# CONSTRUCTION MANAGEMENT IN SPACE: EXPLORE SOLUTION SPACE OF OPTIMAL SCHEDULE AND COST ESTIMATE

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***Marcel Nagatoishi, Engineer of Sustainable Design and Construction,***
***Obayashi Corporation***
***nagatoishi.marcel@obayashi.co.jp***

***Renate Fruchter, Professor,***
***Stanford University***
***fruchter@stanford.edu***

***SUMMARY:*** *Multi-planetary life is one of humanity's audacious dreams. A key challenge towards achieving such a space mission is the design and construction of space habitats, for instance, on Mars. This paper presents a virtual space construction decision framework (SCDF) prototype developed and tested to address the question: "How can space construction project partners make informed decisions and leverage new construction methods and cutting-edge technologies that are developed and transform the AEC terrestrial industry?" We consider six practical and theoretical points of departure reflecting knowledge and technology and their application towards developing SCDF: General Contractor Workflow; BIM; Generative Scheduling and Construction Schedule Optimization; Construction Robotics; 3D Printing; Virtual Reality (VR) and Visualization. SCDF development applied virtual design and construction (VDC) to model - simulate - optimize - visualize - validate a space construction project by exploring the solution space in the context of extra-terrestrial construction environments from concept design to construction completion in the virtual environment before any mission is launched. Results confirm that insights from terrestrial construction apply to extra-terrestrial construction and vice versa. These insights contribute to the six points of departure at three levels: 1. The SCDF; 2. Extensions to existing technology platforms; 3. New approaches and methods.*

***KEYWORDS:*** *BIM, Virtual Reality (VR) and Visualization, Generative Scheduling, Construction Robotics, 3DPrinting, VDC, Space Construction.*

***REFERENCE:*** *Marcel Nagatoishi, Renate Fruchter (2023). Construction management in space: explore solution space of optimal schedule and cost estimate. Journal of Information Technology in Construction (ITcon), Special issue: 'The future of construction in the context of digital transformation (CONVR 2022)', Vol. 28, pg. 597-621, DOI: 10.36680/j.itcon.2023.032*

# 1. INTRODUCTION

Attempts to design and construct space habitats on the Moon or Mars are no longer a futuristic vision. For example, SpaceX announced it would build a self-sustained Mars city by 2029 (Brown, n.d.). Artemis Program from the National Aeronautics and Space Administration (NASA) is another example of the need to build a habitat on another planet. “Space Architecture” is a well-established and recognized domain within the aerospace industry and academia. For example, The American Institute of Aeronautics and Astronautics (AIAA) has a Space Architecture Technical Committee that focuses on the design and development of space habitats (SpaceArchitect.org). On the other hand, there are less numbers of research about “Space Construction” compared to space architecture which focuses on the methods how to build. To address this research gap, this paper presents the rapid prototyping process to explore the solution space to optimize the joined decision process between the stakeholders related to the space constructions and interdependences between the three elements, cost, schedule and resources allocation that are driven by payload. As an outcome of the process, we present a space construction decision framework (SCDF) prototype developed and tested to address the question of the potential stakeholders in a space construction project. Like terrestrial construction, space construction is a multi-disciplinary effort with various stakeholders' perspectives, objectives, questions, and decision criteria, as shown in Table 1. The main stakeholders considered in this research are the client, space habitat designer, general contractor, and launch service provider. The implementation of the preliminary SCDF for space construction workflow leveraged innovative modeling, simulation, optimization, and visualization methods and technologies to assist space construction project partners in exploring "WHAT-IF" scenarios and evaluating the solution space towards optimal cost, schedule, and resource allocation that address the space mission client goals and needs (Nagatoishi, Fruchter & Fischer, 2022). The optimal decision will represent the desired outcome for all the stakeholders.

*Table 1: Different perspectives of the four stakeholders considered in a space construction mission*

| | Stakeholders | | | |
|---|---|---|---|---|
| **Stakeholders' perspective** | Client | Designers | General Contractors | Launch Service Provider |
| **Objectives** | We want to have a research facility on Mars for four researchers, and start operating in 2036 | We want to design a facility that meet the demands of the client and needs of the researchers living on Mars | We want to build the facility safely within budget and schedule | We want to send the resources to the site safely without delay |
| **Questions** | What are the constraints of the mission? | What design criteria responds to the mission specification? | What cost-schedule-resources options should be considered? | What construction decision impact the launch? |
| | How are the interdependencies between cost, environment and operations? | How does the design impact construction? | How are the options limited by the launch constraints? | How many launches do we need and when can we schedule them? |
| **Decision criteria** | Cost: \$, €, ¥, …<br>Operation start date: day | Numbers of researchers: people<br>Required space: m2<br>In-situ resource utilization: % | Construction schedule: days<br>Delivery schedule: days<br>Payload: kg | Launch schedule: days<br>Payload: kg<br>Numbers of launches: times |

# 2. POINTS OF DEPARTURES

This study and development of SCDF are at the intersection of six practical and theoretical points of departure reflecting knowledge and technology and their application in design and construction: General Contractor Workflow; Building Information Modeling (BIM); Generative Scheduling and Construction Schedule Optimization; Construction Robotics; 3D Printing; and virtual reality (VR), and visualization. A specific focus of the SCDF study was to apply virtual design and construction to model-simulate-optimize-visualize-validate the space construction project and explore the solution space from concept design to construction completion in the virtual environment before any mission is launched. This process is critical to ensuring project performance.

## 2.1 General Contractor and Space Construction

Although attempts to be a muti-planetary species are not new, general contractors continue to explore how to approach space construction and what value they can provide to this emerging industry. For example, Obayashi Corporation explored the cable dynamics of a Space Elevator and conducted an exposure experiment of the cable in the International Space Station (Ishikawa et al., 2018). Given the opportunity to build a project on another planet, general contractors will consider three decision criteria typical to terrestrial construction before initiating the project: How much will it cost to get the project done? When should we finish and hand over the project? And what will be the specification and quantity of equipment to be used? Schedule means the process of carrying out a project from the builders' perspective and covers the activities consumed as cost. Therefore, the scope is from shipping any resource to the construction site until the handover to the client. Resources include material, labor, and equipment for space construction. The interdependence between cost, schedule, and resource allocation is an important insight gained by the general contractor and discussed with the client to make rational joint decisions. In terrestrial construction, integrated project delivery starts with understanding the client objective and converting it to a project objective that different stakeholders can measure and understand (Kunz & Fischer, 2020). The methodology for integrating project delivery is called the Virtual Design Construction (VDC) framework, defined as "the use of multi-disciplinary performance models of design construction projects, including the Product (i.e., facilities), Work Processes and Organization of the design - construction - operation team to support business objectives." (Rischmoller et al., 2018). The development of the SCDF is based on the VDC methodology.

## 2.2 Building Information Modeling (BIM)

BIM transformed the terrestrial design and construction industry. Using BIM to develop the entire virtual construction sequence using 4D CAD simulation of the construction enables teams to detect problems in the construction schedule, e.g., impossible sequence, time-space conflict of resources, and accessibility of equipment before the construction starts. Identified issues provide timely feedback from the builders to designers to improve the design and construction process. Similarly, 4D simulation was one of the requirements for NASA's 3D-Printed Habitat Challenge (Muthumanickam et al., 2021). 4D simulation served as a validation of the construction method each team proposed. SCDF aims to provide a constructive feedback loop from 4D simulation to design and resource allocation implemented in a BIM-centered workflow of space construction.

## 2.3 Generative Scheduling and Construction Schedule Optimization

Optimizing construction schedules is a critical objective of the general contractor, and Critical Path Method (CPM) is a widely used method for that purpose. Current scheduling practices show that general contractors typically develop one or a few schedule options on construction projects since the procedure is time-consuming (Fischer et al., 2018). ALICE, from ALICE Technologies, is the first cloud-based generative scheduling software that leverages AI and optimization techniques. It assists general contractors in exploring a solution space of many different schedule alternatives. It compares and further optimizes schedules considering WHAT-IF scenarios of key variables such as the availability of resources or other construction methods. The required input is a BIM, precedence relationships of each element, and the description of the sequence of activities to build element types, called "Recipes". Production rates and resources, such as labor, material, and equipment, are parametrized. ALICE provides insights regarding the interdependencies of cost and schedule for each scenario. In the case of space construction, the total payload is the critical determining factor in monetary and environmental cost, consequently impacting the entire space mission because it determines the number of rocket launches. The corresponding variables to payload are the number of crews and equipment and the material that needs to be shipped from Earth. Therefore, these variables need to be included when considering an extra-terrestrial construction project and optimizing them is essential. It is important to send the correct number of resources and optimize them by assessing multiple schedule scenarios considering payload and mission launch time window constraints.

## 2.4 Construction Robotics

Deploying robots on construction sites is one of the essential factors in enhancing the productivity of construction. Even though implementing robots incurs extra costs, the positive impact of reduced health and safety risks motivates general contractors to consider robots for specific construction tasks (Brosque et al., 2020). This upward trend of robots on construction sites requires innovative contractors to analyze the safety, productivity, quality, and cost impacts of the deployment of robots (Brosque et al., 2021). The Robotic Evaluation Framework (REF) developed at Stanford University supports this assessment. It determines the fit of a given robot to a given construction project, so we used REF in SCDF for the robot selection process.

## 2.5 Space Construction and 3D printing

Additive manufacturing, or 3D printing, is a promising technology for space construction, especially on Mars and the Moon, as indicated by the research on In Situ Resource Utilization (ISRU) (Kading & Straub, 2015). This allows the conversion of local resources at a space destination to provide functional infrastructures and commodities (Starr & Muscatello, 2020). A benefit of ISRU is that it does not require the transportation of construction materials to another planet, which would impact the number of launches and the terrestrial environment. Numerous methods are studied to transform in-situ resources such as regolith into 3D printing-ready material (Yashar et al., 2019). While the mechanism of the 3D printing technologies is not finalized to date, prototype robots have been designed to collect in-situ resources and perform 3D printing. It is crucial to understand how much in-situ material will be used and how much will be shipped from Earth.

BIM-centered workflow, 4D simulation, and visualization are implemented to optimize the number of resources to be sent. One challenge to executing a 4D simulation of 3D printing is that 4D simulation requires discrete information, element by element. However, the model usually represents structural elements like walls as one continuous structure. Therefore, a model transformation must be implemented to define specific modules or segments to run a 4D simulation.

## 2.6 Virtual Reality (VR) and Visualization

Using virtual modeling, optimization, and visualization is crucial for the success of space missions and interplanetary construction projects. The Fuzor VDC VR platform from Kalloc Studio is used to simulate and validate construction site logistics, identify workflow bottlenecks, and validate potential construction schedules. Multiple feedback loops between generative schedules, virtual construction site logistics, and BIM space habitat design models support the goal of continuous improvement in design, construction, and overall mission planning and execution. The software is used for BIM 4D CAD simulation and construction site logistic bottleneck detection for 3D printing robots on the hypothetical project on Mars.

The validity of the 3D printing path is also critical in these projects. Due to the high risk of Extra-Vehicular Activity (EVA) and communication latency, a detailed simulation is required before 3D printing to avoid defects. The literature review shows multiple ways to simulate the behavior of a 3D-printed material (Roussel et al., 2020). Houdini Apprentice from SideFX is used to simulate and validate the segmentation of the building, ensuring that the printing path functions correctly. This software is primarily used for computer graphics, and this research explores its use in simulating construction projects, expanding its usage in the field.

# 3. SPACE CONSTRUCTION DECISION FRAMEWORK (SCDF)

The SCDF framework supports space construction decision-making as a continuous improvement process (Nagatoishi, Fruchter & Fischer, 2022). To achieve these goals, we applied the principles of Design Thinking (Plattner et al., 2010) and PLAN-DO-STUDY-ACT (PDSA) (Corinne, 2002). We formalized SCDF consisting of four Plan-Do-Study-Act phases: Mission, Model, Simulation, and Decision, which were implemented as shown in FIG. 1. SCDF was implemented through an iterative rapid prototyping cycle where feedback loops among the four phases to foster continuous improvement of the mission and space construction project.

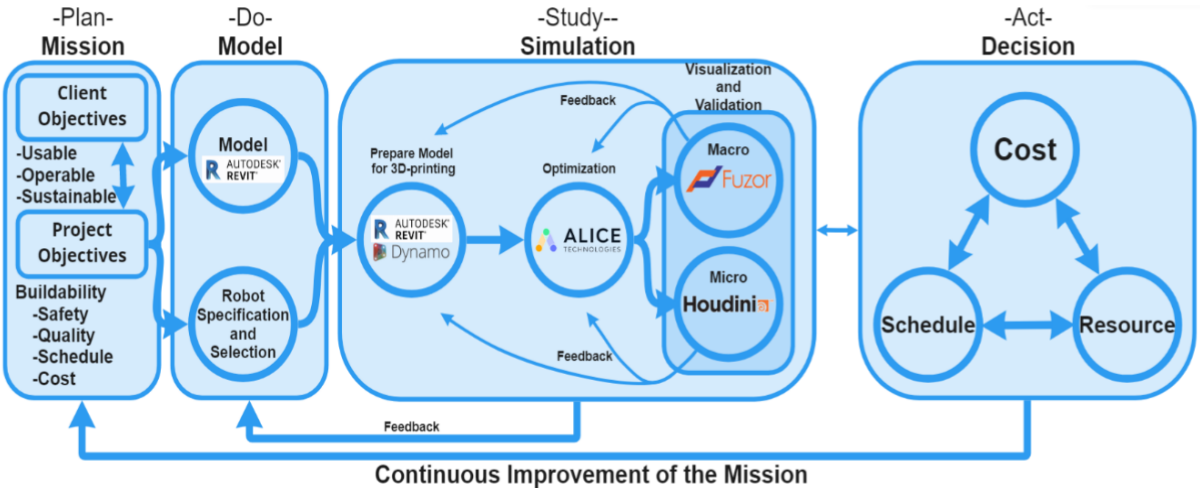



*FIG. 1: Space Construction Decision Framework (SCDF) and Implementation Approach*

The mission is where the decision criteria for the client are addressed by translating the client's goals into measurable project objectives. The buildability objective of a project focuses on - safety, cost, schedule, and quality metrics. The SCDF addresses these metrics in the Simulate step of the space construction workflow. Three key criteria represent the output of SCDF - cost, schedule, and resource allocation – to address the quality of the product. The following explains how each element of SCDF accounts for them.

In the model phase, the space habitat building model and the robots that will be deployed are decided. Robots are critical equipment to be deployed in space construction projects. The REF is used and assesses four metrics – safety, budget, schedule, and safety.

The simulation consists of three steps: 1) Prepare Model for 3D printing, 2) Optimize, and 3) Visualization and Validation of the space construction workflow. Since the current implementation of ALICE does not support continuous tasks such as 3D printing, we developed functionalities to define "Recipes" that simulate continuous tasks such as 3D printing to gain meaningful insights for decision-making. The next step focuses on optimizing the schedule and costs for a given scenario from the "Model." ALICE provides the cost and schedule, which correspond to two of the project performance metrics that address the project objectives. The optimization results are validated and visualized at the macro and micro levels. This is where construction logistics – safety and quality are checked to ensure the buildability of the space habitat. At the macro level, the site logistics are visualized using Fuzor VDC VR to validate the schedule selected from the solution space generated by ALICE. This is where the buildability check is performed, especially for safety and schedule. Potential insights from the visualization include conflicting robot trajectories, impossible ergonomics, and safety issues. Though ALICE considers conflicting workplaces while generating the schedule, it does not consider the movement trajectory of the equipment, such as robots. The reason is that almost every construction activity is assigned to each element of the building model imported in ALICE. Therefore, the relocation of the crew or equipment could be tracked. However, it is not possible to track how they moved. For the same reason, ALICE's functionality currently lacks the capability to account for impossible ergonomics and safety issues. To address these issues, the Fuzor VDC VR platform is used to model, simulate, and visualize the movement of the robots to detect such spatial navigation conflicts.

The micro-level visualization was accomplished using the Houdini Apprentice software platform from SideFX. Houdini is a 3D procedural software with multiple simulation functions. It's Particle Fluid Simulation simulates and visualizes the printing path to ensure the quality of the finished product. After this process, the project team using SCDF can identify the interdependencies of three key decision criteria: cost, schedule, and resource allocation, and decide their values based on all the project objectives. This information is communicated to the client, who will evaluate whether the proposed cost, schedule, and resources meet the mission objectives. Since the interdependencies of the key decision criteria - cost, schedule, and resource allocation - are reported to the client, it will help the client make a rational decision. The user of the SCDF could run the entire iteration from Mission, Model, Simulation to Decision multiple times, and each iteration will provide insights that will contribute to Mission improvement. The Decision phase represents the outcome as a function of the three interdependent criteria – cost, schedule, and resource allocation.

## 4. METHODOLOGY

The objective of this research study is to identify key criteria and variables to be considered in the decision process and optimization of space construction projects. The study presents SCDF to model and optimize the space construction workflow and test it in the context of a space construction project. Deming's Plan-Do-Study-Act (PDSA) cycle and Stanford d-school's Design Thinking framework were utilized towards developing the proposed SCDF. PDSA cycle aims to achieve continuous project improvement. The Design Thinking framework consists of five steps, Empathize, Define, Ideate, Prototype, and Test. This framework has a high affinity with Deming's PDSA cycle because the more iterations are performed using the Design Thinking framework, the higher the quality of the finished product will be. The development of the proposed SCDF integrated the steps of PDSA and Design Thinking as follows:

1) Plan: Empathize/Define - Each iteration starts with observing the problem. Furthermore, it identifies the scope of the challenge and the objective that needs to be achieved in this iteration. In a broad context, the question asked in this step is, "What is given?".

2) Do: Ideate/Prototype - In this step, the options are explored to solve the identified problem. One or more prototypes are created based on the options explored. The criteria for choosing what to prototype differs

from iteration to iteration. The following questions are considered: "What are the choices?", "What was prototyped and how?"

3) Study: Test - The result of the prototype is evaluated to determine whether the identified problem was solved. If the problem is solved, the prototype is going to be incorporated into the SCDF. If not, another measurement was discussed. In both cases, insights are gained by evaluating the prototype. The question here is, "What are the insights of the prototype?".

4) Act: Integrate and Improve/Define next iteration - "What decision was made for the next iteration?". This is the critical question in this step of iteration. This research explores the solution space of extra-terrestrial construction projects using the SCDF workflow. The insights gained from the last part will be incorporated and improved to improve the framework. It is also essential to understand the current limitations that lead to the problem's definition for the next iteration.

In each iteration, the SCDF and essential components were prototyped. This rapid prototyping approach and continuous improvement enabled the rapid development and implementation of the SCDF. The gained insights from each iteration improved the SCDF development and are described in the following sections.

# 5. SPACE CONSTRUCTION DECISION FRAMEWORK RAPID PROTOTYPING

The rapid prototyping development and implementation of the Space Construction Decision Framework (SCDF) leveraged existing software platforms and past construction project management experience. Each iterative prototyping cycle addresses the following research aspects: 1. What is given? 2. What are the choices? 3. What was prototyped? 4. What are the insights gained from the prototype? 5. What decision was made for the next prototyping iteration? Table 2 describes the rapid prototyping iteration cycle overview and its outcomes.

*Table 2: Overview of SCDF Rapid Prototyping Iteration (Nagatoishi, Fruchter & Fischer, 2022)*

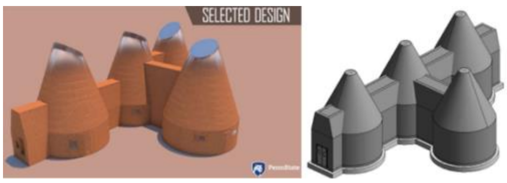
Legend - Related Points of departures: a. General Contractor Workflow b. Building Information Modeling c. Generative Scheduling & Construction Schedule Optimization d. Construction Robotics e. Space Construction and 3D printing f. Virtual Reality (VR) and Visualization

| | Rapid Prototyping Iteration | PoD | Plan/Do (What was done) | Study (Insights from the iterations) | Act (Decision for the next iteration) |
|---|---|---|---|---|---|
| 1 | “Choose the shape of the Mars habitat structure for the first prototype” | a. b. | Modeled the simplified shape of the projects from NASA’s Mars 3D-Printed Habitat Challenge and created a decision matrix to determine the first prototype shape. | Penn State University's habitat concept was created through a BIM-centered process. The model could be simplified e.g. composed of three primary component shapes: cone, cylinder, and box. | Cylinder shape was selected for the first SCDF prototyping iteration. |
| 2 | “Run 4D Simulation” | b, c. e. | A BIM cylinder-shaped prototype and a preliminary ALICE recipe for 3D printing. | Current ALICE functionality does not support to define continuous activities such as 3D printing. | Segment the model to simulate and visualize the construction site situations using 3D printing. |
| 3 | “Segment the model according to robotic specification” | a. b, d. e. | Segmented the cylinder- shaped prototype according to the a given robot specification. | Consider robot options for the project, since the size of the 3D printed segment depends on the robot specification. | Identify robot selection method based on additional constraints to determine the 3D printed segments. |
| 4 | “Apply method to select robot for the project” | a. b, c. d. e. | Use Robotic Evaluation Framework (REF) to evaluate two robots, from Penn State University and NASA. | Current REF compares “Manual” and “Robot” processes. Additional variables need to be considered to address space construction conditions. | Four additional variables: Needs of EVA, Autonomy Level, In-situ Recourse Utilization, and Robot Mass are identified & integrated into REF. |
| 5 | “Automate segmentation” | a. b, e. | Automated the segmentation process using Dynamo. | The segmentation process is based on information from BIM, numbers of robots, 3D printing methods, and choice of material. | Formalize methods in ALICE to explicitly represent relocation and refueling of the robots. |
| 6 | “Relocate and Refuel the Robots” | b, c. d. e. | Integrated relocation and refueling process in ALICE. | Robot reallocation and refueling process could be integrated in ALICE recipes. | Integrate the representation of the robot relocation and charging material activities in SCDF. |
| 7 | “Visualize and Validate” | b, d. e. f. | 4D visualization of ALICE selected schedule using the cylinder-shaped model. Assess constructability using Fuzor VDC VR for macro-level and Houdini for micro-level visualization and validation of construction workflow on site. | Macro-level validation of the site logistics and micro-level validation of robot 3D printing path. Both provide insight to the previous decision in the SCDF regarding the number of robots, construction sequence, and path interferences. | Expand the timeframe to relocate the robot. |

| | Rapid Prototyping Iteration | PoD | Plan/Do (What was done) | Study (Insights from the iterations) | Act (Decision for the next iteration) |
|---|---|---|---|---|---|
| 8 | "Run complete SCDF simulation test - "model-simulate-optimize-visualize and validate" | a. b, c. d. e. f. | Run the SCDF simulation using a proposed concept design from the "NASA 3D-Printed Habitat Challenge" | 1. Visualization and validation process let to identify three types of feedback loops: the potential need for the scaffolding, the order to complete the types of walls, the consideration of the lateral load effects due to strong Mars winds.<br>2. Potential interdependencies of resource allocation, cost, and schedule was identified. | Initialize new SCDF cycle based on feedback insight. |
| 9 | "Explore Interdependencies between the decision criteria" | a. b, f. | Update the model based on the feedback. Simulate scenarios using 3, 5, and 10 robots to identify the interdependencies between key decision criteria - cost, schedule, and resource allocation. | SCDF can provide the interdependencies of the three different scenarios in a short amount of time. | Communicate to stakeholders the results of the three interdependencies to support evidence-based decisions for the mission. |
| 10 | "Make decision based on SCDF workflow output" | a. | Correlate SCDF output with the stakeholders' objectives, questions and decision criteria identified shown in Table 1. | TOPSIS was used to choose the optimal scenario based on the interdependencies of the three key decision criteria. | The optimal scenario to new questions raised by the stakeholders to be addressed in the next cycle of the SCDF. |

## 5.1 Choose the shape of the Mars habitat structure for the first prototype

The first iteration aims to identify the shape of the Mars habitat structure for the first prototype towards modeling and testing the construction schedule, cost, and resources using a 4D CAD simulation platform. The goal is to identify a simplified test structural shape before a more complex structure is modeled for a space construction project. This simplifying process may reduce the time to prototype improvements further and increase the number of iterations to develop and improve the SCDF. To identify options for the shape of the space habitat structure, we considered the projects from the NASA Mars 3D-Printed Habitat Challenge (Carrato, 2021). This challenge was part of the NASA Centennial Challenges program competition, inviting participants to build a 3D-printed habitat for deep space exploration, including the agency's journey to the Moon, Mars, and beyond. NASA designed this multi-phase challenge to advance the construction technology needed to create sustainable housing solutions for Earth and beyond. Eleven teams participated. They were scored and awarded points based on architectural layout, programming, efficient use of interior space, and the habitat's 3D printing scalability and constructability. The teams prepared short videos detailing their design and construction process. For the SCDF research study, we considered the 3D printed Mars/Space Habitat developed by the team from Pennsylvania State University (FIG. 2-(a)) and replicated the 3D model in Revit (FIG. 2-(b)).




(a) (b)

*FIG. 2: Original model from Penn State University; (a) and the replicated for the SCDF testcase; (b)*

*Since the design has been generated, analyzed, optimized, and simulated through a BIM-centered process, there was a high affinity to the SCDF. In contrast to the Penn State team's approach that used the 4D simulation focusing on replica production in a warehouse (Yashar et al., 2019), the SCDF research study used the 4D simulation for the case that the construction would take place on planet Mars. As the BIM model developed by the Penn State team was not publicly available, we recreated a similar model based on the published articles and video that provided the details of the model to be replicated. The shape of the selected design shown in FIG. 2-(b) could be simplified, for instance, being composed of three primary component shapes: cone, cylinder, and box as shown in FIG. 3. This simplification was critical to developing and testing the first prototype to develop the SCDF. The ease of revising the model and running multiple iterations was one criterion for the first prototype to iterate and accumulate insights efficiently. For this reason, the three shapes were modeled in Revit and compared to select one shape as a first prototype. Revit is a Building Information Modeling (BIM) software widely used in practice. To ideate and prototype, we compared the three options to identify the pros and cons of the shapes considering* *two criteria: "Similarity to the original 3D-Printed Mars Habitat project" chosen as a model for developing the SCDF and "Ease to revise the model". Table 3: Selection of the shape for the first prototype*

remodel in REVIT

illustrates the decision matrix to determine which model to utilize for the first prototype. For clarity, the shape is referred to as a "cylinder-shaped prototype" throughout this research.

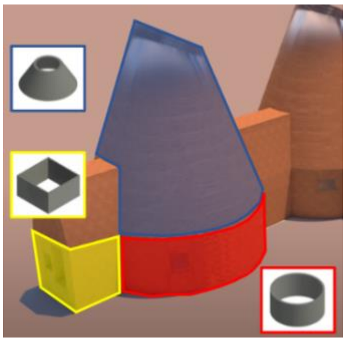


*FIG. 3: Simplification of the project to different shapes*

*Table 3: Selection of the shape for the first prototype*

| |  |  |  |
|---|---|---|---|
| Name of the Shape | Cone | Cylinder | Box |
| Similarity to NASA's Mars 3D-Printed Habitat Challenge | YES | YES | NO |
| Easy to model and remodel in REVIT | NO | YES | YES |

## 5.2 Run 4D Simulation

The next prototyping step aimed to optimize the construction schedule using the selected cylinder shape for the structure. For that purpose, the 4D simulation needs to support "WHAT-IF" simulation scenarios considering different resources as shown in FIG. 4.


*FIG. 4: Testing SCDF; Schedule optimization of the cylinder-shaped prototype*

For the cylinder-shaped prototype, the task duration to finish the building model can be optimized by changing the number of "crews" in the recipe function of ALICE. This process enables the stakeholders to explore and understand the interdependencies between the schedule and the number of robots, gaining a broader view of the possible options and making informed decisions. However, these interdependencies do not yet include other activities, such as relocation of the robots, charging materials, and assembling temporary structures, which may further impact the decision related to the schedule and number of robots. It is essential to model, simulate, and visualize the site logistics when scheduling a construction process.

These issues could be addressed if the model is segmented to simulate and visualize more complex construction site situations. Since the robot has a limited reach, every time it finishes printing one element it can reach, the robot needs to relocate. Relocation has an impact on site logistics. Consequently, tracking the robots' movement, location, and timing is crucial. Therefore, a method to segment the building model is presented in the next iteration. It prepares the building model for a more complex 4D simulation to detect construction site logistic issues.

## 5.3 Segment the model according to robotic specification

As confirmed in the previous iteration, to run a 4D construction simulation with 3D printing robots, segmentation of the shape must be performed beforehand. Therefore, the next rapid prototyping iteration focused on determining how to segment and prepare the model, as shown in FIG. 5.


*FIG. 5: New element in the SCDF workflow; Prepare Model*

The segmentation process depends on the robot's specifications, such as the robot's reach. Each robot has a different reach for 3D printing. Therefore, the first step was to identify the specifications of different robots and choose the robot used to develop the proposed SCDF. The robot used in this iteration was the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) shown in FIG. 6-(a) developed by the National Aeronautics and Space Administration (NASA) ((A. S. Howe and B. Wilcox, 2016). A vital feature of this robot is that each limb could serve as a tool adapter, such as dozer blades, backhoe shovels, and 3D printing attachments as shown in FIG. 6-(b). This robot was chosen due to the availability of detailed specifications, such as geometry and mass, and consideration of additive 3D printing purposes. The geometry and the reach of the limb were essential to identify the potential size of each building segment. From the printing range that was explored in the reference, the size was determined temporarily as length: 2000mm, width: 200mm, and height: 200mm. The model was manually segmented in Revit and imported into ALICE. Two scenarios were explored: one robot and three robots. The result from the 4D simulation shows that deploying three robots will finish the work faster, with a cost increase. This outcome is relatively intuitive, but it could not be achieved without segmenting the model and 4D simulation.

(a) (b)

*FIG. 6: Outlook of ATHLETE;(a) and used as Additive Construction System;(b)*

In this prototyping iteration, the need for the specification of the robots to consider the size of each segment was confirmed. The specifications differ for each robot. It is necessary to determine which robot to use for the project in case there are options. The next iteration explores how to compare different robots and select a certain type.

## 5.4 Apply method to select robot for the project

The previous iteration served to confirm that robot selection is the driver of the construction schedule. This iteration explores a procedure for choosing the robot that will be deployed to construct the habitat structure. This process must be done before preparing the model since the robot's reach determines the size of each segment, as confirmed. This iteration includes the robot selection in the SCDF workflow as shown in FIG. 7.

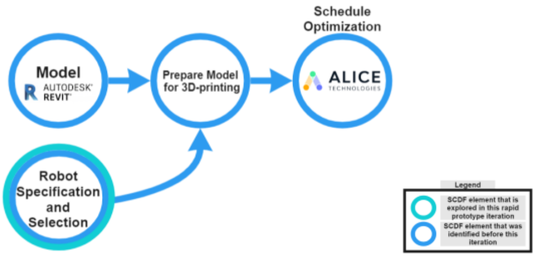



*FIG. 7: Selection of the robot in the SCDF workflow*

To understand the different characteristics of the robots and select one for a specific construction task, we used the "Robotic Evaluation Framework (REF)" developed at Stanford University (Brosque et al., 2021). It is important to note that comparing dependent variables, the second phase of REF, relates to the SCDF study. Space construction will rely more on robotic construction, as discussed in the points of departure. There needs to be a selection process to test which available robots are suited to build the project as part of the SCDF. For this reason, the current REF, which compares "Manual" and "Robot" processes and variables, needs to be expanded to compare different robots when applied to space construction. For that purpose, we propose to add four dependent variables that need to be considered during the comparison and selection of a robot, as shown in FIG. 8; i) Needs of EVA, ii) Level of Autonomy, iii) Availability of the Material, and iv) The Mass of the Robot. The yellow arrows explain the relation of the additional variables to the original variables.

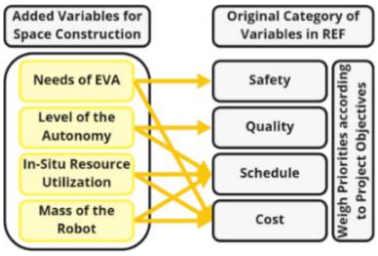



*FIG. 8: Added variables to the REF for space construction projects that will use robots*

We compared two robots in this iteration. One is the robot proposed by the team from Penn State University for the NASA's 3D-printed Habitat Challenge. Not every dimension and size were specified for the robot. Therefore, we assumed the mass of the robot based on the team's YouTube video for the challenge as shown in FIG. 9. The other robot we considered is the ATHLETE since the specifications were available. The team at NASA did the preliminary mass estimation of ATHLETE with its 3D printing functionality. This robot utilizes Freeform Additive Construction System (FACS) that uses a microwave sintering method to process the material (Brosque et al., 2021). The robot selection was performed using REF. We identified additional independent variables to address space construction, as shown by the following comparison we performed.


*FIG. 9: Robot for 3D Printing that the team from Penn State university proposed*

1) Needs of EVA

In the case of the robot proposed by Penn State, the size could be roughly estimated as of the building from observing the video mentioned above. Since one building was estimated to be approximately 7 meters wide and 12 meters high, it would be unlikely that the robot could be shipped to space in one piece, considering the size of available rockets. The astronauts or another robot will need to assemble the parts on Mars. ATHLETE is designed to do the tasks themselves and could be deployed without EVAs.

2) Level of autonomy

Preferably the robots should have autonomous and have preprogrammed movements. Therefore, to evaluate the robot, we expanded the classification of level of autonomy that is originally proposed to self-driving cars (Barabás et al., 2017). The robot from Penn State team were not mentioned if it would need human assistance for operation. However, the entire task was shown automatically in the video for reference, so the robot was evaluated as Level 5. ATHLETE was rated as Level 5 autonomous as well.

3) Availability of the Material

The documentation explaining the robot the Penn State team proposed indicated that it would utilize concrete mixtures. Although materials that could be substituted for aggregates and water are available on Mars, cement material needs to be processed on Mars or shipped from Earth. Building a cement factory could be a future project, so cement needs to be shipped from Earth. Although the water-cement ratio varies, to achieve high compressive strength, around 30% of the entire building mass will have to be shipped from Earth, including a contingency use of cement. ATHLETE utilizes FACS, the microwave sintering method, and requires only the basalt from Mars. Therefore 0% of the material needs to be shipped from Earth to build the project.

4) Mass of the robot

The mass of Penn State's robot was estimated to be 650,000kg since it looks almost the same size as the building, which is around 20 meters wide. The mining truck from Caterpillar was a proxy to estimate the mass. The largest dump truck Caterpillar provides has a height of 15 meters, a length of 14.8 meters, and a width of 9.8 meters. It has a total weight of 623,690 kilograms. For the printing systems and tanks, we estimated around 25,000 kilograms leading up to 650,000 kilograms. For ATHLETE, the entire mass is 3,314.3kg.

The result shows that for a comparison of single robots, ATHLETE is favorable. However, note that the comparison between one robot from Penn State and multiple ATHLETE robots has not been performed. There is a possibility that the robot from Penn State might be favorable in some scenarios. In developing the SCDF, the next step before optimizing the schedule using a 4D simulation is to prepare the model segmentation, as we confirmed in the third rapid prototyping iteration. The segmentation was performed only based on the robot's reach obtained from the specification in the previous attempt. Therefore, the next step aimed to understand whether other constraints determine the size of each segment and formalize this process. Moreover, segmentation is not a one-time process. Based on the result from the schedule optimization, the selection needs to be done again using REF. It is inefficient to perform the segmentation manually, and automation is necessary for this process.

## 5.5 Automate segmentation of space habitat model

The robot that will be deployed in this mission has been tentatively selected from the previous iteration. As an insight, two aspects related to the segmentation process will be considered in this section: 1) Formalizing the size and 2) Automating the segmentation process. This process is done after the selection of the robot. This iteration is an improvement of the existing SCDF element "Prepare Model for 3D-printing", as shown in FIG. 10.

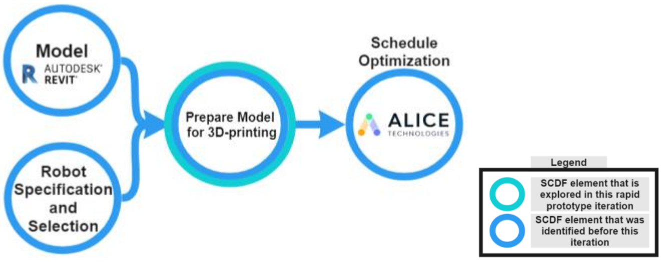



*FIG. 10: Improved SCDF element: Prepare Model*

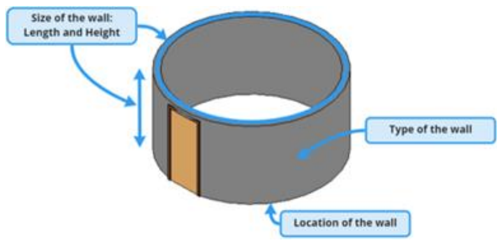
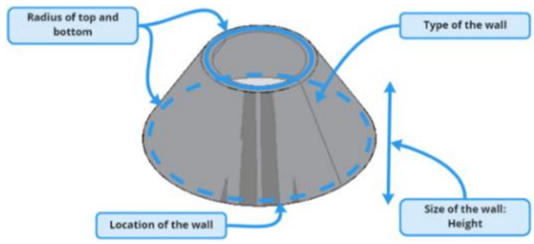
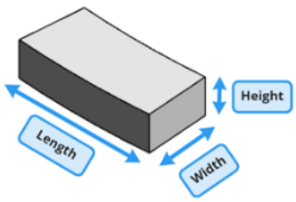
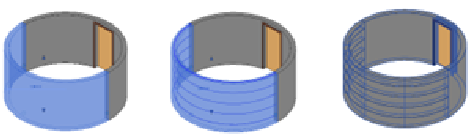
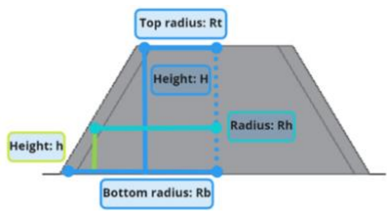
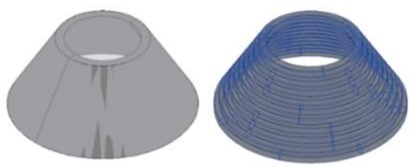
### 5.5.1 Developing a method to define the segment size

Towards defining the size of each segment, three parameters - length, width, and height is defined. The parameters are obtained as a function of the reach of the robot since ATHLETE is utilizing incineration for 3D printing. Method on how to define the segment size with an object with cementitious material is discussed in appendix A.

### 5.5.2 Development of the algorithm of automated segmentation in Dynamo

The following Table 4 explains the general structure of the Dynamo segmentation automation prototype. There are three types of shapes, as discovered in Section 5.1. The cylinder and box shape have three parameters to obtain from the model; location of the wall, size of the wall, type of the wall. On the other hand, the cone shape needs to obtain the radius of the top and the bottom respectively on top of the three parameters.

*Table 4: Algorithm of automated segmentation in Dynamo for different types of walls; Cylinder, Box and Cone*

| | Cylinder | Box | Cone |
|---|---|---|---|
| Parameters obtained from model | Location of the wall<br>Size of the wall<br>Type of the wall | | Location of the wall<br>Size of the wall<br>Type of the wall<br>Radius of top and bottom |
| |  | |  |
| Parameters assigned manually | Size of each segment<br>Length, width, height | | |
| |  | | |
| Segment the model | 1. The location of the walls are split by the Number of curves.<br>[Numbers of curves =Length of the wall / Length of each segment (rounded up)]<br>2. These curves are copied vertically to reflect the height of the wall.<br>3. The wall segments are placed on the curves. | | 1. Draw circles by plugging in the segment height to the equation<br>2. The circles are split by the Number of curves.<br>[Numbers of curves =Length of the wall / Length of each segment (rounded up)]<br>3. The curves are copied vertically to reflect the height of the wall.<br>4. The wall segments are placed on the curves. |
| Example and the steps to segment the model |  | | <br>$Rh = Rb - \frac{(Rb - Rt)}{H} \times h$<br> |

## 5.6 Relocate and Refuel the Robots

In addition to the previous prototyping iteration, relocation and refueling are activities that need to be considered because they will affect the construction site logistics and the schedule. This iteration tests the SCDF workflow focusing on the schedule optimization phase, as shown in FIG. 11. Attempts were made to incorporate these as "Recipes" in ALICE functionalities as described in the following.


*FIG. 11: Testing SCDF with an augmented set of ALICE "Recipes" that include robot relocation and refueling*

1) Relocation

The ideal recipe for relocation would have an if-else condition where the relocation time would be added "if" the robot will relocate and print another segment. However, ALICE does not currently provide such functionality for defining recipes. The ALICE "crane function" was utilized to model the robot's position. The printing time for one segment is 484.44 seconds or 0.1346 hours in the scenario with one robot, as it was calculated in the previous iteration. This activity is assigned a mobile crane, "Default Crane1", with 600 seconds, or 0.167 hours of relocation time. Four locations are set for this Default Crane1, where the crane can sit and serve all segments. Similarly, in the scenario where three robots are deployed, the productivity of one segment is 2906.64 seconds or 0.8074 hours. Since three robots are deployed, the number of cranes will be set as three. The locations of the cranes are going to be the same as in the one robot scenario. This implementation scenario prevents the robot's trajectories from clashing with each other. After entering the task durations for printing and relocating, ALICE performed the 4D simulation using the given model. The entire schedule was examined to ensure there were no time-space conflicts between the robots, and the relocation time was taken into account only when necessary.

2) Charging Material

Recharge the material is another important concept that needs to be considered in the 4D simulation when the primary construction method is 3D printing. Here, the assumption was that the robot needed to refuel every 5 hours of printing. From the discharge rate that was used in the previous iteration. 0.16 cubic meters per hour, it consumes 336 kg of cementitious material per hour (based on the assumption that one cubic meter of mortar typically weighs 2,100 kg). Since the one segment model requires 0.1346 hours for 3D printing, the robot contains only the material for 37 segments (5/0.1346=37.14) and needs to be recharged every time after printing 37 segments. The simple solution is to subtract the recharging time from the production rate of the element. For example, in the one robot scenario, the robot consumes 0.25 hours of recharging for every 5 hours of printing. It means that the time consumption increased by 5% (5.25 hours / 5 hours) for every printing activity. Therefore, by multiplying the task duration of every printing activity by 1.05, the recharging activity will be implied in the recipe. In this case, the production time for each segment became 0.1413 hours (0.1346 hours* 1.05). This rapid prototyping iteration integrated the representation of the robot relocation and charging material activities. Another insight is that the same approach could be used if the robot's mobility power is generated by a battery or another technology that needs a refueling process. This rapid prototyping development iteration provided the process to optimize the schedule for the SCDF, which is used in the next iteration that focuses on the visualization and validation of the optimized schedule.

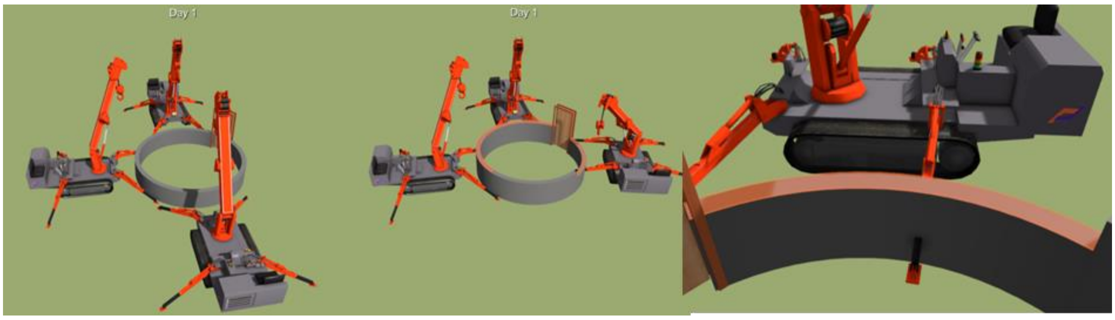
## 5.7 Visualize and Validate

The SCDF rapid prototyping iterations until now provide the model and selection of robots, prepare the model according to the specification, and optimize the construction schedule using ALICE. To complement the current functionalities of ALICE, we used Fuzor VDC to visualize the site logistics of the construction workflow process. This iteration tests the SCDF with the visualization and validation process to potentially include these two in the workflow, as shown in FIG. 12.


*FIG. 12: Testing SCDF with software capable of visualize and validate*

1) Macro-level validation

For macro-level validation, Fuzor VDC VR is used. Fuzor has the functionality to import 3D models, such as the equipment chosen by the user, and simulate the construction site logistics. This research has used ATHLETE as the primary equipment for the 3D printing activity. Since the 3D model of ATHLETE is not publicly available, we substituted ATHLETE with a "Mini Crane" model from the Fuzor content library with a similar size. The schedule created by ALICE is imported into the Fuzor VDC VR, and the construction site logistics workflow simulation was modeled and executed. From the simulation, one logistical issue was detected. As shown FIG. 13 while one robot is moving from one position (FIG. 13-(a)) to the next position (FIG. 13-(b)), the outrigger of the robot conflicts with the building (FIG. 13-(c)). To avoid this kind of incident, the time to relocate the robots needs to have more allowance so that the robots can relocate with more margins.



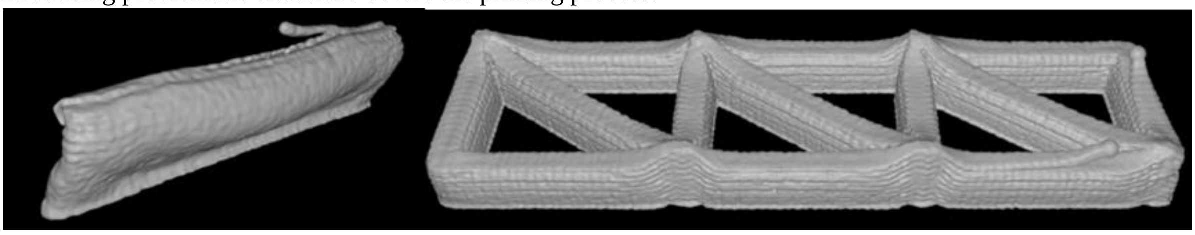
(a) (b) (c)

*FIG. 13: Visualizing the relocation of the robot and the conflict identified*

This issue is fed back to be addressed in the next ALICE construction schedule optimization cycle. Currently, the relocation time is 10 minutes. To avoid this incident type, the relocation activity in the construction schedule needs to be updated.

2) Micro-level validation

Houdini was used for the micro-level validation. Amongst the methods that Houdini offers, the particle fluid method has been chosen for the simplicity of operation. For the gravitational assumptions, we set 3.71m/s2 as the gravitational parameter for the Houdini software before simulation. Two situations were simulated to understand the potential defect. The first situation is elastic buckling of the structure due to the tilted surface and printing layers that are too high, as shown in FIG. 14-(a). The second failure is when the robots' 3D printing paths overlap, as shown in FIG. 14FIG. 14: Screenshot of deliberately occurred elastic buckling-(b). Although in the situation where the designer generates the printing path, it is essential to visualize and confirm that the printing path is not introducing problematic situations before the printing process.



(a) (b)

*FIG. 14: Screenshot of deliberately occurred elastic buckling;(a) and printing path overlap; (b)*

The figures (FIG. 14 and 15) in this section are a captured from the YouTube video created during this study and the link are enclosed in Appendix B. The result documented the positive effect of having validation and visualization in the tested SCDF. Therefore, the Fuzor VDC VR and Houdini were integrated and included in SCDF. The workflow from developing a project model to creating and validating an optimized schedule was established. The next step focused on testing SCDF in the NASA 3D-Printed Habitat Challenge project context. The selected project is the one proposed by the Penn State University team that was selected in the first iteration.

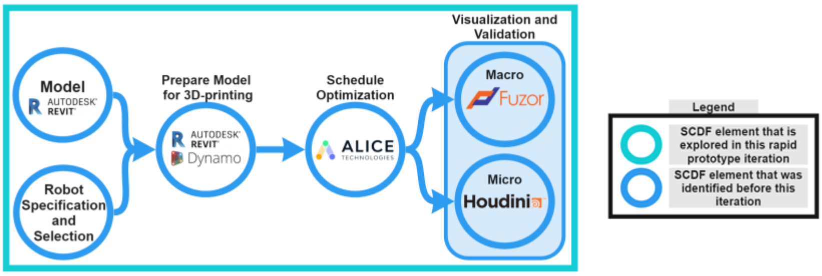



*FIG. 15: Test SCDF "model-simulate-optimize-visualize and validate" workflow approach*

## 5.8 Run complete SCDF simulation test "model-simulate-optimize-visualize and validate"

This rapid prototyping iteration applies and tests the proposed SCDF approach using the proposed project from Penn State University from the NASA 3D-Printed Habitat Challenge as shown in FIG. 15.

### 5.8.1 Model

The SCDF developed a project Revit model consisting of four buildings connected by corridors. The shell of the structure, the width of the walls, and the thickness of the floors and roofs were assumed to be 300mm. The interior walls are assumed to be 120mm wide, and the inner floors are 150mm thick. The Foundation was built below the perimeter of the exterior structural wall and was assumed to be 600mm in depth and 900mm in width.

### 5.8.2 Robot Specification and Selection

Based on the extended REF analysis, the ATHLETE robot proved to be a good fit for this project. The assumption is that ATHLETE will use its original incinerating technology to print the building.

### 5.8.3 Preparing the model for 3D-printing

The maximum size that can be printed as one part needs to be determined to segment the model. The length and width of the segment are defined as a function of the robot's reach. Since the technology of incineration utilized in the context of 3D printing is not mature yet, time constraints to determine the height of the segment were not set. Instead, the height was also defined as a function of the robot's reach. The maximum size of a segment will be 3.7m length * 0.9m width * 0.6m height. The developed Dynamo code segmented all the vertical elements, as shown in FIG. 16 This model was used in further SCDF tasks.

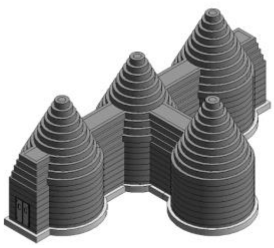


*FIG. 16: Segmented model for SCDF workflow testcase*

### 5.8.4 Schedule Optimization

To run the 4D simulation in ALICE, the production rate of 0.16 cubic meters/hour was assumed based on the case study from the Obayashi Corporation 3D printing robot. Based on the information from the robot, the following equation was used to calculate the task duration to print one segment.

$$T = v \times \frac{\left\{\frac{\left(4.414 \times \frac{a - a_t}{2 \times w} + w\right) \times w_t}{\frac{a - a_t}{2}}\right\}}{Q}$$

T: Task duration for one segment
w: Width of each segment
v: Volume of the segment
a: Area of the surface of the segment
a_l: Area of the lateral surface of the segment
Q: Productivity of robot (Discharge Rate)
w_t: Width of printing path

For this project, there will be three corresponding to the respective widths of the segments - 120mm, 300mm, and 900mm. Besides the segments that will be the walls and the foundations, the model has five element types: slabs, roofs, airlocks, stairs, and railings. The slabs and roofs will be 3D printed, so the same productivity (0.16 cubic meters per hour) will be used to calculate the task duration. On the other hand, the airlocks, stairs, and railings are assumed to be sent from Earth. One robot will be in charge of holding the parts while the others are printing the surrounding material. The task duration until these parts are fully embedded is assumed to be 90 minutes. After including this information in the recipe, we run the schedule optimization with three, five, and ten robots to explore the schedule differences and understand the interdependencies. For the cost of a robot, we considered $18,000 per hour per robot. The assumption is based on the development cost of "Perseverance", which was $2.2 billion. According to NASA, Perseverance was meant to operate for 14 years on Earth's timeframe. Since autonomous robots can work 24 hours, seven days a week, the robot is depreciating around $18,000 per hour until the shutdown. FIG. 17 shows the results considering different numbers of robots in terms of cost and schedule. Each dot in the graph represents a potential schedule as a function of cost and construction duration. The blue dots show the three robots scenario where construction takes the most time. The red dots stand for five robots and the purple for ten. Enclosed are the links to the three results of the 4D simulation.

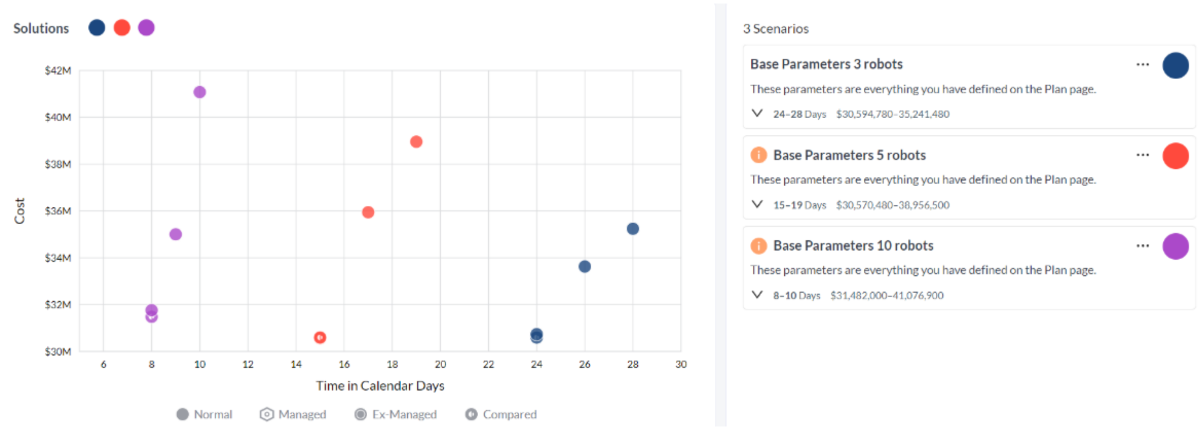



*FIG. 17: ALICE generated schedule options for 3 different scenarios using 3, 5, 10 robots*

### 5.8.5 Visualization and Validation

The macro-level visualization, which provides the site logistics, has been done first utilizing Fuzor VDC VR. This visualization provided two essential insights and feedback: The robots' reach is insufficient to print the segments that are higher than three meters. For this purpose, the model needs to include information on the scaffolding. In addition, the task of printing the scaffolding needs to be included in the 4D simulation of ALICE. This information needs to be fed back to the design of the building.

The other feedback is not to finish the outer wall before ATHLETE finishes printing the interior walls. Since the airlock size is smaller than the robot, there will be a clash with the printed structure. FIG. 19 illustrates this situation in Fuzor. The elements highlighted in blue indicate the printed elements at that time. While the robot on the right is printing the exterior wall without any issue, the left robot is clashing with the interior walls. This information should be contained in ALICE's "supports" functionality to generate the schedule.

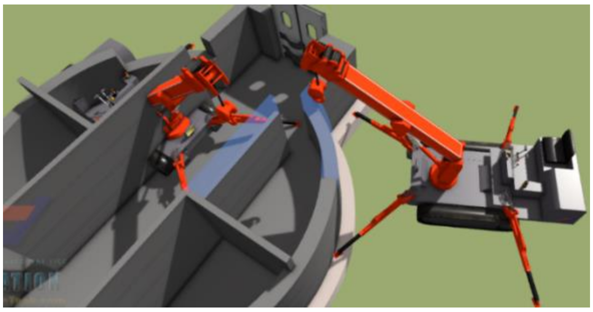


*FIG. 19: Robot conflicting with printed structure*

The micro-level visualization was performed using Houdini software. Although there was no defect found in the printing path itself, we modeled the effect of lateral loads from strong winds on Mars, as shown in FIG. 18.

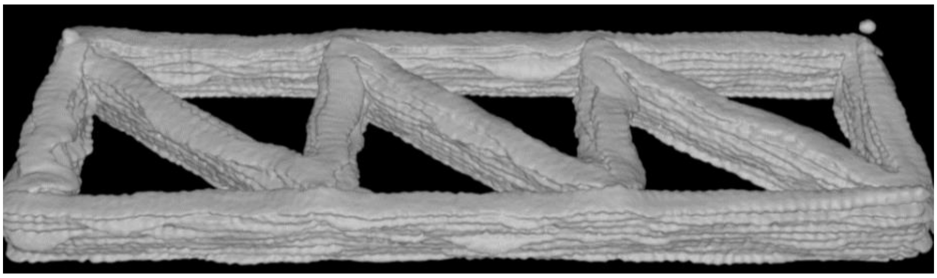


*FIG. 18: Wind affected printing path*

As observed, the structure's surface is clearly influenced by strong winds that impact the quality of 3D printing and concern about the structure's integrity. While the threshold of the wind speed to abort the printing process should be considered in future studies, at this point, the potential feedback to the schedule has been considered.

FIG. 19 and 20 are a captured from the YouTube video created during this study and the link are enclosed in Appendix B. The visualization and validation process detected two constructability issues and one environmental issue. Therefore, the interdependencies of the three decision criteria are not accurate enough to be discussed by all the stakeholders. Moreover, the information represents only the construction duration and does not consider the transportation of the robots to the project site on Mars. In this project, additional equipment was not assumed, and only the material that could not be 3D-printed in the model was considered to be sent from Earth. The breakdown of the material sent from Earth is the stairs, railings, and air, and the total estimated payload is 3,052kg.

Table 5 provides the final outcome of the SCDF, which is focused on the interdependencies between the three key decision criteria: Cost, schedule, and resource allocation. "Robot Utilization" will also be added to the three decision criteria as the fourth decision criterion. Since robots are an expensive investment for the general contractor, idle time needs to be reduced to maximize the utilization of robots.

*Table 5: Result from the SCDF workflow*

| Resource Allocation (Number of Robots) Options | Total Cost ($ Million) | Construction Schedule (Numbers of Hours to Complete) | Robot Utilization (% of Working Hours to Total Schedule ) |
|---|---|---|---|
| 3 | 119.1 | 434 | 98% |
| 5 | 186.1 | 270 | 97% |
| 10 | 284.6 | 155 | 92% |

There are two main insights gained from this iteration in this rapid prototyping iteration. First, three different feedback loops were observed from the visualization and validation process that impacted the previous decision. Second, the potential interdependencies of cost, schedule, and resource allocation were identified. This covers the key questions that every stakeholder has in mind. In the next iteration, the identified feedback will be considered, and the schedule optimization will be performed again to determine the interdependencies of the three key criteria.

## 5.9 Explore Interdependencies between the decision criteria

The purpose of this rapid prototyping iteration is to test the SCDF workflow with the same project from the previous iteration and output the interdependencies, as shown in FIG. 21. From the iteration before, there were three insights that needed to be taken into account, which are "Potential need for scaffolding", "Order of printing to avoid interference of the robot and structure", and "Consideration of the wind effect".

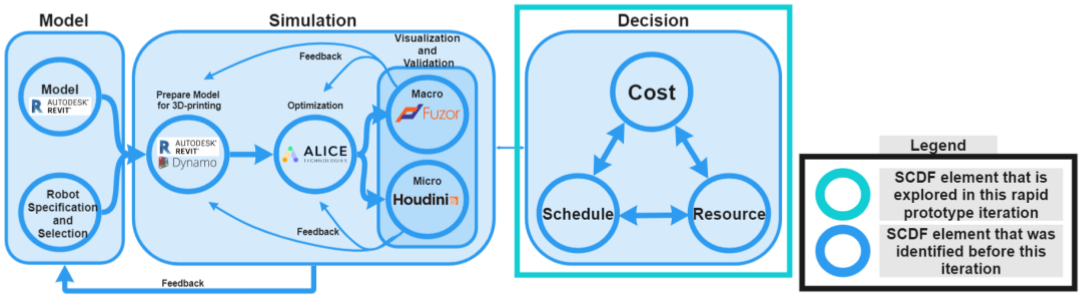


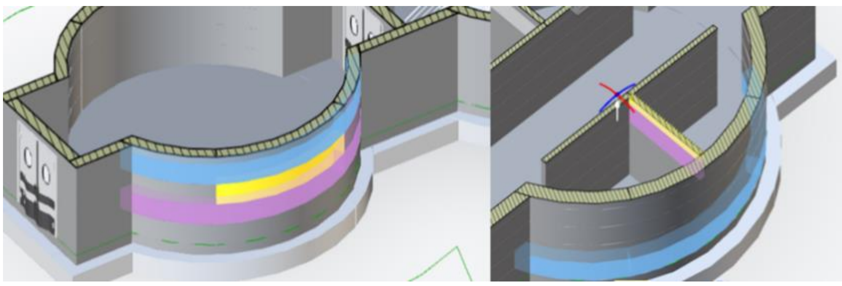

*FIG. 21: Testing SCDF: Interdependencies between Cost, Schedule, and Resource*

### 5.9.1 Potential need for scaffolding

The first consideration in this stage focused on the case if the 3D printing robot cannot move vertically, there will be a need for scaffolding. ATHLETE has the capability to build scaffolding. In order to integrate the scaffolding-related activities into the schedule, it first has to be modeled as an abstract form in Revit. The discharge rate of 0.16 cubic meters per hour has been used to print one panel. The printing duration time for one single panel is estimated to be 0.625 hours. These panels need to be printed before assembling the scaffolding. The recipe "Assemble scaffolding" was written to require these materials to ensure the robots do not start building without the scaffolding being ready. The task duration was set to 15 minutes to assemble one scaffolding plate. The model was updated for the schedule to incorporate the additional time for assembling and dismantling the scaffolding. Since some of the scaffoldings are two stories, it was essential to ensure that the lower-level scaffoldings were completed before the top-level scaffoldings started to be assembled. Similarly, the top-level scaffoldings should be dismantled first and the lower-level second in the dismantling phase. This information was incorporated into the recipe function of ALICE. By considering the scaffolding's specifications, task duration, recipes, and precedence, ALICE can include the scaffolding-related activities in the schedule.

### 5.9.2 Order of printing to avoid interference of the robot and structure

To avoid the situation where the robot cannot finish a task because a part of the building is already 3D printed, the sequence was reengineered in ALICE. FIG. 22-(a) indicates the example of "Support" functionality in ALICE. As introduced in the points of departure, the support function describes the precedence information between related elements. For example, in FIG. 22-(a) , the segment highlighted in yellow is the "support" of the blue highlighted segments. It means that the yellow segment needs to be finished before the blue ones start to be printed. Likewise, the segments highlighted in purple are the "support" of the yellow segment. These segments need to be finished in order to start printing the yellow element. To avoid the conflict due to a possible clash, the support has been updated to finish the interior walls before the exterior walls. FIG. 22-(b) shows the example of the updated support around the interior walls. The exterior wall will start printing after the interior wall are printed since the blue segments are the first ones that need to be printed for the exterior walls.



(a) (b)

*FIG. 22: Support functionality of ALICE; (a) and the updated sequence of constructing the walls; (b)*

#### 5.9.3 Consideration of the wind effect

Research studies indicated that intense sandstorms occur every few Martian years. Therefore, for the scope of developing and testing the SCDF, we assumed there would be no sandstorm event during the construction period.

These three decisions were made in response to the feedback and insights gained in the previous rapid prototyping iteration. The schedule was generated for the three scenarios, with the different numbers of robots - three, five, and ten - representing the construction crew. The assumptions about the material sent from Earth and the vehicle used remained the same. Consequently, the same SCDF process was used in this iteration. Enclosed are the links to the individual ALICE 4D simulations from the optimal schedule.
To confirm that the three issues raised in the previous section are addressed, another cycle of visualization and validation was performed using Fuzor VDC VR. Since there is no change in the segment size, micro-level visualization with Houdini was not required. The first issue was the interference of the robot with the finished structure. The schedule has been changed to finish the interior walls first, then the exterior walls. As confirmed in FIG. 23-(a), there is no interfering issue anymore. From the visualization, it can be observed that the scaffoldings are in use for segments that are higher than 3 meters. FIG. 23FIG. 23: Confirmed no interfering with the robot and the finished structure; (a) and three robots collaborating in different levels of scaffoldings; (b)-(b) shows that the three robots are collaborating to finish the project from different levels of scaffoldings and ground. While the two robots on scaffoldings are printing the building structure, the robot on the ground is preparing the scaffolding panels for assembly.

(a) (b)

*FIG. 23: Confirmed no interfering with the robot and the finished structure; (a) and three robots collaborating in different levels of scaffoldings; (b)*

However, another issue could be observed in the visualization simulation. The length of the corridors between the buildings is not wide enough to fit the ATHLETE robots. Since construction has not started yet, the solution space in the schedule component for this problem is vast. The finding could be fed back to the design team of the building to request a redesign of the corridors to be longer to fit the robot, or the feedback could go to the robot developer and ask to change the dimension of the robot to fit in the space.

FIG. 23 and 24 are captured from the YouTube video created during this study and the link are enclosed in Appendix B. Another ALICE simulation and optimization cycle provides the interdependencies in this rapid prototyping iteration. These interdependencies will be passed back to the stakeholders to help make evidence-based decisions that influence the entire mission. There was potential feedback from the design stakeholder. Giving feedback on the design process is valuable at this point when the construction has not begun. Once the construction starts, any change on the design needs to be checked for coexistence with the already finished part of the construction. It incurs additional cost, schedule, and sometimes rework, which severely downgrades the builders' motivation. Therefore, any infeasible design due to constructability issues should be detected and fed back to the design team before the construction starts.

### 5.10 Make decision based on SCDF workflow output

The previous SCDF iteration output provided information focused on the interdependencies of the three key decision criteria: cost, schedule, and resource allocation. This SCDF workflow accounts for the five categories of project objectives. Safety and quality were simulated and validated in the "Robot Specification and Selection" and "Visualization and Validation". ALICE optimized the cost and schedule. Buildability was validated in

"Visualization and Validation". Therefore, the project objectives are implied in the interdependencies of the three key decision criteria. The purpose of the current iteration is to make decisions based on the SCDF output as well as recall the client objectives and project objectives to see whether the output of the SCDF workflow answered the questions that the stakeholders had, as shown in Table 1. This prototype iteration presents a decision matrix for the stakeholders and their potential decision considering the output from SCDF. Since this is a multiple-objective decision-making problem, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was used. TOPSIS is a practical and valuable technique for ranking and selecting alternatives. It is essential to weigh the decision matrix to reach the desired result. From the client's point of view, the cost is essential for the project. Therefore, we allocated 70% to the cost criteria. The schedule is an essential criterion as well. Like the cost structure where transportation occupies most of the entire cost, the transportation duration is longer than the construction duration. For example, in this project, the transportation duration is 5~7 months, whereas the construction duration ranges from 16 to 53 days. It is only 8% to 35% of the entire schedule. It means that the resource allocation decision, as does the project cost, does not significantly influence the project schedule. Therefore, the weight was set to 20%, which is significantly lower compared to the weight allocated to the cost. The robot utilization was set to 10%. In this scenario, where the general contractor owns the robot and provides them for the construction, the client side is relatively indifferent to the utilization of the equipment, similar to terrestrial construction. The ranking reflects the client's preference for lower cost and recommends the three robots scenario. If the preference of the client changes and relocates the weight, the decision will be updated. The SCDF result is flexible in terms of change preferences. In addition, new criteria can be added. In this scenario, the decision was made accordingly to Table 7, and three ATHLETE robots are going to be printing the structure on Mars.

*Table 7: TOPSIS result*

| | Weight from the decision makers | | | | | | |
|---|---|---|---|---|---|---|---|
| | 70% | 20% | 10% | | | | |
| Resource Allocation (Number of Robots) Options | Total Cost ($ Million) | Construction Schedule (Numbers of Hours to Complete) | Robot Utilization (% of Working Hours to Total Schedule ) | Si+ | Si- | Pi | Rank |
| 3 | 0.2654 | 0.1745 | 0.0581 | 0.1220 | 0.2634 | 0.3166 | 1 |
| 5 | 0.3741 | 0.0825 | 0.0575 | 0.1128 | 0.1800 | 0.3851 | 2 |
| 10 | 0.5288 | 0.0525 | 0.0575 | 0.2634 | 0.1220 | 0.6834 | 3 |
| V+ | 0.2654 | 0.0525 | 0.0581 | | | | |
| V- | 0.5288 | 0.1745 | 0.0575 | | | | |

Table 8 shows the answers to the stakeholders' questions presented in Table 1. Note that the "Required space", a decision metric determined by designers, was not explicitly discussed during the rapid prototyping iteration; however, it was omitted since the total space of the building could be easily obtained from the Revit model.

*Table 8: Decision made by the SCDF*

| | **Stakeholders** | | | |
|---|---|---|---|---|
| **Stakeholders' perspective** | Client | Designers | General Contractors | Launch Service Provider |
| **Answers and decision** | Based on the SCDF decision matrix,<br>3 ATHLETE robots are going to be sent for this mission | | | |
| **Decision criteria** | Cost: $165.5 million<br>Operation start date: April 2026 | Numbers of researchers: 4<br>Required space: 246 m2<br>In-situ resource utilization: 100% | Construction schedule: 54 days<br>Delivery schedule: 180 days<br>Payload: 12,995 kg | Launch schedule: September 2035<br>Payload: 12,995kg<br>Numbers of launches: 1 |

This output concludes one SCDF cycle. Although this cycle addressed many questions posed by the stakeholders, other questions may arise. The purpose of the SCDF workflow is to foster dialog among the stakeholders and continue to improve the mission through further iterations of the SCDF cycle. The next iteration of the SCDF workflow will start the new cycle with the updated design of the space habitat model, the chosen schedule, cost, and resources, and further questions posed by the stakeholders as shown in Table 9.

Since there was a design update request, the concern of the stakeholders will focus on the impact of the design change on cost-schedule-resources. However, the impact could be assessed once the building habitat model is redesigned and the SCDF workflow is applied to decide on the updated cost-schedule-resources. Once the preliminary construction schedule has been decided, the client's focus pivots to the operation stage, such as the move-in schedule. Another common interest among the stakeholders is the landing location, construction site location, and location of the equipment and material. Similar to terrestrial construction projects, the supply chain will be considered. The ability to compare different scenarios is the strength of the SCDF. The question of the optimal landing point could also be formulated as a multi-objective decision-making problem. The visualization software could perform the move-in simulation.

This iteration has received and understood the feedback loop from the SCDF output to the mission. It means that the output from the SCDF workflow influences the overall mission. It provides insights to make informed decisions by the stakeholders and improve the mission. Running the SCDF multiple times improves the mission continuously. Another observed point is that the SCDF workflow is similar to the PDSA cycle. By including the elements of the PDSA cycle, the SCDF workflow was completed, as shown in FIG. 1.

There were answers to the question in this rapid prototyping iteration regarding the project building. It was observed that even more questions emerged. These questions will be considered in the next cycle of the SCDF. The model will be modified according to the question and will be studied through the simulation. The updated interdependencies of the decision criteria will be generated, and by answering the question, the mission improves.

*Table 9: Other questions stakeholders may pose after a preliminary decision*

| | **Stakeholders** | | | |
|---|---|---|---|---|
| **Stakeholders' perspective** | Client | Designers | General Contractors | Launch Service Provider |
| **Next questions** | What are the constraints for set up the equipment inside the building? | What constructability issues does the updated design pose? | What is the cost-schedule-resources impact on the updated design? | What is the optimal location to deliver? |
| **Decision criteria** | Additional cost for updated design: $<br>Equipment move-in date: day | Required space: m2<br>In-situ resource utilization: %<br>(For updated design) | Construction schedule: days<br>Delivery schedule: days<br>(For updated design) | Landing point: Coordinates |

## 6. INSIGHTS AND CONTRIBUTIONS

This study explored the solution space of construction management in extra-terrestrial projects. Although many technologies and frameworks were available, both practical and theoretical, these diverse solutions are not yet integrated. We developed an experimental framework called "Space Construction Decision Framework (SCDF)" applying a rapid prototyping approach based on the Stanford d-school Design Thinking framework and Denning's PDSA cycle. The SCDF is tested and demonstrated using a hypothetical space habitat project on Mars. The rapid prototyping iterations continuously improved SCDF and tested its applicability in a space construction project context. The contributions and insights gained through this process regress to the six points of departure. This study presents contributions from three perspectives: the SCDF as a general framework that can be further extended and applied to both space and terrestrial construction. These innovative approaches build and expand existing platforms, such as ALICE and REF, and identify and develop new approaches and methods driven by specific space construction needs and SCDF development and testing efforts.

### 6.1 General Contractor and Space Construction

i. Development of SCDF

The developed SCDF proposes a novel workflow that could be utilized for space construction, to the authors' knowledge to date. It provides insights into the industry of terrestrial construction and how to approach the space industry leveraging the existing expertise in the four different stages -Mission, Model, Simulation, and Decision - of SCDF. In terrestrial construction, integrated project delivery starts with understanding the client objectives and converting them into project objectives that could be measured and understood by different stakeholders such as designers and contractors. This approach is similar to the Mission stage of SCDF, and it starts to identify the key decision criteria of the client, such as "Total Payload" and "Numbers of Launches". Since general contractors are familiar with BIM-centered workflow for the Model-Simulation-Decision, the optimization, validation, and visualization cycle can be incorporated easily. Therefore, the SCDF demonstrates that general contractors have opportunities to leverage their skills and the daily routine in extra-terrestrial construction conditions.

ii. Integrating SCDF with Virtual Design Construction (VDC)

The five critical elements of the VDC framework are as follows, 1) Client Objectives, 2) Project Objectives, 3) Integrated Concurrent Engineering (ICE), 4) Product Modeling, and 5) Project Production Management (PPM). Especially, SCDF shows the strength to answer "How is the project team going to accomplish the project objectives" since the workflow provides integrated information for decision-making. The Model, Simulation, and Decision are the SCDF steps corresponding to Integrated Concurrent Engineering, Product Modeling, and Project Production Management.

- Integrated Concurrent Engineering (ICE)

ICE is a collaboration method initially developed in the Jet Propulsion Laboratory (JPL) of NASA. Here, team members from multiple disciplines come together for an intense combined work session, using integrated information to solve complex problems. In this SCDF workflow, four different stakeholders have been identified -Clients, Designers, Construction Managers, and Launch Vehicle Providers. These four stakeholders will participate in the work session using the integrated information provided as an output of SCDF. In the presented project example, the four stakeholders identified the optimal number of robots to be sent to Mars to accomplish the mission. The next topic to be discussed in an ICE session will be how long the space habitat corridor should be in response to the constructability visualization and validation analysis feedback.

- Product Modeling

The SCDF is a Building Information Modeling (BIM) centered workflow. Revit was used as the BIM tool for the model of the project. It contained information such as the size and the material of the building. To run the schedule optimization, it was necessary to segment the model as a function of the robot's reach or the material constraints. Even after the segmentation, the model remained at the center of the workflow and was imported to different software platforms such as ALICE, Fuzor VDC VR, and Houdini. To avoid workflow confusion, it was necessary to keep only one model in the workflow.

- Project Production Management

This research considered the project building as one product and simulated the entire production sequence. Production metrics such as robot utilization were discussed as part of the result of schedule optimization. This production metric will be the target of operation during the actual construction process. The deviation from the target will be in the interest of the stakeholders, and the countermeasure will be discussed in the next ICE session.

The output of SCDF provides the interdependencies of different decision criteria in a decision matrix. The decision matrix considers the client objective and decisions that drive the project objective. For example, in this project, the hypothetical client weighed the importance of each decision criterion, and a new project objective was determined: to complete the construction in 1274 hours. In SCDF, the client objectives and project objectives are combined in the mission, since the output of SCDF enables changes in the project objective accordingly to the change of client objective as explained.

## 6.2 Building Information Modeling (BIM)

This research developed a parametric modeling approach for BIM segmentation to facilitate the link to 4D simulation software. This approach enabled the BIM-centered workflow of SCDF. As discussed in the point of departure, the importance of BIM-centered workflow enabled 4D simulation even in space construction. The BIM-centered workflow that was introduced to date did not fully utilize the potential of the feedback from the 4D simulation. This research showed that important decisions could be made based on the simulation result and influences the design of the model.

## 6.3 Generative Scheduling and Construction Schedule Optimization

The research developed a method to represent 3D printing activities in the 4D simulation software (ALICE), by segmenting the building model. Moreover, this research discussed how to consider these activities' productivity to calculate the task duration, a critical input for 4D simulation. ALICE had no functionality to represent 3D printing activities, which are challenging to simulate. However, the workflow introduced in SCDF, which is the model segmentation, gives a sequence to simulate the different scenarios rapidly. Another contribution is that this research explored how to represent and simulate temporary structure-related tasks such as assembling and dismantling scaffoldings. The detailed description of how to define the recipe and the precedence of the elements could also be applied to terrestrial construction. Moreover, the schedule includes the on-site manufacturing of the scaffoldings. In industrialized construction, it is essential to consider on-site manufacturing and deliver the manufactured elements to the assembly point. This research did not just include manufacturing and transportation but also visualized them to identify logistic bottlenecks further. This visualization changes the strategy to plan the construction site logistics. This updated strategy will contribute to further research for the industrialized and digitalized construction site for Mars and the terrestrial construction.

## 6.4 Construction Robotics

This research discussed using the Robotic Evaluation Framework (REF) for space construction. There, the applicability to space construction has been proposed considering two aspects. First, REF can potentially compare different robots, not just manual construction tasks. Although REF was produced to evaluate the compatibility of manual processes and robotic tasks firsthand, it could be utilized in the selection process of similar tasked robots. This fact applies not only to space construction but also to terrestrial construction. The construction robotics market will increase at a compound annual growth rate of 10.4% from 2018 to 2026. There will likely be different robots with similar tasks lined up soon, and the construction managers will choose one of them, similar to what they do for construction equipment, such as cranes and excavators. This research proved the potential of REF that could be utilized on such occasions. The second contribution to REF is that this research identified four additional variables (1) Needs of EVA, 2) Level of Autonomy, 3) In-Situ Resource Utilization, and 4) The Mass of the Robot) to be considered in the use of SCDF. In a space construction mission, the four variables will affect two or more of the original four categories of variables in REF - Safety, Quality, Schedule, Cost. For example, the "Needs of EVA" impacts safety and cost. Therefore, these variables need to be considered before comparing the individual variables inside the categories. This is a new insight into the use of REF. Another contribution to the field of construction robotics is that the SCDF workflow was able to determine the number of robots for the project scenario. By leveraging REF, the SCDF workflow achieves high synergy. The REF determines the type of robot, and the SCDF defines the optimal number of robots to be deployed.

## 6.5 Space Construction and 3D printing

This research study explored how to evaluate the schedule for a space construction project where the building is larger, and many robots interact. Moreover, this schedule evaluation applies not only to space construction but also to terrestrial construction. Especially the discussion about how to determine the size of a segment from the five variables, 1) Amount of material, 2) Time constraints of the material, 3) Reach of the robot, 4) Productivity of the robot, and 5) Numbers of the robot, is novel. Moreover, the equation discussed in this research considers the physical feature of cementitious material, which is the most used 3D printing method in the construction field on Earth. In addition, to identify the interdependencies, this research also created a set of Dynamo codes that could be used to segment the model into different sizes within a short time. It enables rapidly changing the construction's overall setup with the synergistic use of the equation developed. For example, when the material has time constraints, the segment heights change in response to the number of robots. If the segmentation were done manually, this process would be time-consuming, and the motivation to explore the solution space will deteriorate.

## 6.6 Virtual Reality (VR) and Visualization

This research developed and demonstrated the benefits of integrating visualization and validation into the SCDF workflow. The workflow confirmed two types of validation that could be categorized as macro and micro-level. The macro-level visualization validates the schedule from the perspective of constructability and site logistics, such as detecting issues related to robots clashing with the structure. These detected issues were reported to the schedule optimization to improve the construction sequence and update the schedule. The micro-level visualization validated the printing path of individual 3D-printed segments. This research confirmed the potential of giving feedback on the schedule and segmentation size by analyzing in a physics engine containing software.

## 7. DISCUSSION AND NEXT STEPS

Given the opportunity, two domains deserve to be highlighted related to possible future research directions. The first is related to what insights and state-of-the-art experience from terrestrial construction can contribute to space construction and the SCDF. The second looks at what insights and opportunities space construction and the SCDF can contribute to innovative approaches in terrestrial construction.

1. SCDF limitation for space construction and the framework.

The research explores the solution space for estimating the schedule and cost of space construction projects. It presents the Space Construction Design Framework (SCDF) as a tool for optimizing construction schedules. However, there are limitations to be considered, such as the risk of latency in scheduling due to weather conditions and rocket launch delays. These uncertainties need to be considered to generate a more accurate construction schedule. The real estate industry's due diligence principle could be applied to space construction to understand local conditions better and assess profitability. Financing studies will be necessary to sustain building projects in extra-terrestrial environments, and there may be a future job role of a "Space Real Estate Developer."

Another opportunity is that various space construction processes are ongoing research topics besides 3D printing. For example, the inflatable structure is one construction method in an extra-terrestrial environment. There are ongoing studies that consider the structure and the assembling sequence. The SDCF workflow will provide valuable insights into the design, especially by visualizing the construction sequence and validation.

This research demonstrated that SCDF workflow is useful for exploring solution space and optimize the schedule and cost when mobile 3D printing robots do the construction. However, there are not only mobile 3D printing but static solutions available. For example, the Danish COBOD solution is to assemble a large printing machine on-site consisting of pillars and beams. The movable nozzle extrudes the material according to the predetermined printing path. The current usage of this robot requires manual assembling in the first place. If this robot was deployed in the scenario explored in this research, the necessity of EVA might affect the score poorly in the robotic selection phase of the SCDF. However, if the assembling could be done by another robot automatically, there are chances that these types of 3D printing robots might be a solution.

The interaction of multiple robots provides another valuable insight into terrestrial construction. Ambitious general contractors, such as Obayashi Corporation, have attempted a dam construction project with numerous construction robots. Although humans partially assist these robots, the interaction of humans and the different types of robots provide valuable insight into extra-terrestrial construction. It will be critical to consider the role of humans and understand the process when organizing the astronaut's crew.

2. Lessons learned and opportunities from space construction to terrestrial construction.

The SCDF provides insights that can be applied not only to the Architecture, Engineer, and Construction (AEC) industry but to the whole Civil and Environmental Engineering (CEE) industry, particularly regarding local material utilization. The SCDF quantifies in-situ resource utilization to decide on the robot, and this philosophy is applicable in terrestrial construction. Micro-level visualization also applies to the terrestrial construction site, especially when the building is considered an entity composed of a kit-of-parts. This research segments the building into kit-of-parts to enable a detailed simulation of the construction process and manufacturing of the kit-of-parts of the temporary structure. To think of the building as a kit-of-parts and manage the detailed itinerary to reach to assembly point is vital to achieving industrialized construction.

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# REFERENCES


A. S. Howe and B. Wilcox. (n.d.). *Outpost assembly using the ATHLETE mobility system*. Retrieved April 16, 2023, from https://ieeexplore.ieee.org/document/7500794

Barabás, I., Todoruţ, A., Cordoş, N., & Molea, A. (2017). Current challenges in autonomous driving. *IOP Conference Series: Materials Science and Engineering*, *252*(1), 012096. https://doi.org/10.1088/1757-899X/252/1/012096

Brosque, C., Skeie, G., & Fischer, M. (2021). Comparative Analysis of Manual and Robotic Concrete Drilling for Installation Hangers. *Journal of Construction Engineering and Management*, *147*(3), 05021001. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002002

Brosque, C., Skeie, G., Örn, J., Jacobson, J., Lau, T., & Fischer, M. (2020). Comparison of Construction Robots and Traditional Methods for Drilling, Drywall, and Layout Tasks. *2020 International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA)*, 1–14. https://doi.org/10.1109/HORA49412.2020.9152871

Brown, M. (n.d.). *SpaceX Mars City: Why, when, and how Elon Musk wants to build his ambitious plan*. Inverse. Retrieved October 16, 2022, from https://www.inverse.com/innovation/spacex-mars-city-codex

Carrato, P. J. (2021). *Use of BIM and 3D Printing in Mars Habitat Design Challenge*. 780–790. https://doi.org/10.1061/9780784483374.072

Fischer, M., Garcia-Lopez, N. P., & Morkos, R. (2018). Making Each Workhour Count: Improving the Prediction of Construction Durations and Resource Allocations. In I. F. C. Smith & B. Domer (Eds.), *Advanced Computing Strategies for Engineering* (pp. 273–295). Springer International Publishing. https://doi.org/10.1007/978-3-319-91635-4_15

Ishikawa, Y., Otsuka, K., Yamagiwa, Y., & Doi, H. (2018). Effects of ascending and descending climbers on space elevator cable dynamics. *Acta Astronautica*, *145*, 165–173. https://doi.org/10.1016/j.actaastro.2018.01.031

Johnson Corinne, N. (2002). The benefits of PDCA. *Quality Progress*, *35*(5), 120.

Kading, B., & Straub, J. (2015). Utilizing in-situ resources and 3D printing structures for a manned Mars mission. *Acta Astronautica*, *107*, 317–326. https://doi.org/10.1016/j.actaastro.2014.11.036

Kunz, J., & Fischer, M. (2020). Virtual design and construction. *Construction Management and Economics*, *38*(4), 355–363. https://doi.org/10.1080/01446193.2020.1714068

Muthumanickam, N. K., Duarte, J., Nazarian, S., Bilén, S., & Memari, A. (2021). *BIM for Design Generation, Analysis, Optimization, and Construction Simulation of a Martian Habitat*. https://doi.org/10.1061/9780784483374.112

Nagatoishi, M. G., & Fischer, M. (2022). *Construction management in space: Explore solution space of optimal schedule and cost estimate*. Stanford University.

Plattner, H., Meinel, C., & Leifer, L. (2010). *Design Thinking: Understand – Improve – Apply*. Springer Science & Business Media.

Rischmoller, L., Reed, D., Khanzode, A., & Fischer, M. (2018). *Integration Enabled by Virtual Design & Construction as a Lean Implementation Strategy*. 240–249. https://doi.org/10.24928/2018/0521

Roussel, N., Spangenberg, J., Wallevik, J., & Wolfs, R. (2020). Numerical simulations of concrete processing: From standard formative casting to additive manufacturing. *Cement and Concrete Research*, *135*, 106075. https://doi.org/10.1016/j.cemconres.2020.106075

Starr, S. O., & Muscatello, A. C. (2020). Mars in situ resource utilization: A review. *Planetary and Space Science*, *182*, 104824. https://doi.org/10.1016/j.pss.2019.104824

Yashar, M., Chenniuntai, N., Nefedov, S., Ciardullo, C., Morris, M., Pailes-Friedman, R., Day, A., Aronis, J., & Pender, S. (2019). *Robotic Construction & Prototyping of a 3D-Printed Mars Surface Habitat*.

## APPENDIX A: "CASE STUDY OF HOW TO SEGMENT A 3D PRINTED OBJECT WITH CEMENTITIOUS MATERIAL"

If a cementitious material is used for 3D printing, time constraints need to be considered. In a 3D printing process of cementitious material, gravity affects the printed segment, and the inner stress gradually increases. The gradual increase leads to two failure mechanisms: elastic buckling or plastic collapse. Therefore, depositing the layers too fast before the material starts to harden leads to high construction risk. The risk can occur if the layering process takes too long as well. If the layer below is already dried up, it extracts moisture from the currently printed layer. This phenomenon is called local capillary suction and is one reason for crack formation in the 3D-printed structure. Therefore, there is a specific timeframe for the next layer to be deposited to obtain structural integrity. This fact leads to the discussion of the two types of time constraints to determine the maximum height of one printing activity.

1) The maximum height is obtained from physical properties. The robot should stop 3D printing before elastic buckling or plastic collapse occurs. Although obtaining the maximum height involves physical calculation, recent technology of physical simulation methods, such as the Finite Element Method and Particle Fluid Method, provides methods to visualize the failure. The maximum height could be obtained by observing the behavior simulation of the 3D-printed segment.

2) The robot must print the next layer before the cementitious material dries up to avoid a cold joint material behavior. To determine the interdependencies of the maximum height of each segment, four independent variables - Numbers of robots, Productivity of the robot, Thickness of one layer, and Time constraints of the material - are identified. The following equation is defined and referred to as "Time Constraints Inequation" in this research.

$$\left(\frac{h \times p}{t \times V} + Tr\right) \times \frac{L}{l \times N} - \frac{p}{V} \leq T$$

| | | |
|---|---|---|
| h: Heights of each segment | V: Productivity of robot (Nozzle Speed) | l: Length of each segment |
| p: Length of printing path | Tr: Time to relocate the robot | N: Numbers of robots |
| t: Thickness of one layer | L: Total length of one cycle | T: Time constraints of the material |

The variables - "d: Thickness of one layer", "Q: Productivity of robot", and "l: Length of each segment" - are obtained from the robot specification. "N: Number of robots" is determined based on an initial assumption in the project, and it will be updated while the SCDF continues to optimize the number of robots. "L: Total length of one cycle" is obtained from the Revit model of the project. "p: Length of printing path" is calculated from the generated printing path for the segment. By converging the Time Constraints Inequation, the height of each segment can be identified by solving the following inequation.

$h \leq \left\{\left(T + \frac{V}{p} - 1\right) \times \frac{l \times N}{L} - Tr\right\} \times \frac{t \times V}{p}$We assumed that the cementitious material extrusion was used in ATHLETE to test the process of deciding the size of the segment from the time constraints. There are ongoing studies for the 3D printing specifications from Obayashi's 3D printing robot; we used this specification to determine productivity. For other specifications, such as the reach of the robot, the parameters from ATHLETE are used since the 3D printing robot from Obayashi is not mobile. The following data was used to solve the inequation.

| | | | |
|---|---|---|---|
| p:16,148mm | t: 15mm | L:14,451mm | N:one and three |
| V:100mm/sec | Tr:600 sec | l:3,613mm | T:3,600 sec |

The length of the printing path p should be decided from the generated printing path of each segment. In this study, generating the printing path was beyond the research scope since there was no access to such a program or software. Future studies should consider the printing path-generating tool to be included in the workflow of SCDF. For the present study, the path length was estimated using the following formula referred to as the "Printing Path Length Estimation Equation".

$$p = 4.414l + w$$

l: Length of each segment
w: Width of each segment

The equation assumes that one rib and brace needed to be printed every period of the width to shape a square with one diagonal brace inside the segment. The number of squares in each segment could be obtained by dividing the length by the width of the segment, or l/w. The length of the three sides of the square and the diagonal brace is 3w+1.414w from the Pythagorean theorem. Therefore,
$p = (3w + 1.414w) \times \frac{l}{w} + w$, or $p = 4.414l + w$. Since $l = 3{,}613mm, w = 200mm, p = 16{,}148mm.$

The thickness of one layer t and the productivity of robot (nozzle speed) V have a relation to the discharge rate of the 3D printing mechanism and could be described in the following formula.

$$Q = t \times w_t \times V \times \frac{3{,}600}{10^9}$$

| | |
|---|---|
| Q: Discharge rate | w_t: Width of printing path |
| t: Thickness of printing path/layer | V: Nozzle Speed |

When considering the time constraints, the relocation time of the robot needs to be considered. On the Martian surface, the rover from NASA, Perseverance was designed to achieve a top speed of 152 meters per hour or 2.53 meters per minute. Since the diameter of the cylinder-shaped prototype is 2.3 meters and the perimeter length is 14.451 meters, 10 minutes will give the robot enough to relocate itself. Since the estimated speed of ATHLETE on Mars was not available, the rate from Perseverance was used for this SCDF workflow. The length of one cycle, and the length of each segment, are derived from the model. It is the dimensions of the cylinder-shaped prototype in this case. For the time constraints of the cementitious material, the American Society for Testing and Materials (ASTM) defines that concrete should be discharged within 90 minutes after the material has been mixed. These time constraints are not defined just to avoid cold joints, but it is reasonable to refer to them for this purpose from the assumption that ASTM does consider cold joints when the specification has been created. However, considering that the time constraints start when the materials have been mixed and there will be a certain time elapsed until the first layer is printed, for flexibility, 10 minutes were subtracted, and 4,800 seconds has used.

From the assumptions and information, the heights of each segment have been calculated for a one-robot scenario and three-robots scenario.

1) Height of each segment when the number of robots is one

   Since one layer is 15mm, the height of one segment is 45mm with three layers. The printing time for one segment is 484.44 sec.

2) Height of each segment when the number of robots is three

   Since one layer is 15mm, the height of one segment is 270mm and is composed of 18 layers. The printing time for one segment is 2906.64 sec.

The size of each segment for each scenario has been determined by calculating the Time Constraints Inequation identified in this iteration. These sizes are the input for the Dynamo code generated in the next section.

## APPENDIX B: LINK TO THE YOUTUBE VIDEOS RELATED TO THE IMPLEMENTATION OF THE SCDF PROTOTYPE

### 7.1 NASA Mars Habitat used as reference towards developing and testing the SCDF prototype

"NASA 3D Printed Mars Habitat Challenge Phase 3 - Penn State - Virtual Construction Level 2", https://www.youtube.com/watch?v=iVDY5m2lx3w&t=3s

### 7.2 YouTube videos created to demonstrate key aspects of the SCDF prototype development.

### Video illustration in support of Section 5.7 Visualize and Validate

"SCDF Prototype (3 robots) – YouTube" https://www.youtube.com/watch?v=y_6DVab5Y4M

### Video illustrations in support of Section 5.8 Run complete SCDF simulation test "model-simulate-optimize-visualize and validate"

"Fuzor 2022 VDC 3robots logistical issue - YouTube" https://www.youtube.com/watch?v=Ge7OH2I4ZoI

"Project6 normal mantra1 - YouTube" https://www.youtube.com/watch?v=wk3cMpK1SmE

"Project4 Mesh mantra1 - YouTube" https://www.youtube.com/watch?v=GwofkNB0uYg

"Project5 wall mantra1 - YouTube" https://www.youtube.com/watch?v=Ur4ZCLVCCoQ

### Video illustrations in support of Section 5.9 Explore Interdependencies between the decision criteria

"SCDF Project (with Scaffolding, 3 robots) - YouTube" https://www.youtube.com/watch?v=VdUWKb8JYmQ

"SCDF Project (with Scaffolding, 5 robots) - YouTube" https://www.youtube.com/watch?v=y34LUzsKtQw

"SCDF Project (with Scaffolding, 10 robots) - YouTube" https://www.youtube.com/watch?v=SBp2obivsDE

"SCDF Project (without Scaffolding, 3 robots) - YouTube" https://www.youtube.com/watch?v=WYcL8lZonos

"SCDF Project (without Scaffolding, 5 robots) - YouTube" https://www.youtube.com/watch?v=eEv-ojzuCuc

"SCDF Project (without Scaffolding, 10 robots) - YouTube" https://www.youtube.com/watch?v=hduV_UZslIA