condemn and Replace SRU). Once the replacement arrives for the condemned SRU, it is placed into stock and made available to repair an LRU. If reparable, the SRU is repaired (Repair SRU) and placed into stock and made available to repair an LRU.

Scheduling Logic

Scheduling logic refers to the non-trivial rules applied to schedule resources. Scheduling logic is used in the RLV maintenance process to schedule the LRU and SRU workcenters. The following diagram emphasizes the two points of scheduling logic, which are denoted by six-sided objects:
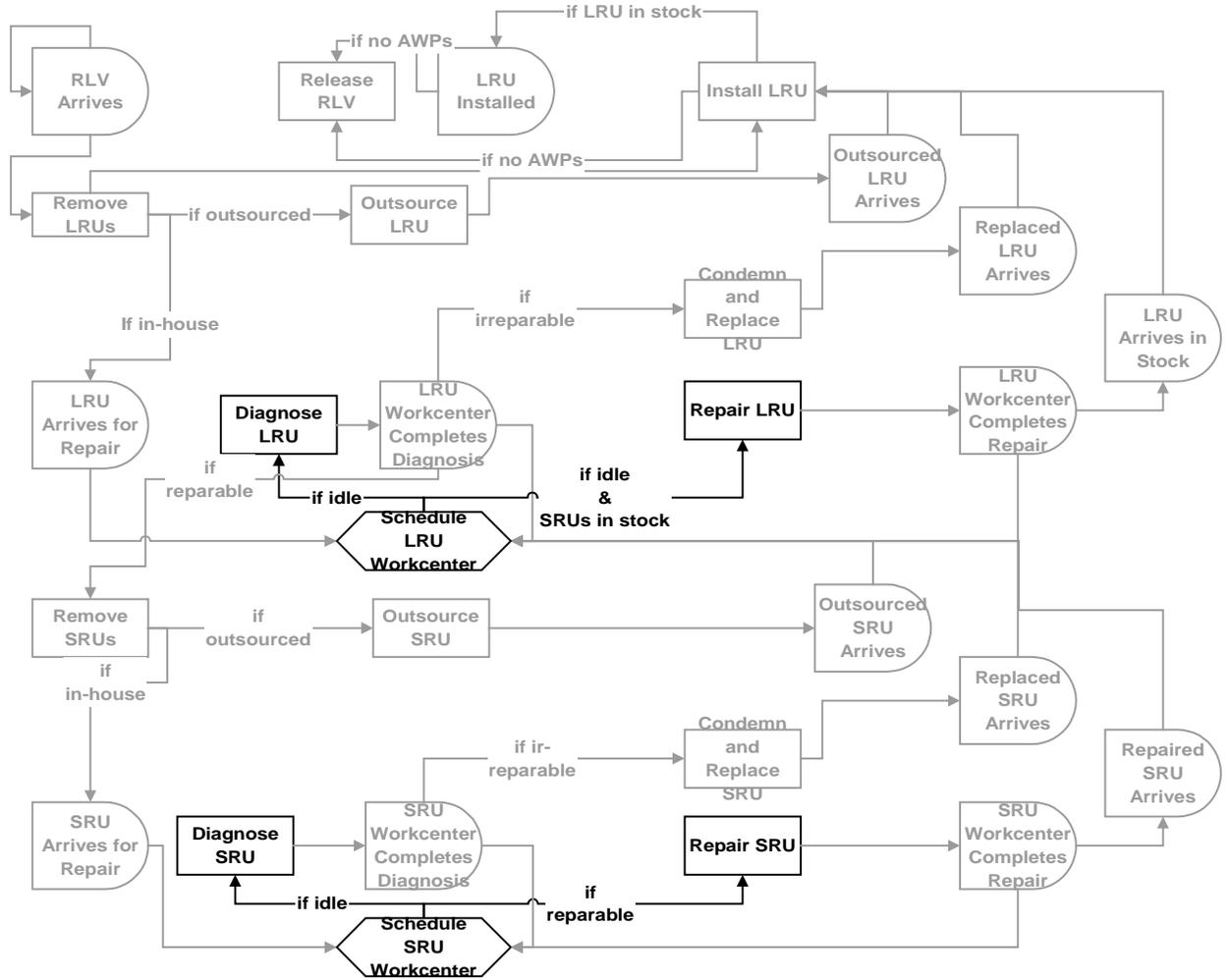
Figure 3: Logic in the RRCS Programming Model

Scheduling LRU and SRU workcenters involves complex logical evaluations of the state of the system. These evaluations use inventory levels, expected runout times, and other key factors to prioritize work flow in the LRU and SRU workcenters. The overall goal of these prioritization rules is to minimize backorders that cause RLV launch delays. These rules are described in detail in the next section.

Inventories

Inventories are collections of RLVs, LRUs, or SRUs at various stages of diagnosis and repair within the RLV maintenance process. In the following diagrams, the points at which inventories are tracked are denoted by diamond-shaped objects. At each stocking point, the program tracks separate inventories for each LRU or SRU type.

Different activities and events trigger inventory adjustments. For example, when an LRU workstation complete failure diagnosis, the "LRUs in Diagnosis" inventory for the diagnosed LRU type decreases by one and the "LRUs to Repair" inventory for that LRU type increases by one. The following diagram illustrates the 20 different stocking points where inventories are managed by the RRCS:
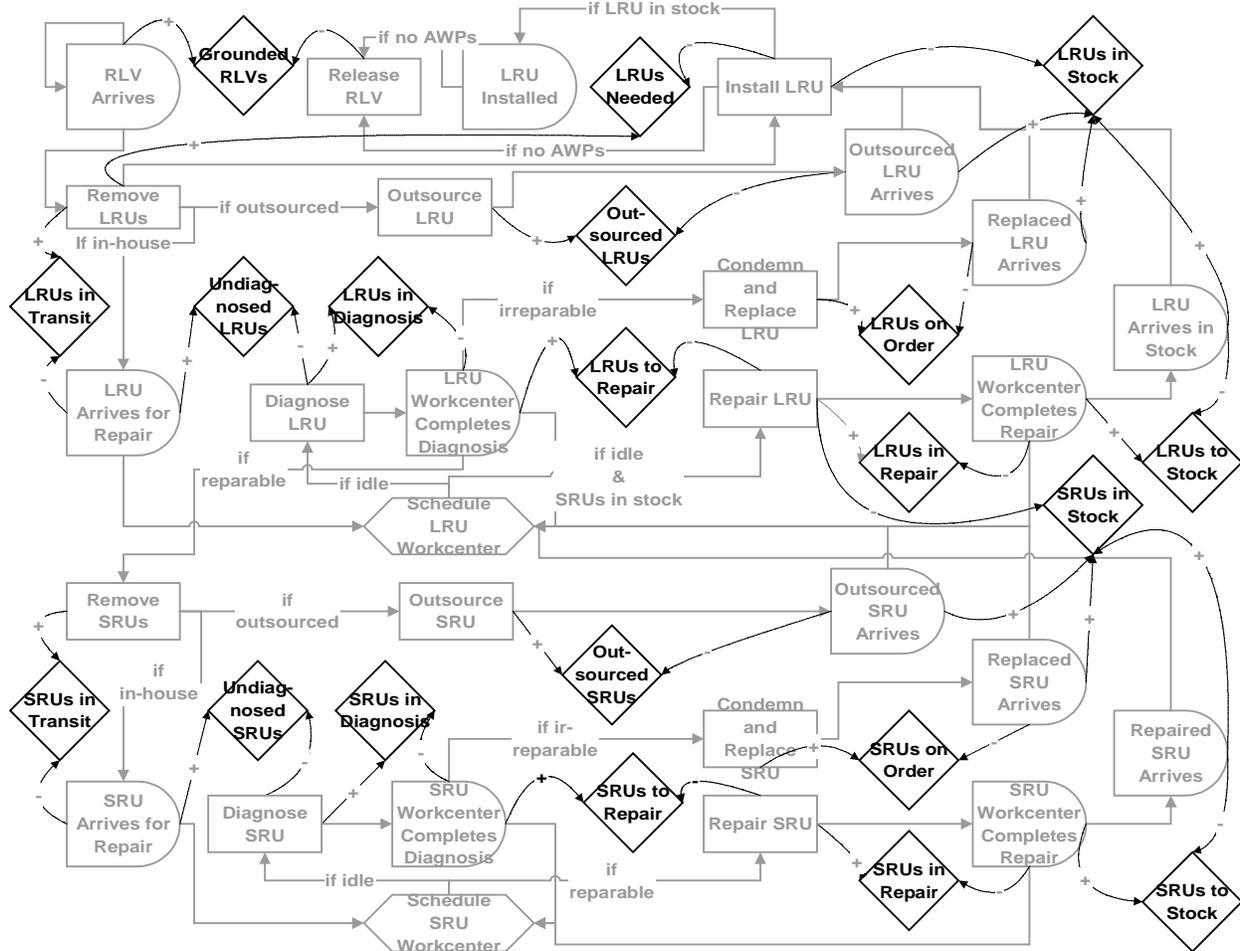
Figure 4: Inventories in the RRCS Programming Model

Similar to the activities in the programming model, the 20 stocking points can be categorized as follows:

- RLV-related: The stocking point "Grounded RLVs" counts the number RLVs that have been grounded, waiting for one or more LRUs. When the last LRU for an RLV has been installed, then the RLV is released and the Grounded RLVs count is decremented by one. While the RLV is grounded, the inventory "LRUs Needed" keeps track of which LRUs remain to be installed. Observe that "LRUs Needed" is essentially a backorder

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count because if a needed LRU is in stock, it will be immediately removed from stock and the LRUs Needed will be decremented (the Release RLV will not occur until the installation is complete).

- LRU-related: Nine stocking points are for LRUs at various stages in the repair process. These stages include: in-transit, outsourced, undiagnosed, in diagnosis, on order, to repair, in repair, to stock, and in stock.

- SRU-related: Nine inventories relate to SRUs at various stages in the repair process. These stages include: in-transit, outsourced, undiagnosed, in diagnosis, on order, to repair, in repair, to stock, and in stock.

Operating the Simulator

This subsection highlights the important steps for operating the RRCS. The following subsections, called "Entering Data" and "Viewing Output," contain a greater detail about the two key components of the RRCS.

The RRCS was developed using Microsoft Excel and Visual Basic for Applications. Microsoft Excel is widely available as a tool for engineering and business systems analysis. Visual Basic for Applications is a powerful programming language that retains much of the simplicity of the Basic programming syntax. Microsoft Excel worksheets serve as screens for entering and viewing simulation data. Visual Basic for Applications serves as the engine for processing input data, running the simulation, and generating output statistics. The typical user of the RRCS will not need to understand or view the Visual Basic code.

The following table describes the steps for operating the simulator:

Operation	Instructions
Opening the RRCS	1. Open the RRCS by opening the Microsoft Excel file called "RLVRepair.xls"
Entering Data	1. Select the tab called "Inputs" on the lower left of the screen. This displays the worksheet for entering simulation parameters.
	2. Enter the simulation control data into the section labeled "Simulation Run Controls."

	3. Enter data into the section labeled "RLV Characteristics."
	4. Enter data into the section labeled "LRU Workcenters." Insert additional rows as necessary by selecting Insert/Row from the Excel menu bar.
	5. Enter data into the section labeled "SRU Workcenters." Insert additional rows as necessary by selecting Insert/Row from the Excel menu bar.
	6. Enter data into the section labeled "LRU Characteristics." Insert additional rows as necessary by selecting Insert/Row from the Excel menu bar. Ensure that the LRU workcenter referred to in this section exists in the "LRU Workcenter" section above it.
	7. Enter data into the section labeled "SRU Characteristics." Insert additional rows as necessary by selecting Insert/Row from the Excel menu bar. Ensure that the SRU workcenter referred to in this section exists in the "SRU Workcenter" section above it.
	8. Enter data into the section labeled "LRU-SRU Usage Matrix." Enter a "1" if the SRU of this type is contained in the LRU of this type, otherwise enter "0". Insert additional rows as necessary by selecting Insert/Row from the Excel menu bar. Ensure that the LRU and SRU types referred to in this section exist in the respective LRU and SRU characteristics sections above it.
Running the Simulation	1. Select the tab called "StockPoint Statistics" on the lower left of the screen. This displays the worksheet for viewing simulation output.
	2. Press the button called "Initialize." This executes code that clears the simulation output screens and loads the input data into the simulation.
	3. Press the button called "Simulate." This runs the simulation for the period of time specified in the Simulation Run Controls. While the simulation is running, the Current Level of the Stocking Points is continuously updated. This provides a simple form of animation. The Simulate button remains depressed until the simulation is complete.
	4. To continue the simulation, press the button called "Simulate." You can continue the simulation as many times as you like. The output statistics are accumulated over the total length of your simulation. The simulation

	can be continued only while the simulation is loaded. Once you close the worksheet, the simulation is unloaded.
Viewing Output	1. Select the tab called "StockPoint Statistics" on the lower left of the screen. This displays the accumulated statistics on the average inventory levels and duration (sojourn times: how long a unit spends in inventory assuming First-In-First-Out). 2. Select the tab called "Workcenter Statistics" on the lower left of the screen. This displays the utilization rates of the different workcenter stations. 3. Select the tab called "RLV Releases" on the lower left of the screen. This displays a history of each RLV's arrival, need date, and release date. If the release date comes after the need date, then the number of LRUs still needed at the need date is also displayed. The last LRU to be installed on the RLV is also recorded. 4. Select the tab called "RLV Delays" on the lower left of the screen. This displays graphs of the number of days RLVs are delayed past their need date and which LRUs cause those delays.

Entering Data

This subsection describes the data entry screen and fields for the RRCS. The RRCS has just one Microsoft Excel worksheet with input fields. The worksheet, called "Inputs," contains six sections:

- RLV Characteristics: Provides an area for entering overarching RLV launch parameters.

- LRU Workcenters: Used to enter information about each LRU workcenter, including parameters such as number of stations in the workcenter and changeover time for each station.

- SRU Workcenters: Similar to the section above it, this area is used to enter data about each SRU workcenter, such as number of stations and changeover time.

- LRU Characteristics: Provides fields for entering specific traits about the LRUs in the system, such as initial inventory levels and failure probabilities.

- SRU Characteristics: Similar to the section above it, this area provides fields for entering specific traits about the SRUs in the system, such as initial inventory levels and failure probabilities.

- LRU-SRU Usage Matrix: An area for entering information about LRUs and their use of certain SRUs.

Each of these six sections contains entry fields for the user to enter critical parameters for simulation. Each entry field is described below.

RLV Characteristics

This section contains two fields related to the RLV launch schedule:

Field Name	Description	Units	Input Rules
Days Between Arrivals	The number of days between individual RLV arrivals.	Days	• A number greater than or equal to 0. • Decimals allowed.
Time to Install LRU	The number of hours available to install LRUs. The amount of time the RLV is in the ground maintenance process.	Hours	• A number greater than or equal to 0. • Decimals allowed.
Days Until Launch	The number of days in the RLV maintenance cycle.	Days	• A number greater than or equal to 0. • Decimals allowed.

LRU Workcenters

This section contains five fields related to the workcenters for maintaining line replaceable units. Additional rows for additional LRU workcenters can be added by selecting Insert/Row from the menu bar of Excel:

Field Name	Description	Units	Input Rules

Field Name	Description	Units	Input Rules
LRU WC	The LRU workcenter ID. A positive integer. An ID of zero indicates that the workcenter is an outsourcing facility: do not enter a row for outsourcing.	None	• A number greater than 0. • Decimals not allowed.
Name	The name of the LRU workcenter. For example, LRUWC01.	None	None
Number of Stations	The number of LRU workstations within this workcenter. All stations within a workcenter are identical and work in parallel.	Stations	• A number greater than or equal to 0. • Decimals not allowed.
Hours per Day per Station	The number of hours per day available for service on each workstation within the workcenter.	Hours	• A number between 0 and 24, inclusive. • Decimals allowed.
Changeover Time	The minimum number of minutes required between services for each station within the workcenter. This changeover time is needed for setup and maintenance. The changeover time is incurred whenever the part index on the workcenter changes.	Minutes	• A number greater than or equal to 0. • Decimals allowed.

SRU Workcenters

This section contains five fields related to the workcenters for maintaining shop replaceable units. Additional rows for additional SRU workcenters can be added by selecting Insert/Row from the menu bar of Excel. The five fields are identical to those for the LRUs:

Field Name	Description	Units	Input Rules
SRU WC	The SRU workcenter ID. A positive integer. An ID of zero indicates	None	• A number greater than 0.

	that the workcenter is an outsourcing facility: do not enter a row for outsourcing.		• Decimals not allowed.
Name	The name of the SRU workcenter. For example, SRUWC01.	None	None
Number of Stations	The number of SRU workstations within this workcenter. All stations within a workcenter are identical and work in parallel.	Stations	• A number greater than or equal to 0. • Decimals not allowed.
Hours per Day per Station	The number of hours per day available for service on each workstation within the workcenter.	Hours	• A number between 0 and 24, inclusive. • Decimals allowed.
Changeover Time	The minimum number of minutes required between services for each station within the workcenter. This changeover time is needed for setup and maintenance. A changeover is incurred whenever the part index on a workcenter changes.	Minutes	• A number greater than or equal to 0. • Decimals allowed.

LRU Characteristics

This section contains 16 fields related to properties of line replaceable units. Additional rows for additional LRU types can be added by selecting Insert/Row from the menu bar of Excel. Each row in this section represents an LRU type, not a specific LRU:

Field Name	Description	Units	Input Rules
LRU Index	The LRU type ID. A positive integer.	None	• A number greater than or equal to 0. • Decimals not allowed.
Name	The name of the LRU type. For	None	None

	example, LRU01.		
Initial Inventory in Stock	The number of LRUs of this type in stock when the simulation begins. It is also the target inventory: the system will always seek to replenish this inventory.	LRUs	• A number greater than or equal to 0. • Decimals not allowed.
Removal Delay Days	The number of days from the start of the maintenance cycle	Days	• A number between 0 and Days Until Launch • Decimals allowed.
Removal Probability	The probability that an LRU of this type will is removed from the RLV after failing the initial test.	None	• A number between 0 and 100, inclusive. • Decimals allowed.
LRU WC Required	The ID of the LRU workcenter that this LRU type requires. An ID of zero indicates that the workcenter is outsourced.	None	• A number greater than or equal to 0. • Decimals not allowed. • Must correspond to an existing ID or 0, for outsourcing.
Transport Time to Repair	The mean number of hours required to transport an LRU of this type to the workcenter.	Hours	• A number greater than or equal to 0. • Decimals allowed.
Transport Time Coefficient of Variation	The variability of the transportation time to the workcenter for repair for this LRU type. This parameter is used with the Beta probability distribution to generate random transportation durations.	Hours Squared	• A number greater than or equal to 0. A c.v. of 0.5 would "normal"; 1 would be "large"; 2 would be "very large." • Decimals allowed.
Time to Diagnose	The mean number of minutes required to diagnose an LRU of this	Minutes	• A number greater than or equal to 0.

	type.		• Decimals allowed.
Diagnosis Time Coefficient of Variation	The variance of the diagnosis time for this LRU type. This parameter is used with the Beta distribution to generate random diagnosis durations.	Minutes Squared	• A number greater than or equal to 0. A c.v. of 0.5 would "normal"; 1 would be "large"; 2 would be "very large." • Decimals allowed.
Condemnation Probability	The probability that an LRU of this type is condemned. This parameter is ignored for outsourced parts.	None	• A number between 0 and 100%, inclusive. • Decimals allowed.
Time to Repair	The mean number of minutes required to repair an LRU of this type.	Minutes	• A number greater than or equal to 0. • Decimals allowed.
Repair Time Coefficient of Variation	The variability of the repair time for this LRU type. This parameter is used with the Beta distribution to generate random repair durations.	Minutes Squared	• A number greater than or equal to 0. A c.v. of 0.5 would "normal"; 1 would be "large"; 2 would be "very large." • Decimals allowed.
Transport Time to Stock	The mean number of hours required to transport an LRU of this type to the stocking facility.	Hours	• A number greater than or equal to 0. • Decimals allowed.
Stock Time Coefficient of Variation	The variability of the transportation time for this LRU type to reach its stocking facility. This parameter is used with the Beta distribution to generate random transportation durations.	Hours Squared	• A number greater than or equal to 0. A c.v. of 0.5 would "normal"; 1 would be "large"; 2 would be "very large." • Decimals allowed.

Replace Time to Stock	The mean number of hours required to replace an LRU of this type. This parameter is ignored for outsourced parts.	Hours	• A number greater than or equal to 0. • Decimals allowed.
Replace Time Coefficient of Variation	The variability of the replacement time for this LRU type. This parameter is used with the Beta distribution to generate random replacement durations. This parameter is ignored for outsourced parts.	Hours Squared	• A number greater than or equal to 0. A c.v. of 0.5 would "normal"; 1 would be "large"; 2 would be "very large." • Decimals allowed.

For outsourced parts, the mean duration of outsourcing is taken to be the sum of the mean times for "Transport Time to Repair," "Time to Diagnose," "Time to Repair," and "Transport Time to Stock." The variability of outsourcing duration is computed from the corresponding variabilities of these same components, assuming each of the compenents is probabilistically independent of the other.

SRU Characteristics

This section contains 16 fields related to properties of shop replaceable units that are identical to the fields for the LRUs. Additional rows for additional SRU types can be added by selecting Insert/Row from the menu bar of Excel. Each row in this section represents an SRU type, not a specific SRU.

LRU-SRU Usage Matrix

This section contains fields in a matrix format relating SRU types to LRU types. Additional rows for additional LRU types can be added by selecting Insert/Row from the menu bar of Excel. Additional SRU types can be added by simply typing the new SRU indices and names in the existing, designated rows. It is important that each LRU and SRU type included in this matrix exist in the respective LRU or SRU characteristics section of the input sheet:

Field Name	Description	Units	Input Rules
All fields in the matrix	The usage indicator specifying	None	• The number 0 or 1.

	whether an SRU type is contained within an LRU type. These fields match SRU types to LRU types by taking a 1 if they are used together or 0 if they are not.		• Decimals not allowed.

Viewing Output

This subsection describes the data output screen for the RRCS. The RRCS has just one Microsoft Excel worksheet displaying output. The worksheet, called "StockPoint Statistics," contains five sections, four of which are identically formatted:

- Current Level: Displays the number of RLVs, LRUs, and SRUs at various stages in the maintenance process when the simulation ends.

- Average Level: Displays the average number of RLVs, LRUs, and SRUs at various stages in the maintenance process.

- Maximum Level: Displays the maximum number of RLVs, LRUs, and SRUs at various stages in the maintenance process.

- Average Duration: Displays average periods of time that RLVs, LRUs, and SRUs remain at various stages in the maintenance process.

- Workcenter Utilization: Displays the percentage of time that workcenter stations are in service (diagnosis or repair) throughout the entire simulation.

Each of these five sections contains output fields for the user to view after simulation. Each output field is described below.

Current Level, Average Level, Maximum Level

This section describes the simulation statistics for three sections on the output sheet. It includes 20 fields:

Field Name	Description	Units
Index	The index for the RLV, LRU type, or SRU type. Refer to this	None

	field to understand which RLV, LRU type, or SRU type corresponds to the statistics.	
RLVs On Ground	The number of RLVs in the ground maintenance process.	RLVs
LRUs Needed	The number of RLVs waiting for LRUs of this index.	RLVs
LRUs In-Transit	The number of LRUs of this index in transit to the (in-house) LRU repair facility.	LRUs
LRUs Outsourced	The number of LRUs of this index outsourced.	LRUs
LRUs Undiagnosed	The number of LRUs of this index that were not diagnosed.	LRUs
LRUs In Diagnosis	The number of LRUs of this index that were being diagnosed.	LRUs
LRUs To Repair	The number of LRUs of this index that required repair.	LRUs
LRUs In Repair	The number of LRUs of this index that were being repaired.	LRUs
LRUs To Stock	The number of LRUs of this index that were being transported to the stocking facility.	LRUs
LRUs On Order	The number of LRUs of this index that were awaiting replacement after condemnation.	LRUs
LRUs In Stock	The number of LRUs of this index in inventory.	LRUs
SRUs In-Transit	The number of SRUs of this index in transit to the (in-house) SRU repair facility.	SRUs
SRUs Outsourced	The number of SRUs of this index outsourced.	SRUs
SRUs Undiagnosed	The number of SRUs of this index that were not diagnosed.	SRUs
SRUs In Diagnosis	The number of SRUs of this index that were being diagnosed.	SRUs
SRUs In Repair	The number of SRUs of this index that were being repaired.	SRUs
SRUs To Stock	The number of SRUs of this index that were being transported to the stocking facility.	SRUs
SRUs On Order	The number of SRUs of this index that were awaiting replacement after condemnation.	SRUs

Average Duration

This section describes the simulation statistics for the average period of time that RLVs, LRUs, and SRUs remained at specific stages in the maintenance process throughout the simulation. It includes 20 fields that are identical to the previous three sections, but involve units of time instead of vehicles and parts:

Field Name	Description	Units
Index	The index for the RLV, LRU type, or SRU type. Refer to this field to understand which RLV, LRU type, or SRU type corresponds to the statistics.	None
RLVs On Ground	The average duration of time that RLVs were in the ground maintenance process.	Minutes
LRUs Needed	The average duration of time that RLVs waited for LRUs of this index.	Minutes
LRUs In-Transit	The average duration of time that LRUs of this index were removed from an RLV.	Minutes
LRUs Outsourced	The average duration of time that LRUs of this index were serviced by an outsourced party.	Minutes
LRUs Undiagnosed	The average duration of time that LRUs of this index waited to be diagnosed after arriving at the workcenter.	Minutes
LRUs In Diagnosis	The average duration of time that LRUs of this index were being diagnosed.	Minutes
LRUs To Repair	The average duration of time required for LRUs of this index to be repaired after they were diagnosed.	Minutes
LRUs In Repair	The average duration of time that LRUs of this index were being repaired.	Minutes
LRUs To Stock	The average duration of time that LRUs of this index were being transported to the stocking facility.	Minutes
LRUs On Order	The average duration of time required for LRUs of this index	Minutes

	to be replaced after they were condemned.	
LRUs In Stock	The average duration of time that LRUs of this index were in inventory.	Minutes
SRUs In-Transit	The average duration of time that SRUs of this index were removed from an RLV.	Minutes
SRUs Outsourced	The average duration of time that SRUs of this index were serviced by an outsourced party.	Minutes
SRUs Undiagnosed	The average duration of time that SRUs of this index waited to be diagnosed after arriving at the workcenter.	Minutes
SRUs In Diagnosis	The average duration of time that SRUs of this index were being diagnosed.	Minutes
SRUs In Repair	The average duration of time that SRUs of this index were being repaired.	Minutes
SRUs To Stock	The average duration of time that SRUs of this index were being transported to the stocking facility.	Minutes
SRUs On Order	The average duration of time required for SRUs of this index to be replaced after they were condemned.	Minutes

Workcenter Utilization

This section describes the statistics for workcenter usage levels. It includes a list of workcenters and one field, utilization:

Field Name	**Description**	**Units**
Utilization	The percentage of time that this LRU or SRU workcenter is busy. One minus this percentage equals the percentage of time that this workcenter is idle.	Percentage

RLV Releases

This section describes the simulated history of the RLV arrivals and releases.

Field Name	Description	Units
Index	Index of the RLV, in order of RLV arrival date.	
Arrival	The date (possible fractional to represent time of day) of the RLV arrival for repair.	Days (from start of simulation)
Need by	The date the RLV is needed for next launch. The difference between Arrival and Need by dates is a fixed duration. See "RLV Characteristics" in the input section.	Days
Late LRUs Count	Number of LRUs that the RLV was awaiting at its Need by date. If zero, then the RLV was released before the Need by date.	Days
Release	The date the last LRU needed by this RLV was installed.	Days
Delay	The excess of Release date over Need by date.	Days
Last LRU	Index of the last LRU to be installed in this RLV	1…Number of LRU Types

RLV Delays

This section provides a graphical analysis of the history of RLV delays. It is an analysis of the RLV Arrival and Release History showing the frequency of delay days and the average delay associated with particular Last LRU indices.

RRCS WORKCENTER SCHEDULING RULES

A vitally important (yet often overlooked) aspect of resource strategy design is that an effective resource strategy entails not only a plan for *what* resources will be put in place, it also entails a plan for *how* these resources will be used. The scheduling logic components of RRCS were designed with this in mind. Specifically, a set of intelligent, state-dependent selection rules for each type of workcenter has been embedded in RRCS in order to capture the work prioritization that would realistically take place. While workcenter scheduling is a relatively unimportant issue when spare parts are readily available and repair capacity sufficiently dominates the failure process, it becomes vastly important in the face of backorders and lengthy repair queues.

This section is divided into three subsections as follows:

- Definitions

- LRU Workcenter Scheduling Rules

- SRU Workcenter Scheduling Rules

Definitions

The following definitions will be useful in understanding the LRU and SRU workcenter scheduling rules:

- For any LRU or SRU type, the *available stock level* at a particular point in time is the number of units immediately available for use (i.e., the number of "LRUs in Stock" or "SRUs in Stock"). An LRU or SRU type is said to be *available* at a particular point in time if the available stock level is greater than zero.

- A *backorder* is an unfulfilled order for an LRU (i.e., a "hole" in an RLV that must be filled before the RLV can launch). Backorders are associated with specific RLVs. A backorder that exists at the end of the maintenance window of its associated RLV is called *delay-causing*. Note that only LRUs give rise to backorders. The unavailability of SRUs can cause delays in the LRU repair process, but SRUs do not directly cause backorders.

- With respect to the LRU and SRU repair processes, a *decision point* is a point in time at which a service (i.e., diagnosis or repair) may be initiated at a workcenter. The decision to be made is *which* part to service next.

- A failed LRU that is queued for service is said to be *eligible (for service)* if one of the following two conditions apply:

  – The failed LRU has not yet undergone failure diagnosis at a workcenter to determine its reason for failure (i.e., it is *undiagnosed*)

  – The failed LRU has undergone diagnosis, and all of the SRU components needed for the repair of the LRU are currently available.

  Clearly the notion of eligibility is time-dependent. An LRU *type* is said to be eligible if at least one LRU of that type is eligible. A failed LRU that is not eligible is said to be *ineligible*. Note that an undiagnosed LRU becomes eligible for service as soon as it enters the repair queue and remains eligible until it is selected for diagnosis. Once the LRU is diagnosed and is deemed to be repairable, it is repaired immediately if the needed SRU components are available. If the needed SRU components are not available, the LRU is removed from the workcenter and remains ineligible until the needed SRU components become available.

- For any LRU type, the *(LRU) inventory level* at a particular point in time is the available stock level (LRUs in Stock) plus the number of units in-transit to serviceable stock (LRUs to Stock) plus the number of units actively being serviced at LRU workcenters (LRUs in Diagnosis + LRUs in Repair) minus the number of backorders (LRUs Needed).

  Note that in this definition no distinction is made between those units that are actively being diagnosed at a workcenter and those that are actively being repaired. Also, the probability of condemnation is not considered. Hence, the LRU inventory level calculation optimistically assumes that the units that are actively being diagnosed at a workcenter will be repairable immediately upon completion of the diagnosis.

  Note also that at any point in time, either the available stock level (LRUs in Stock) or the number of backorders (LRUs Needed) for a particular LRU type must be zero. If, at a particular point in time, the LRU inventory level becomes negative, then this LRU type is said to have *unaddressed backorders.* The number of unaddressed backorders in this case is

the absolute value of the LRU inventory level. Since backorders for a particular LRU type are filled on a FCFS basis, we can determine the specific backorders that are unaddressed at any point in time.

- For any SRU type, the *(SRU) inventory level* at a particular point in time is the available stock level (SRUs in Stock) plus the number of units in-transit to serviceable stock (SRUs to Stock) plus the number of units actively being serviced at SRU workcenters (SRU in Diagnosis + SRUs in Repair) minus the number of queued, already-diagnosed LRU hulks (LRUs to Repair) that require the SRU type to complete repair.

  Due to the nature of the LRU repair process, for any SRU type, both the number of SRUs to Stock and the number of LRUs to Repair that require the SRU type to complete repair may be positive. If, at a particular point in time, the SRU inventory level becomes negative, then this SRU type is said to have *unaddressed hulks*. The number of unaddressed hulks for the SRU type in this case is the absolute value of the SRU inventory level.

LRU Workcenter Scheduling Rules

In this subsection we classify the points in time at which LRU service may be initiated and describe the selection rules implemented at each of these decision points.

LRU Decision Points

Two conditions must be met for a time to be an LRU decision point:

- An LRU workcenter must be idle, and

- There must be at least one eligible LRU queued for that workcenter type.

There are three scenarios that give rise to LRU decision points:

(L1)   An LRU workcenter is idle, and a failed LRU joins the service queue.

The workcenter may be idle because there are no LRUs awaiting service or because none of the LRUs in the service queue is eligible at the time the failed LRU arrives. The new arrival, however, is eligible for service since it is undiagnosed. The selection decision is trivial in this case because there is only one eligible LRU.

(L2)   An LRU workcenter completes a service, and at that time the set of eligible LRUs is nonempty.

> In this case, the set of eligible LRUs may contain both undiagnosed and diagnosed LRUs. If there is more than one eligible LRU, the scheduling decision is nontrivial.

(L3)   An LRU workcenter is idle, and an SRU becomes available that causes one or more previously ineligible LRUs to become eligible.

> In this case, the workcenter is idle because all of the LRUs in the service queue are awaiting some SRU component. In the case that the SRU arrival causes more than one LRU unit to become eligible, the scheduling decision is nontrivial.

Selection Rules

The selection rule for decision points of type (L1) is obvious: Choose the new arrival for service. The scheduling logic imbedded in the RRCS at LRU decision points of types (L2) and (L3) is described below.   These rules were developed with the goal of minimizing delay-causing backorders.

At an (L2) or (L3) decision point, we have two cases to consider: Either an unaddressed backorder exists that we can address immediately, or no unaddressed backorder exists that we can address immediately.   Recall that unaddressed backorders exist for a given LRU type if the LRU inventory level is negative.

Case 1: At least one unaddressed backorder exists for which there is an eligible LRU.

In this case, we want to choose among the eligible LRU types that have an unaddressed backorder, because these backorders will become delay-causing with certainty if nothing is done to fill them.

   Selection Logic for Case 1:

   1.   Determine the oldest unaddressed backorder for which there is an eligible LRU, breaking ties arbitrarily. Restrict the selection candidates to eligible LRUs of this type.

   2.   If all eligible LRUs of this type are undiagnosed, select one arbitrarily. Otherwise, restrict the selection candidates to diagnosed eligible LRUs of this type and proceed to step 3.

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3. If there are multiple diagnosed eligible LRUs of this type, select the LRU that, if repaired now, will induce the fewest number of negative SRU inventory levels among the SRU components belonging to the LRU type. Break ties arbitrarily.

Case 2: No unaddressed backorder exists for which there is an eligible LRU.

Here we must choose among eligible LRU types that all have nonnegative inventory levels. In this case, we want to choose an eligible LRU type to service that is likely to have a negative inventory level sooner than other eligible LRU types.

Selection Logic for Case 2:

1. Among the eligible LRU types, determine the type that has the shortest expected waiting time until a negative LRU inventory level exists. (A method for performing this computation is discussed below.)

2. If any eligible LRUs of this type are undiagnosed, select one arbitrarily. Otherwise, select the LRU that, if repaired now, will induce the fewest number of negative SRU inventory levels among the SRU components belonging to the LRU type. Break ties arbitrarily.

Step 2 of this logic is somewhat counterintuitive, since we choose to diagnose a unit with unknown defects before repairing a unit with known defects. The reasoning is as follows: Since no unaddressed backorders currently exist for the chosen LRU type, we are not forfeiting the opportunity to address a known unaddressed backorder by choosing an undiagnosed unit to service. By choosing an undiagnosed unit to service, we will provide more information about failed SRUs that can be used immediately in making decisions at SRU workcenters, assuming the information is readily available. If the information is not readily available at the SRU workcenters, then there is no advantage or disadvantage in choosing undiagnosed LRUs over diagnosed ones.

Approximating the expected waiting time until a negative LRU inventory level exists for a given LRU type:

The calculation method described here is only an approximation since it assumes that all LRUs currently being diagnosed at LRU workcenters will be repairable immediately upon the

completion of diagnosis, and it assumes that all LRU failures for a given RLV are recognized at the same time.

Let p_l denote the probability that an LRU of type l is removed from an RLV upon its return from a mission, and let I_l denote the current inventory level of LRU type l.

Because, by assumption, each RLV contains exactly one LRU of each type, the expected number of RLV landings before LRU l goes into a negative inventory level, assuming no services for LRU type l are initiated, is given by $\dfrac{I_j + 1}{p_j}$. The expected number of RLV landings is equivalent to the expected waiting time, so to determine the LRU type with the shortest expected waiting time until a negative inventory level occurs, it suffices to compute this ratio for each LRU type and select the type with the smallest ratio.

SRU Workcenter Scheduling Rules

In this subsection we classify the points in time at which SRU service may be initiated and describe the selection rules implemented at each of these decision points.

SRU Decision Points

Two conditions must be met for a time to be an SRU decision point:

- An SRU workcenter must be idle, and

- There must be at least one SRU queued for that workcenter type.

There are two scenarios that give rise to SRU decision points:

(S1)   An SRU workcenter is idle, and a failed SRU joins the service queue.

   This can only happen if there are no SRUs queued for the workcenter type prior to the new arrival. The selection decision is trivial in this case.

(S2)   An SRU workcenter completes a service, and at that time the service queue is nonempty.

   If there is more than one SRU type in the queue, the scheduling decision is nontrivial.

Selection Rules

As with the LRU selection logic, the SRU selection logic that has been implemented attempts to contribute to the overall objective of minimizing delay-causing backorders. This contribution, however, is indirect since serviceable SRUs themselves cannot fill backorders. Recall that the role of the SRU repair process is to help the LRU repair process run as efficiently as possible. The LRU repair process is most efficient when two conditions are met:

- No LRU workcenter sits idle when there is a nonempty repair queue. Such unnecessary idle time can be introduced when the SRU components are not available to fix any LRU in the queue. In such situations, the effective decrease in the LRU service rate increases the effective utilization factor ρ at the LRU workcenters, which in turn increases the mean waiting time and the mean number of units in the LRU repair queue. While keeping the

LRU workcenters busy is not the ultimate goal, having workcenters sit idle while there are units queued for repair clearly reduces system performance in the long run.

- No LRU has to wait for SRUs to complete repair. Ideally, the SRU repair process provides enough of the right components so that no waiting time is introduced into the LRU repair process.

The scheduling rules for SRU workcenters were designed with these points in mind.

The selection rule for decision points of type (S1) is obvious: Choose the new arrival for service. At an (S2) decision point, we have two cases to consider: Among the set of queued SRUs requiring the workcenter type, either one or more SRU inventory levels is negative, or all SRU inventory levels are nonnegative.

Case 1: Among the set of queued SRUs requiring the station type, one or more SRU inventory levels is negative.

In this case, we want to choose an SRU type to service that has a negative inventory level.

Selection Logic for Case 1:

Among the queued SRU types, determine the type with the most negative inventory level and select an SRU of this type to repair.

Case 2: Among the set of queued SRUs requiring the station type, all SRU inventory levels are nonnegative.

In this case, we want to choose an SRU type to service that is likely to be in a negative SRU inventory level sooner than other queued SRU types.

Selection Logic for Case 2:

Determine the SRU type that has the shortest expected waiting time until a negative SRU inventory level exists, and choose an SRU of this type to repair.

Approximating the expected waiting time until a negative inventory level exists for a given SRU type:

The calculation method described here is only an approximation since it assumes that all SRUs currently being diagnosed at SRU workcenters are repairable and none are condemned.

Let n_j denote the number of LRU types of which SRU type j is a component. Let p_j denote the probability that SRU type j fails, and let I_j denote the current inventory level of SRU type j.

The expected number of RLV landings until SRU j goes into a negative inventory level, assuming no repairs for SRU type j are initiated, is given by $\dfrac{I_j + 1}{n_j p_j}$. To determine the SRU type with the shortest expected waiting time until a negative inventory level exists, compute this ratio for each SRU type and select the type with the smallest ratio.