**ENSE 622 Project Proposal**

**Project Title: A simulation-based sensitivity and trade-off analysis of Self Replicating Robot System Configurations**
**Team Name: Project Team C**
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**Desired Faculty Advisor:** Scott David Simpkins

## 1. Introduction:

Self-replicating robots can prove to be beneficial for use in areas that are difficult for humans to access or where it is prohibitive to bring in materials and supplies. Though these may be the primary areas of benefit, this type of robot system could also be used in a wide variety of other applications like space exploration.

The objective of this analysis is to simulate the performance of 6 different system configurations for self-replicating robot systems (SRRSs). A simulation shall be developed to provide a means to implement, assess and compare these system configurations and to perform trade-off analysis to yield a recommendation of the best course of action (COA) for the user to employ.

For this analysis, we categorize the self-replicating robot systems into 6 categories (system configurations) and perform analysis on this individually using the proposed simulation approach. The simulation is conducted with parameters that may fit a variety of mission constraints in order to inform the decision-makers on how an SRRS should be configured and commanded.

### 1.1. Analysis Customer/Consumer:

As launching materials into space can be prohibitively expensive, which may drive a need for utilizing in-situ materials, the primary consumer for this analysis is the National Aeronautics and Space Administration (NASA) and SpaceX. In an aerospace application, a mission might use an SRRS to print a larger structure (such as a habitat), and therefore, a number of 3D print-capable robots would be needed.

This analysis shall be conducted over a period of two months and it can be used by the customer throughout the lifecycle of a deployed SRRS.

### 1.2. Analysis Goal/Purpose/Objective:

The goal of the analysis is to provide a framework to assist customers and stakeholders, by investigating and simulating 6 categories(configurations) of SRRSs to lower mission costs and enhance mission capabilities by allowing the in situ collection of materials used for robot fabrication.

The simulation of different system configurations of the SRRSs will be used to formulate results that shall be utilized as heuristics which shall aid in determining which types of buildable robots or how many such robots shall be built for a particular mission or objective. For instance, the initial resources provided to the system may influence the rate at which different system configurations can expand. The 6 configurations shall be compared against the following metrics; assembly capacity, collection capacity, printing capacity, and the number of robots built.

A design option shall be recommended to the stakeholder using the Multi-Attribute Value Function (MAVF) for the above-described categories of SRRSs.

### 1.3. Team Responsibilities:

**Table 1:** Team Responsibilities Matrix

| CLIN | Deliverable | Product Lead |
|---|---|---|
| S1 | Implementation of SRRSs configuration using analytical modeling in MATLAB | Siddharth Gopal |
| S2 | Implementation of 3 SRRSs configurations using Monte Carlo in MATLAB | Vishal Gattani |
| S3 | Implementation of 3 SRRSs configurations using Monte Carlo in MATLAB | Siddharth Gopal |
| S4 | Multi-Attribute Value function for trade-ff analyses | Vishal Gattani |
| S5 | Sensitivity Analysis | Siddharth Gopal |
| S6 | Documentation | Vishal Gattani |

### 1.4. System Description (8):

There are three different types of resources that shall be considered in the simulation system. These resource types are as follows:

1) Non-Printable components: components that the robot system does not have the capability to print (or otherwise make in-situ), such as control units (processors) and motors.
2) Printable components: components that are fabricated by the robot system during the simulation, such as frames and other structural elements for new robots.
3) Raw printing materials: materials that are used in the printing process. The printing process would yield the printable component resource type, so the raw material type requires a fabricating step before materials are usable (as components) to build new robots.
4) The environment also has a certain amount of raw printing material available that robots can collect.

There are four task types in the simulation: three which perform an action (depicted in Figure 1) and one which represents a default state indicating that a robot is currently performing no action (idle).

1) Collect: A task type where the robot gathers raw printing materials from the environment and adds the gathered materials to the robot system's inventory. Upon completion of this task, raw printing materials are removed from the environment and added to the robot system's resource pool.
2) Print: A task type where the robot takes raw printing materials and fabricates them into printable components. Upon completion of this task, raw printing materials are removed from the robot system's resource pool, and printable components are added to the robot system's resource pool.
3) Assemble: A task type where the robot takes non-printable components and printable components from the robot system's resource pool and assembles them into a new robot. This task type has a duration that varies by the robot type being assembled. Upon completion of this task, the newly assembled robot is added to the robot system.
4) Idle: A default task type that is assigned to any robot not performing any other action during a time step. This task type has no associated duration because it does not have any completion

actions/events.

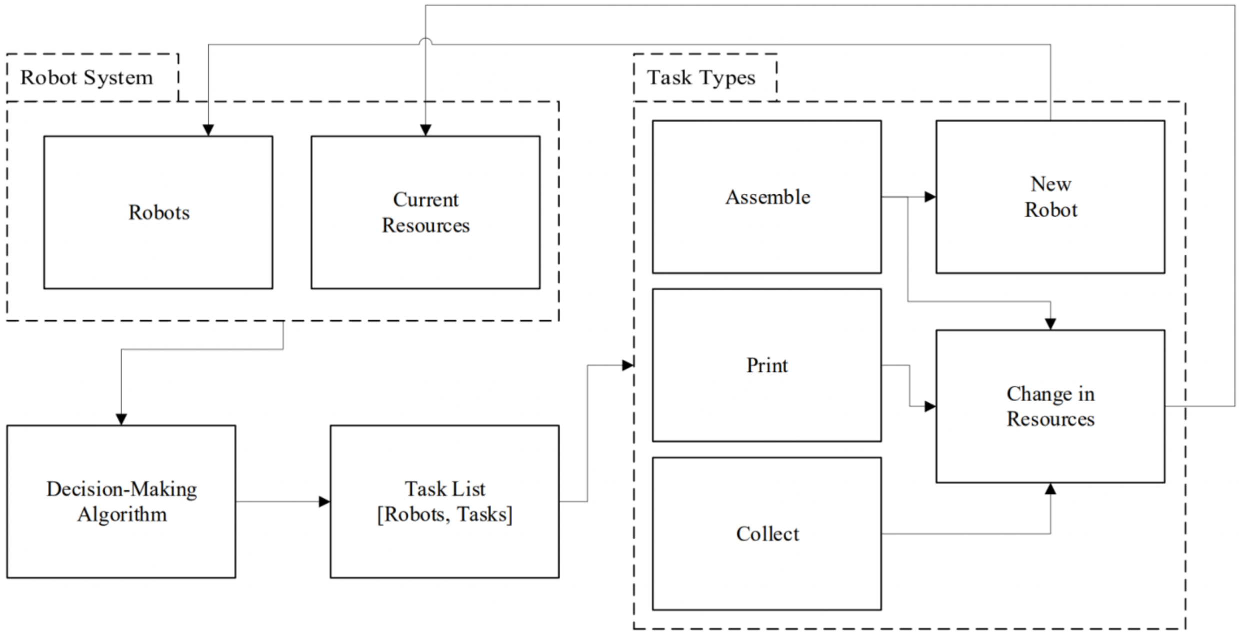


**Figure 1:** Overview of the decision-making system responsibilities.

There are four types of robots: normal, printer, assembler, and replicator. In each time-step, each robot is either idle, gathering resources, printing components, or assembling a new robot. However, certain robot types are restricted in what types of tasks they can perform as shown in Table 2.

**Table 2:** Robot capabilities based on the type of robot.

| Robot Type | Collects Resources | Print Components | Assembles Robots |
|---|---|---|---|
| Normal | TRUE | FALSE | FALSE |
| Assembler | TRUE | FALSE | TRUE |
| Printer | TRUE | TRUE | FALSE |
| Replicator | TRUE | TRUE | TRUE |

The material cost of each robot type is directly related to its capabilities. Capability costs for each included capability are added together to determine the cost of the robot type. For example, the normal robot type cost is just the base cost, while the printer robot type’s cost is calculated by adding the base cost plus the printing capability cost.

The categorization consists of a combination of two separate classifications. The first classification, the replication approach, consists of centralized, decentralized, and hierarchical. The second classification, the production approach, consists of heterogeneous and homogeneous. Table 3 shows which robot types are produced in a certain system configuration.

**Table 3:** Buildable Robot types by system configuration.

| Buildable Robot Types | Centralized | Decentralized | Hierarchical |
|---|---|---|---|
| **Homogeneous** | Normal | Replicator | Replicator<br>Normal |
| **Heterogeneous** | Normal | Assembler<br>Printer | Assembler<br>Printer<br>Normal |

After determining what each of the robots needs to assemble (if anything), the decision making algorithm assigns all currently idle print-capable robots to fabricate printable components. These assignments are limited by the robot system's current amount of available raw printing materials (robots will not be assigned to printing tasks that materials are not available for).

After these assignments, all robots that are idle are assigned to collect materials from the environment. If robots return no materials, then it is assumed that the environment is out of raw materials and the system stops assigning any robots to the collection task once this happens.

## 2. Analysis Overview:

### 2.1. Analysis Factors:

An important capability of a self-replicating robot system is the ability to fabricate parts and assemble new robots. This introduces the question of the quality of the built robot, as a robot built in-situ may have quality defects (without the ability to simply discard it with minimal impacts, such as in a factory setting). To facilitate assessment, the simulation assigns each robot a build quality. A robot's build quality value ranges from zero to one, with one being very high quality and zero being very poor quality. The quality value is a decimal value.

Tasks have a risk of failing in a manner that harms or destroys the robot performing the task. The risk amount values are adjustable parameters within the simulation system. The build quality of the robot performing a task shall affect the associated risks of performing a given task. The rationale behind this is that as the quality of a robot decreases, the risk of it encountering problems performing a task would likely increase.

Thus, the input factors for the 6 configurations are the initial amount of resources, initial build quality that shall be the same for all the configurations as shown in Table 4.

**Table 4:** Input Factors for different system configurations.

| Initial Printable | Initial Non-Printable | Initial Materials | Environmental Materials |
|---|---|---|---|
| 300 | 100 | 50 | 500 |

### 2.2. COA/Design Options:

The various design options and their characteristics are described in Table 5.

**Table 5:** Design Options Characteristics.

| ID | Design Option | Characteristics |
|---|---|---|
| 1 | Centralized homogeneous (CHO) | One robot is responsible for both printing components and assembling them. Constructed robots are of the normal type and either gather resources or complete other objectives. |
| 2 | Decentralized homogeneous (DHO) | All robots have the capability to print components, assemble them, and gather resources or complete other objectives. |
| 3 | Hierarchical homogeneous (HHO) | There are a variable number of robots capable of printing components and assembling them. There are also a variable number of normal type robots. |
| 4 | Centralized heterogeneous (CHE) | One robot is responsible for printing components, and another (distinct) robot is responsible for assembling them. Constructed robots are of the normal type and either gather resources or complete other objectives. |
| 5 | Decentralized heterogeneous (DHE) | Robots have either the capability to print components or the capability to assemble them. All robots can gather resources or complete other objectives. |
| 6 | Hierarchical heterogeneous (CHE) | There are a variable number of robots capable of printing components, a variable number capable of assembling them (distinct from the printing group), and a variable number of normal type robots. All robots can gather resources or complete other objectives. |

The three different replication approaches; centralized, decentralized, and hierarchical approaches, are shown in Figure 2, Figure 3, and Figure 4 respectively.

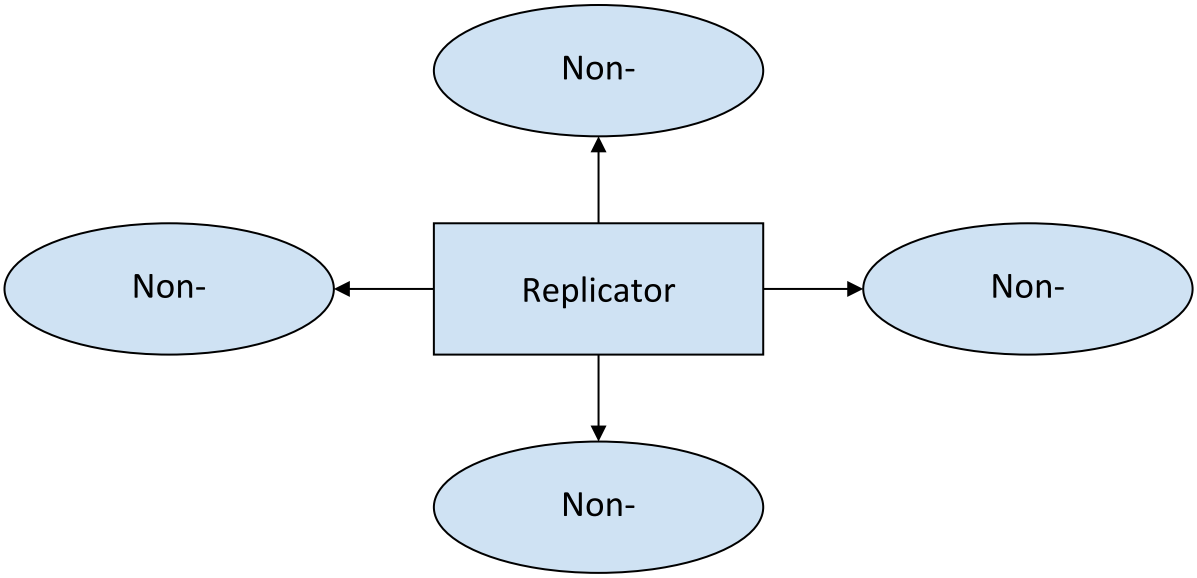


Figure 2: Centralized Replication Approach.

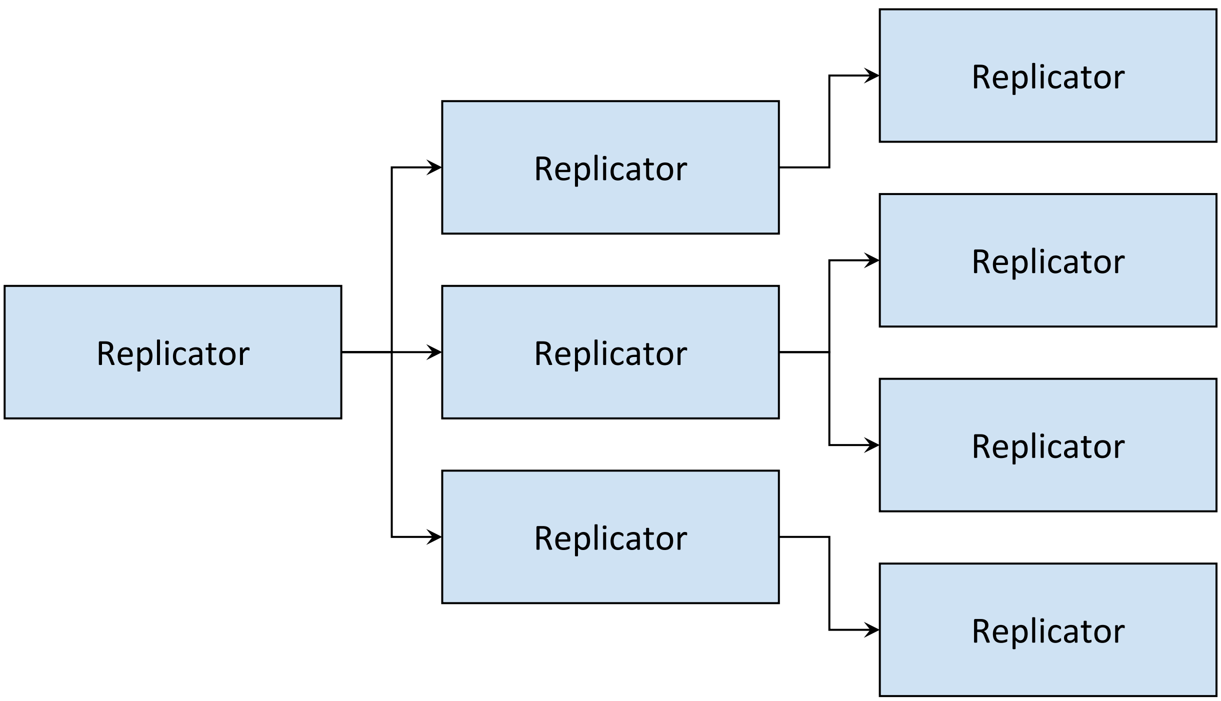


Figure 3: Decentralized Replication Approach.

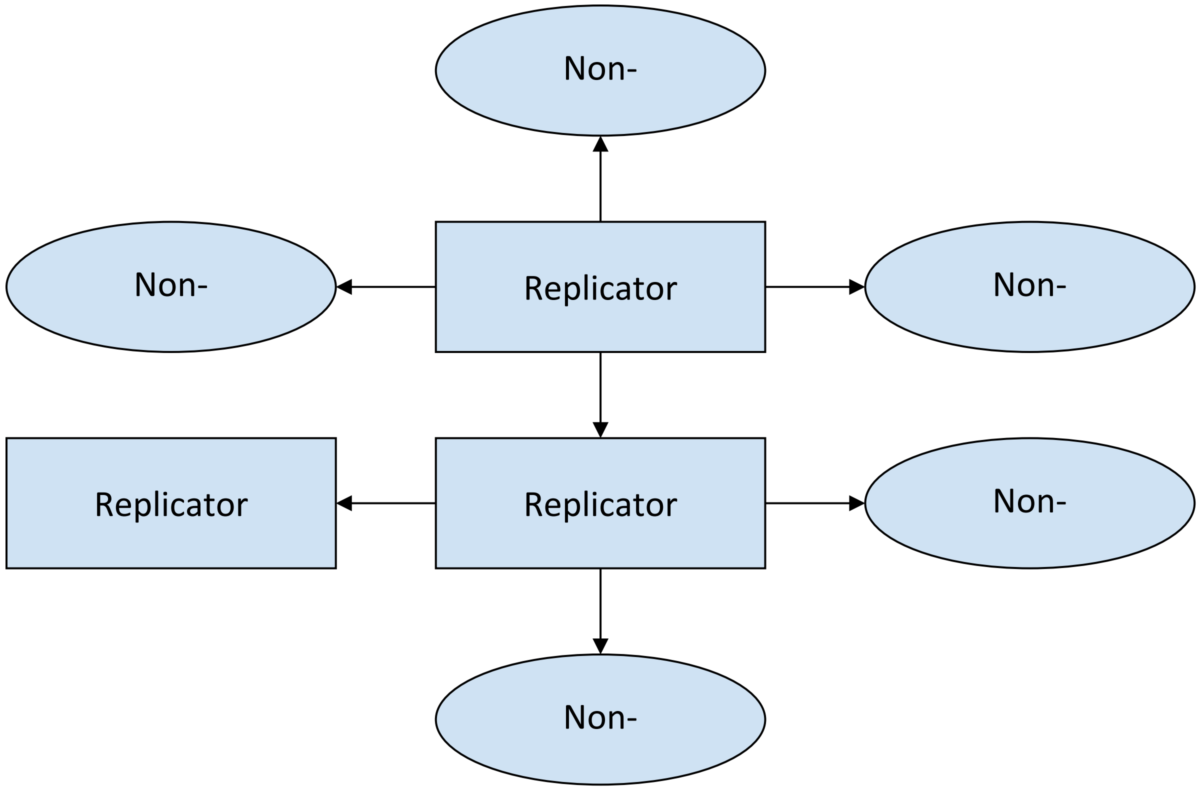


Figure 4: Hierarchical Replication Approach.

The production approach categorization is made in addition to (and is distinct from) the replication approach categorization. The production approach consists of two classifications, homogeneous and heterogeneous. For multi-robot systems, in general, a homogeneous system is composed of robots that are all of the same design, while having multiple types of robots makes the system heterogeneous.

### 2.3. Analysis Metrics:

The primary metrics for which data are collected by the simulation include are as follows:

1) Assembly capacity: The number of robots that have the assembly capability at the end of a simulation run. This includes replicator and assembler robot types, which have not succumbed to a task risk and lost their capability.
2) Collection capacity: The number of robots that have the collect capability at the end of a simulation run. All robot types have this capability in this simulation, so this is always equal to the current number of robots in the system.
3) Print capacity: The number of robots that have the print capability at the end of a simulation run. This includes replicator and printer robot types, which have not succumbed to a task risk and lost their capability.
4) The total number of robots built using the system configuration.

These metrics shall be obtained from the results generated from the analytical method and Monte Carlo simulation runs.

### 2.4. Methodology and Analytic Approach:

The analysis approach that shall be taken is as follows:

1) Analysis of 6 design options (provided in Table 4) based on the analytical model of each system configuration.
2) Linear programming approach to maximize key analysis metrics for each of the proposed 6 design options; Assembly capacity, Collection capacity, Print capacity, and the total number of robots built.
3) The Multi-Attribute Value Function (MAVF) analysis of key analysis metrics.
4) Sensitivity analysis shall be conducted on the MAVF to study the impact of uncertainty of key input factors in the analysis.

### 2.5. Response Models:

The response model as shown in Figure 5 shall be followed for all the 6 configurations of SRRSs.

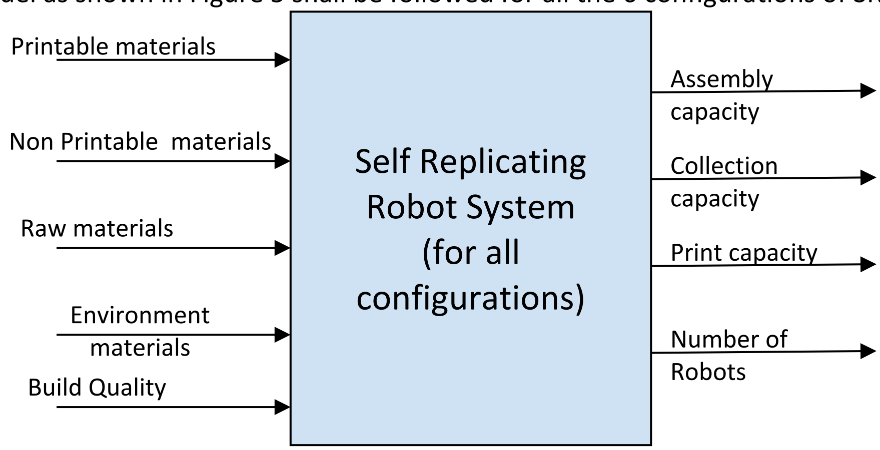


Figure 5: Response model of simulation.

A single configuration shall be selected from the 6 configurations using Multi-Attribute Value Function (MAVF) analysis given the ratings for the metrics using Rank Order Distribution to calculate swing weights as shown in figure 6.

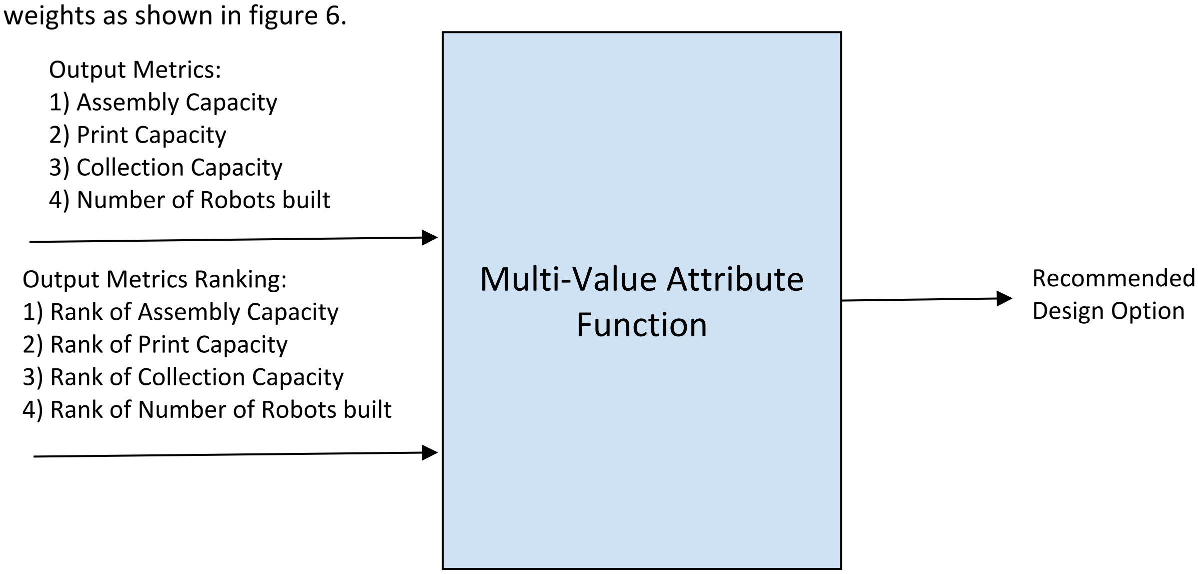


Figure 6: Response model for MAVF analysis.

## 3. Models and Simulations Overview:

### 3.1. Analysis, Modeling, and Simulation Techniques:

The following list of principal analysis, modeling, and/or simulation techniques shall be used to support our analysis:

1) Monte Carlo simulation
2) Multi-Attribute Value Function (MAVF)
3) Sensitivity Analysis

The metrics for the 6 configurations of SRRS is obtained through time-dependent Monte Carlo. Furthermore, a single design option is obtained through a MAVF analysis.

The Monte Carlo simulation shall be used to simulate multiple runs of the building of robots using the 6 different routing configurations being evaluated. The Monte Carlo simulation shall be used to vary the robot build quality, task risks, print efficiency, print amount, and collection amount, in each time step in order to represent variations due to environmental phenomena. This change in factors will be reflected in the output metrics and help in defining the risk associated with each configuration. The aggregate data from the entire simulation shall be then used to calculate the mean of the output metrics, which shall be fed into the MAVF model to determine the best design option given the metric rankings.

In each time-step of the simulation, SRRS-simulated robots perform tasks that involve acquiring resources, converting resources, or assembling new robots. The robots in the simulation are considered single-task (ST) robots that carry out single-robot (SR) tasks with a time-extended assignment (TA). The resources and task types, robot types and their capabilities, and task risks are described in Section 1.3 of this document.

The choice of when to build a new robot, and what type it should be, is decided by a predefined criterion.

Then a sensitivity analysis shall be performed on the design option with the highest recorded MAVF.

### 3.2. Specific Model and Simulation Descriptions:

Table 5 describes the Monte Carlo simulation model and the list of simulation parameters is tabulated in Table 9. Table 7 provides a brief description of the MAVF model that recommends the design option suited for a mission objective. Table 8 provides a brief description of sensitivity analysis that shall be performed on the design option with the highest MAVF score.

**Table 6:** Monte Carlo Simulation model.

| Model | Input | Output | Description |
|---|---|---|---|
| Monte Carlo Simulation | 1) Number of iterations/time-steps that the simulation goes through.<br>2) The robot system's starting quantity of nonprintable components.<br>3) The robot system's starting quantity of printable components.<br>4) The robot system's starting quantity of raw printing materials.<br>5) The environment's quantity of collectible raw printing materials.<br>6) Factor that scales raw printing materials to printable components - Print Efficiency.<br>7) Amount of raw materials converted per print task - Print Amount.<br>8) Raw printing materials per collecting robot per timestep - Collection amount. | 1) Assembly capacity<br>2) Collection capacity<br>3) Print capacity<br>4) Number of robots built | 1) To facilitate assessment, the simulation assigns each robot a build quality. A robot's build quality value ranges from zero to one, with one being very high quality and zero being very poor quality.<br>2) The risk amount values are adjustable parameters within the simulation system. The build quality of the robot performing a task shall affect the associated risks of performing a given task.<br>3) The choice of when to build a new robot, and what type it should be, is decided by a predefined criterion.<br>4) The Monte Carlo simulation shall be used to vary the robot build quality, task risks, print efficiency, print amount, and collection amount, in each time step in order to represent variations due to environmental phenomena. |

**Table 7:** Multi-Attribute Value Function (MAVF) model.

| Model | Input | Output | Description |
|---|---|---|---|
| Multi-Attribute Value Function (MAVF) | 1) Assembly capacity<br>2) Collection capacity<br>3) Print capacity<br>4) Number of robots built | Optimal Design Option or Course of Action | 1) Computing the swing weights for input metrics based on Rank-Order Distribution.<br>2) Computing Single-Attribute Value Function (SAVF) for each metric, and finally computing the MAVF value. |

**Table 8:** Sensitivity Analysis model.

| Model | Input | Output | Description |
|---|---|---|---|
| Sensitivity Analysis (SA) | Uncertainties in each of input key metrics values pertaining to recommended design options obtained from MAVF. | Variation of MAVF from the reference value taken from the recommended Design Option or Course of Action. | 1) Sensitivity analysis on MAVF to study the impact of uncertainty in simulation. |

**Table 9:** List of Monte Carlo simulation parameters.

| Parameter | Default value | Description |
|---|---|---|
| Number of Steps | - | Number of iterations/time-steps that the simulation goes through. |
| Initial Non-Print | 300 | The robot system's starting quantity of non-printable components. |
| Initial Print | 100 | The robot system's starting quantity of printable components. |
| Initial Materials | 50 | The robot system's starting quantity of raw printing materials. |
| Env Materials | 500 | The environment's quantity of collectible raw printing materials. |
| Base Cost Non-Print | 1 | Base robot cost of nonprintable components. |
| Print Cost Non-Print | 1 | Print capability cost of nonprintable components. |
| Assemble Cost Non-Print | 1 | Assemble capability cost of nonprintable components. |
| Base Cost Print | 2 | Base robot cost of printable components. |
| Print Cost Print | 2 | Print capability cost of printable components. |
| Assemble Cost Print | 2 | Assemble capability cost of printable components. |
| Base Cost Time | 2 | Base robot cost of build time (in time-steps). |
| Print Cost Time | 2 | Print capability cost of build time (in time-steps). |
| Assemble Cost Time | 2 | Assemble capability cost of build time (in time-steps) |

## 4. References:

[1] Jones, A., & Straub, J. (2021). Simulation and Analysis of Self-Replicating Robot Decision-Making Systems. Computers, 10(1), 9. https://doi.org/10.3390/computers10010009
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