In-Situ vs. Prefab 3D Printing Considerations for CO2-free Pop-up Architecture

Atousa Aslaminezhad [1,2], **Arwin Hidding** [3], **Henriette Bier** [3], **Giuseppe Calabrese** [3, 4]

[1] *University of Antwerp (Belgium)*
[2] *Heriot-Watt University (UAE)*
[3] *Delft University of Technology (Netherlands)*
[4] *International Research School of Planetary Sciences (Italy)*

Abstract

This paper revisits existing pop-up typologies in architecture to identify opportunities for new shelter models to address current housing demands and future habitation requirements on Mars. It presents advancements in design to production methodologies based on computational and robotic techniques to meet current requirements and affordances while integrating sustainable and adaptive functionalities. The main goal is to advance pop-up architecture by developing methods and technologies for rapidly deployable on- and off-Earth habitats while addressing challenges of carbon-free architecture by means of 3D printing. By reviewing state-of-the-art in-situ vs. prefab 3D printing approaches with a particular focus on Human-Robot Interaction (HRI) supported Design-to-Robotic-Production-Assembly and -Operation (D2RPA&O) methods developed at TU Delft material, process, and energy efficiency using locally sourced materials is achieved.

Keywords

Pop-up architecture, computational design, robotic production, assembly and operation, in-situ and prefab 3D printing, human-robot interaction

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1 Introduction

By studying current models developed for pop-up structures, in a range of specific contexts and by reexamining precedents, the potential and challenges for developing new design-to-production methodologies based on advanced computational and robotic techniques are identified with the aim to frame new models for pop-up structures.

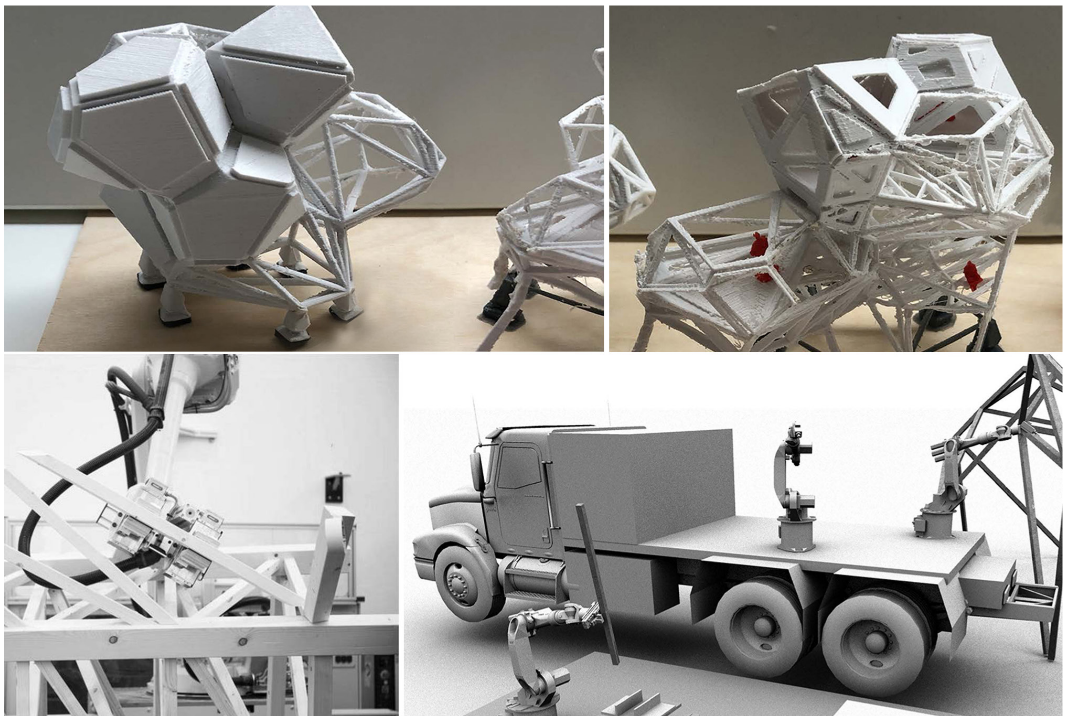

FIGURE 1 Design-to-Robotic-Production and -Assembly of wood-based hybrid structures (Bier, Hidding, et al., 2020)

Current models such as the pavilion developed at the Institute of Building Structures and Structural Design (aka ITKE) at the University of Stuttgart use a robotic fabrication process that is weaving fiber composite material to develop an enclosure (Doerstelmann et al., 2015) and the multi-material wood-based structures (Bier, Hidding, et al., 2020) developed at Delft University of Technology (TU Delft) that both rely on design to manufacturing and assembly methods using robots (Fig. 1), give insight into the potential of computational and robotic techniques. While the first one employs an in-situ weaving approach, the second engages in a prefab approach with in-situ robotic assembly to produce simple structures that can be upgraded to fully functioning housing units in due time. In the prefab approach, robots are not only involved in the fabrication but also in the aggregation of various housing units for the redevelopment of settlements in post-disaster situations.

The potential of such approaches lies in the fast deployment and construction of building envelopes on site, while the challenge remains the operation of robots on site considering their sensitivity to environmental factors. In terms of materials, the advantage of wood-based vs. fiber composite materials is that while wood may be resourced in-situ, fiber composites are not. Hence, the challenge is to identify methods that increase In-situ Resource Utilization (IsRU) and contribute to CO_2 reduction while ensuring that the material properties of the created material meet the requirements for structural performance, durability over time, etc.

2 Methods and Approaches

This paper focuses on computational design and robotic construction methods such as Design-to-Robotic-Production-Assembly and -Operation (D2RPA&O) developed in the Robotic Building (RB) lab at TU Delft (Bier, Latour, et al., 2020) that are employed to advance locally customizable approaches in order to address not only on-Earth post-disaster and emergency challenges but also off-Earth construction problems requiring pop-up architecture. This is because of their versatility in terms of materials, tools, and techniques that are employed. Furthermore, by connecting them with mobile energy systems such as the kite-power system developed at TU Delft production units become autarchic and can be deployed off-grid (Bier et al., 2017). Additionally, by integrating Artificial Intelligence (AI) in current D2RPA&O methods and by taking sustainable approaches into account, not only in terms of production but also the operation of shelters, a new model is proposed capable of improving in time and thus supporting habitation not only short but also mid and long term.

3 Precedents

21st-century pop-up architecture models rely on knowledge developed in experiments of the 20th century such as Prouvé's prefabricated house (Bell, 2018) designed for war victims (Prouvé, 2017), Webb's mobile inflatable structure, Cushicle and Suitaloon (Archigram.net, 1964), and Herron's Walking City (MoMA, 2013) that are proposing systems for customizable mobile habitats (Steiner, 2009).

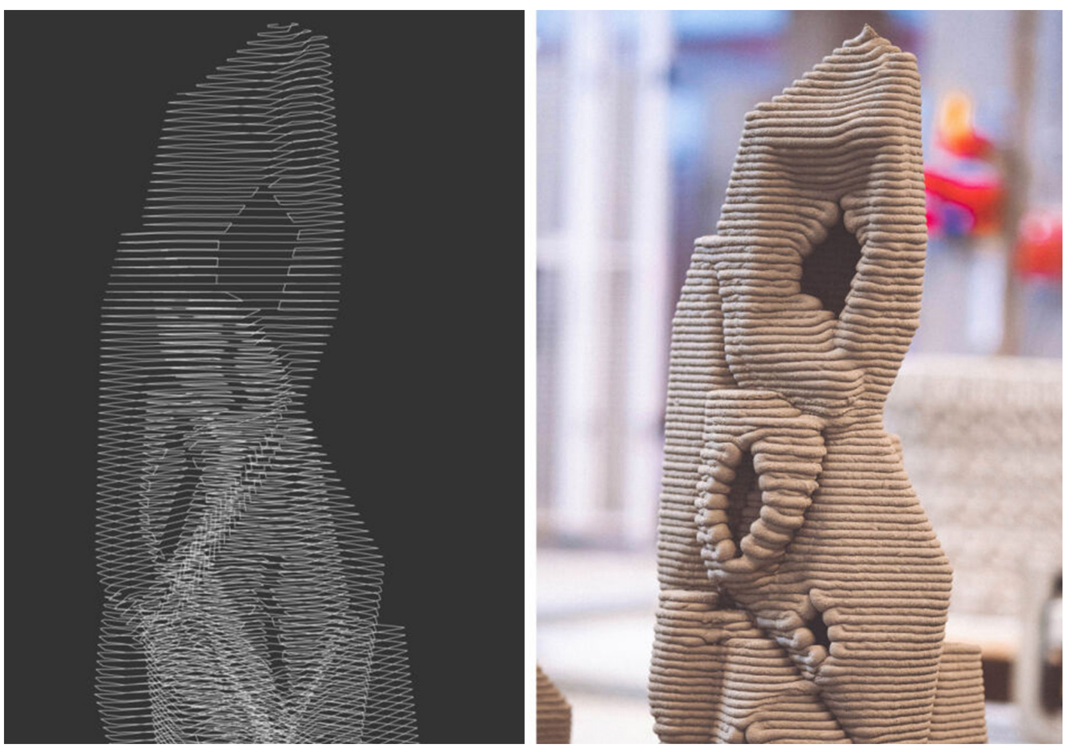

FIGURE 2 Computer-generated toolpath (left) and 3D printed prototype (right) by Vertico 3d printing specialists (©RB lab, TU Delft).

This wide design spectrum of typologies, approaches, and scales is further enlarged by extreme climate design for arctic exploration modules and off-Earth habitats, as well as emergency response and temporary specialist structures. In this context, pop-up structures to support the underserved in economically underdeveloped communities (Bertino et al., 2019), as well as habitats for extreme environments need further investigation. In particular, their design and construction by means of advanced computational design and robotic production and operation technologies have the potential to create customizable structures that can be optimized for various performances. For instance, structural optimization reduces material usage while ensuring the creation of structures that use less material and need less production time. Hence, the parametric design is customized based on the functional and structural requirements of spaces, as well as environmental factors. In the design process, the parametric model is also informed by the limitations of the computer numerically controlled production equipment (Fig.2).

4 Application and Development

Technology influences the architecture of pop-up structures in various ways. The 3D printing approach developed so far for the Rhizome 1.0 project developed at TU Delft involves a Voronoi-based material and architectural design (Fig. 2).

The habitat is to be constructed in empty lava tubes on Mars. By building below ground level not only natural protection from radiation is achieved but also thermal insulation because the temperature below ground is more stable due to insulating qualities derived from the rock's thermal properties at depth. The idea is that a swarm of autonomous mobile robots developed at TU Delft, Zebro, scans the caves, mines for in-situ resources, and with the excavated regolith that is mixed with cement, 3D prints the habitat by means of D2RP&O. The 3D printed rhizomatic habitat is a structurally optimized structure with increased thermal insulation properties due to its porosity. Similar to previous projects (Bier et al., 2017; Bier, Hidding, et al., 2020), the production and operation/ use of the habitat are powered by renewable energy systems, which in this case combine an automated kite-power system with solar panels. The ultimate goal is to develop an autarkic D2RP&O system for building off-Earth subsurface autarkic habitats from locally obtained materials (Bier et al., 2022).

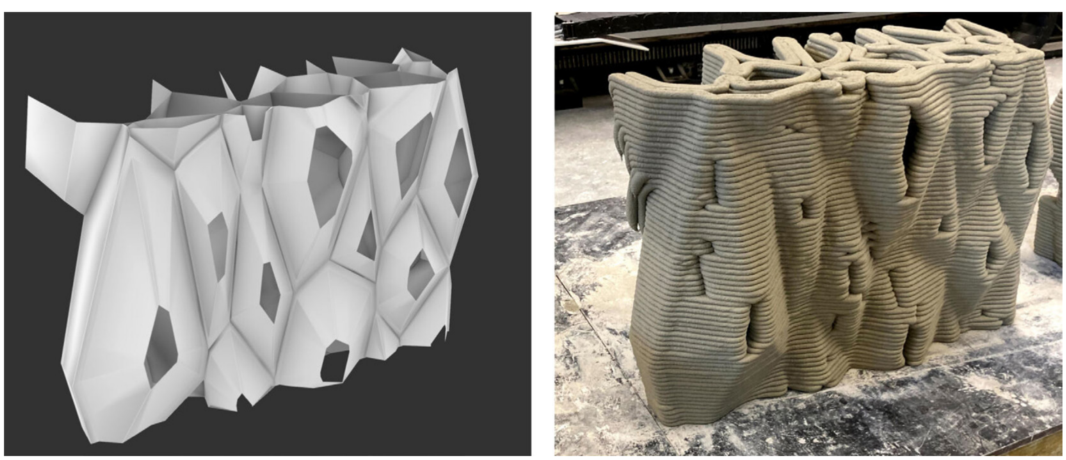

FIGURE 3 At Vertico 3D printed prototype of a fragment of the rhizomatic habitat on Mars developed at TU Delft ©RB lab, TU Delft.

In the first two prototyping sessions of Rhizome 1.0 presenting considerable differences between the digital model and the 3D printed fragment (Fig. 3) has been identified how the cell sizes, the robotic setup, and the material influence each other.

Rhizome 1.0, which indicates the potential of D2RP&A for developing innovative designs for pop-up architecture is now followed up by Rhizome 2.0. The innovation lies not only in the material design but also in the autarchic D2RP&A approach using IsRU. The knowledge developed in Rhizome 1.0 project (Bier, Latour, et al., 2020) will allow to scale up from 3D printed componential approach to building scale in Rhizome 2.0 project (Bier et al., 2023) while employing cementless concrete with the mid- and long-term goal to implement technology transfer from off-Earth to on-Earth applications.

5 In-Situ vs. Prefab 3D Printing

In the context of CO2-free pop-up architecture, in situ and prefab 3D printing have pros and cons. In situ 3D printing involves constructing structures on-site using eco-friendly materials and reducing transportation emissions while allowing for site-specific customization. This method is, however, considerably influenced by weather conditions. In contrast, prefab 3D printing involves manufacturing building components off-site, which enables increased quality control. Material durability and adaptability remain key concerns for in-situ 3D printing of pop-up structures. Material extrusion is a frequently employed method of 3D printing, especially with concrete as a prime material.

CONPrint3D, for instance, is an extrusion-based printing method for on-site, monolithic 3D concrete printing that provides high mechanical strength and consistent printability to the concrete up to 90 minutes after water addition, which is a promising approach for rapid response and large-scale construction (Nerella & Mechtcherine, 2019).

Profile 3D printing is a mold-less additive/subtractive manufacturing approach that combines the deposition of concrete for a rough layup with precision tooling for surface finishing of architectural building components (Bard et al., 2018). This method offers a framework for robotic concrete finishing and the production of mold-less custom designs. This approach is favorable for the pop-up structures' interior and exterior surfaces that require a fair finishing quality.

In the context of in-situ 3D printing for pop-up structures, another important aspect to consider is the impact of local materials on sustainability. Using locally sourced materials for 3D printing further reduces CO2 emissions associated with transportation and contributes to a more environmentally friendly construction process. Local materials also add unique character and cultural relevance to the structures, enhancing their connection to the surrounding environment. Moreover, due to the elimination of formwork, and manual labor, and the reduction of material wastage, some savings in material, process and energy are expected.

In this context, the parametric design is customized to accommodate specific needs or unforeseen challenges that may arise during the construction process. This adaptability is particularly valuable for pop-up architecture, where time and efficiency are critical factors in both disaster and extreme environments scenarios. On the other hand, prefab 3D printing offers solutions to increase efficiency and reduce the cost of construction processes while delivering higher quality control and safer working environments (Anton et al., 2021). However, weight and size constraints of the to-be-assembled components need to be considered.

Also, while casting concrete on site reduces transport issues, it increases sensitivity to temperature variations in different environmental conditions (Burger et al., 2023). In summary, both in-situ and prefab 3D printing methods present unique strengths and challenges for CO2-free pop-up architecture. In-situ printing and assembly offers benefits like adaptability to local materials and site conditions, while prefab printing excels in quality control and efficiency.

Furthermore, cementless concrete formulations present an opportunity to significantly diminish the environmental impact of pop-up structures. They are often based on geopolymers or other ecologically sound alternatives that substantially curtail the carbon emissions linked to conventional cement production. Moreover, the digital workflow not only heightens the precision of the end product but also mitigates material wastage, while the human-robot collaborative nature of the process facilitates efficient construction.

6 Artificial Intelligence and Human-Robot Interaction (HRI)

Simulation, algorithmic and parametric methods involving feedback analysis make it possible to rapidly prototype, test, and refine a wide range of designs from which the optimal design is selected to meet specific needs (Dunn, 2012). In particular, Artificial Intelligence (AI) helps design by, amongst others, analyzing environmental and human needs in order to actively propose designs customized for specific environments and users (Tamke et al., 2018), while through cloud-computing technologies, designs are increasingly transferred and fabricated across various locations.

When it comes to construction, AI assists the Human-robot Interaction (HRI) assembly process (Peternel et al., 2018) as well as the operation of environmentally controlled housing units. The interaction between the environment and the human and non-human agencies requires definition in terms of identifying tasks that are automated and tasks that rely on HRI versus tasks that remain in human control. These aspects have been in the Rhizome 1.0 and continue to be explored in 2.0. Both projects are co-funded by the European Space Agency (ESA) and the 3D printing firm Vertico.

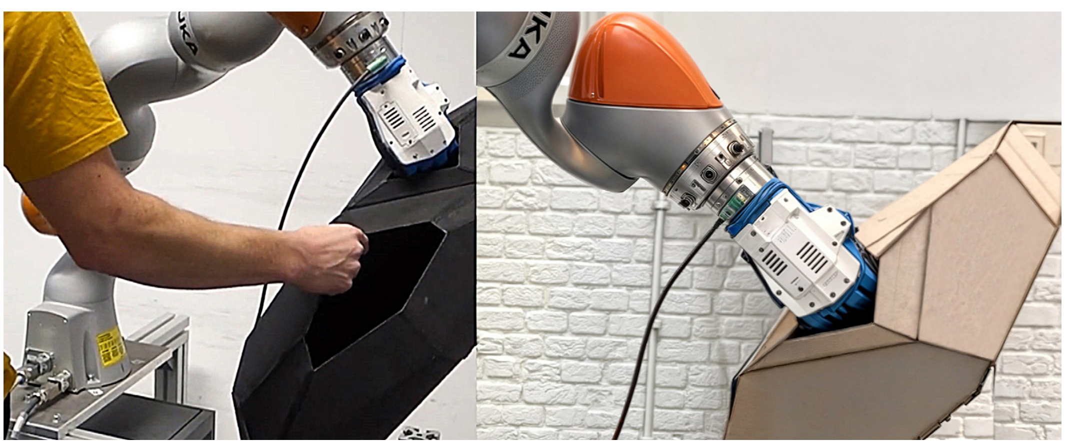

FIGURE 4 Collaborative construction using HRI method developed at CoR, TU Delft..

 In this context, the team at Cognitive Robotics (CoR) at TU Delft developed HRI methods for the assembly of prefab 3D printed components. These Voronoi-based building components, which have variable shapes, are picked up from the printing location and moved to the place where the envelope of the habitat is being built. The carried component is then placed to the specific location. To implement this task, intelligent collaborative robots are employed to safely assist humans by handling the heavy loads, while the human takes over the cognitively complex aspects of the task (Fig. 4).

The challenges of scaling up Rhizome 1.0 from component to building are extensive. In Rhizome 1.0 one component was picked and placed using HRI. When this process is scaled up to the assembly of a whole habitat multiple challenges arise. The first challenge is to stack multiple components horizontally and vertically while maintaining component stability and keeping the robotic arm within the range of possible positions for picking and placing.

Developing the HRI process in combination with Computer Vision (CV) will ensure the correct recognition and placement of the components, while picking and placing relies on sharing the responsibility of tasks between humans and robots (Peternel et al., 2021).

Since the structure is much larger than the workspace of the robotic arm another challenge of scaling up is providing access to the structure at increasingly growing heights. Both on-site printing and assembly of prefab components will rely on ramps that will have to be integrated in the structure (Fig. 5 and 6). The challenge extends to encompass the intricate interplay between the robotic system and human operators, where effective communication and coordination become essential to harmonize the movements of the robotic arm and the activities of the human workforce.

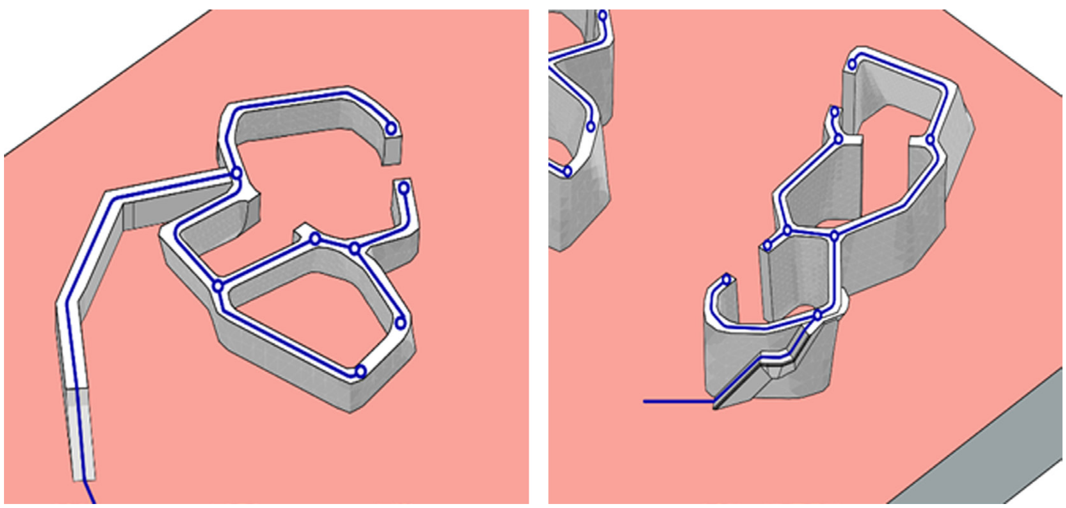

FIGURE 5 Diagram showing approach for printing or assembling in-situ using an integrated ramp

Maneuvering the components into their designated location, cementing them together and coating them for achieving airtightness requires path-planning algorithms informed by real-time sensor feedback and computational modeling.

Furthermore, the electromechanical systems to sustain the Life-support System (LSS) have to be integrated into the structure and will have to be accessible for maintenance.

7 D2RPA&O for Carbon-free Pop-up Architecture

D2RPA&O represents a significant advancement in the field of CO2-free pop-up architecture. With increasing awareness of environmental issues and the need for sustainable solutions, TU Delft collaborates with partners, such as ESA, Vertico, University of Antwerp, International Research School of Planetary Sciences Pescara to address these challenges by optimizing material and energy usage through structural optimization and use of cementless concrete. A review of the literature has unveiled the potential viability of adopting a lime-centered methodology as a prospective resolution for Rhizome 2.0 (Bier et al., 2023). On the other hand, geopolymers present alluring material traits with a concurrent reduction in energy demands (Davidovits, 2013). It is crucial to underscore that the distinct material attributes of both lime-infused and geopolymer amalgamations will significantly hinge upon the distinctive attributes of the regolith simulant applied. Sustainability and waste reduction are key considerations in the development of pop-up habitats, ensuring their adaptability in spatial, environmental, social, and economic aspects of design.

This cutting-edge approach integrates computational design methodologies and robotic production technologies, providing flexibility and customization for pop-up architecture applications. By optimizing shape complexity and employing cementless concrete in Rhizome 2.0, D2RPA&O enhances material efficiency, resulting in better overall environmental performance due to reduced CO2 emissions.

While there are challenges to overcome in in-situ production, such as robot sensitivity to environmental changes and autonomous operation in unstructured environments, the incorporation of AI within D2RPA&O offers promising solutions by enabling learning and improvement over time (Bier et al., 2023). This approach leads to the development of customizable models for carbon-free pop-up habitats, addressing social, environmental, technological, and economic needs with local material utilization and CO2 low approaches as core principles.

While growing awareness of the impacts of global warming, environmental threats, and the need to build sustainably have initiated efforts undertaken by local and international organizations and governments, TU Delft in collaboration with various partners aims to contribute to reducing material and energy use by implementing structural optimization and therefore utilizing material only where it is structurally or functionally needed.

Also, environmental consequences of 3D printing using concrete are currently reconsidered in Rhizome 2.0 by printing with cementless concrete. In comparison to the conventionally manufactured concrete structures, 3D printed cementless structures will promote better overall environmental performance for the pop-up structures throughout their lifespan which results in CO2 emission reduction.

8 Discussion

Various computational design methodologies and robotic production technologies are advanced in the design and building processes of Rhizome 1.0 and 2.0 developed in the RB lab in collaboration with various intergovernmental, academic, and industrial partners (Bier et al., 2023; Bier, Latour, et al., 2020). In particular, for pop-up architecture applications, the D2RP&O approach is valuable because of its versatility and ability to link the design to customized production and operation processes. Challenges of production in-situ remain to be addressed with respect to the sensitivity of robots towards environmental changes as well as their semi- and autonomous operation in unstructured environments.

The proposed D2RP&O methods offer multidimensional advantages responding to social, environmental, technological, and economic needs such as potential for community engagement in production, assembly and operation processes, use of easy-to-operate tools and locally obtained materials, increased material, and energy efficiency, etc. Their advancement through integration of AI will offer solutions to some challenges by providing the system with the ability to learn and improve in time. Machine Learning (ML) algorithms and Computer Vision (CV) systems can analyze the generated data during robotic 3D printing and provide real-time feedback for quality control in the production process. Additionally, robotic path planning tools optimize this process by reducing material waste and printing time. The ultimate goal is to advance autarchic D2RP&O methods and develop customizable models for pop-up habitats.

For diverse construction applications, in-situ and prefab 3D printing provide significant advantages and challenges. Customization, quick building, and design flexibility are all strengths of in-situ 3D printing. It reduces the need for huge components to be transported, resulting in lower costs and on-demand production. This technology is ideal for disaster relief and remote research, where construction time and flexibility are important. In-situ 3D printing, on the other hand, presents obstacles in terms of equipment transportation, labor intensity, weather limits, and restricted scalability for major projects.

Prefabricated 3D printing, on the other hand, features controlled manufacturing and rapid assembly, ensuring uniformly consistent quality and replicability of designs across projects. The independence from on-site weather conditions, as well as the reduction in on-site labor, improve safety and minimize disturbance. Prefabricated components can be inspected and delivered off-site, maximizing resource utilization and scalability. Material adaptability allows for a wide range of applications, including utility integration and automation. However, when compared to in-situ technologies, prefabricated 3D printing may have limits in terms of customization and design adaptability. Transportation expenses, storage requirements, and coordination issues can complicate logistics, reducing cost-effectiveness.

In the context of off-Earth applications, combination of both in-situ and prefab 3D printing approaches may be a more practical solution, reinforcing the advantages of each method to optimize the efficiency and effectiveness of construction on Mars.

The presented D2RPA&O approach in CO_2-free pop-up architecture represents a substantial advancement, meeting the critical requirement for long-term solutions in the face of environmental issues. The research at RB Lab optimizes material and energy usage in collaboration with partners through structural optimization and innovative technologies. The prospective use of lime-centered approach and geopolymers improves pop-up habitats' environmental impact. The integration of computational design and robotic production empowers designers by optimizing shape complexity and reducing CO_2 emissions using cementless concrete.

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