Computational Design and International Cooperation in Space Architecture Education

IAC-22-E1.4.4 (72123)

# Computational Design and International Cooperation in Space Architecture Education

**V. Sumini[a]*, M. Rossi[b]**

[a]**Politecnico di Milano, Italy, MIT Media Lab, USA*, valentina.sumini@polimi.it, vsumini@mit.edu
[b] *Politecnico di Milano, Italy*, marta2.rossi@mail.polimi.it

* Corresponding Author

**Abstract**

Space architecture is an interdisciplinary field that involves many different branches of knowledge, like space science, engineering, architecture, industrial design, medicine, psychology, and art, covering all aspects and needs for human space exploration in LEO and other celestial bodies, like the Moon and Mars. For this reason, the educational effort should involve a set of different skills in the various fields in order to design a safe and livable environment for sustaining human's life in space. Since 2020, the course at Politecnico di Milano "Architecture for Human Space Exploration" for the School of Architecture, Urban Planning, and Construction Engineering is implementing this multi-disciplinarity thanks to external reviewers, that are experts in the Space Architecture domain, and the collaboration, in the actual A.Y. 2021-22, with the Webinar Series at MIT Media Lab "Design Exploration: towards a Moon Architecture". The Webinar Series, open to all MIT and Harvard students, addressed numerous topics and aspects of designing a lunar settlement with several experts about history of space architecture, crewed missions, habitation systems and habitability requirements, In Situ Resources Utilization, Human Factor Design principles, radiation shielding technologies, sustainability of space exploration, and inspirational talks. The talks gathered space architects, engineers and professionals from NASA JPL, NASA JSC and ESA, astronauts, faculty from different universities (University of Houston - SICSA, UW-Madison, Université Paris-Saclay, SDU, University of Bologna, Politecnico di Milano, MIT Media Lab and MIT AeroAstro) and companies (Trotti Studio, Thales Alenia Space, SOM, ICON). Indeed, the students attending this collaborative classroom had to develop a space architecture project for the Moon or Mars. Therefore, the possibility to actively participate to this Webinar Series resulted extremely effective since students applied the acquired knowledge directly to their Space Architecture projects. The approach is different in case of short and deeply focused Workshop on computational design applied to Space Architecture on worldwide educational platforms, like the Workshop "Explore Moon Architecture" for Digital Futures and the Workshop "Mars Architecture" for Parametric Architecture. The educational strategy for these Workshops is based on the development of customized computational design tools for generating form-finding, multi-objective and topology optimization processes for space structures. Students learned how to use Grasshopper, an algorithmic modeling software, and several other plugins, like Octopus©, Ameba©, Karamba3D©, Kangaroo©, Weaverbird© and others. In this paper, some Space Architecture projects resulting from these two educational strategies will be briefly presented and discussed.
**Keywords:** space architecture, computational design, education, multidisciplinarity

**Acronyms/Abbreviations**

AHSE = Architecture for Human Space Exploration
DEMA = Design Exploration: towards a Moon Architecture
EMA = Explore Moon Architecture
ESA = European Space Agency
MIT = Massachusetts Institute of Technology
NASA=National Aeronautics and Space Administration
PA = Parametric Architecture
SICSA = Sasakawa International Center for Space Architecture
ISS = International Space Station
STEM = Science, Technology, Engineering and Mathematics
ISRU = In Situ Resources Utilization
ICE = Isolated, Confined and Extreme
HCI = Human-Computer Interaction
BESO = Bi-directional Evolutionary Structural optimization

## 1. Introduction

Education in Space Architecture is strongly characterized by a multidisciplinary approach that makes this didactic activity unique and requiring non-standard approaches. Indeed, Space Architecture courses are not usually included in common STEM educational paths since it is the result of a cross-pollination of several branches of knowledge. Space Architecture is mainly taught in specific Master programs, like for instance the Sasakawa International Center for Space Architecture (SICSA) at University of

Houston, or through other extra-curricular training activities. Therefore, generating a didactic multi-disciplinary capsule of Space Architecture, to be included within Bachelor and/or Master programs for Architecture, Urban Planning, and Construction Engineering as well as thematic workshops on global platforms, is challenging since it presents several constraints in relation to the different students' backgrounds and the need to develop customized computational design tools for supporting students along the design process.

The aforementioned peculiarities of this didactic activity also require international collaborations in order to integrate the course contents with several experts in each field and take into account the real context of a fast evolving domain.

This paper presents and discusses the results of two different didactic experiences, one related to a Space Architecture course at Bachelor and Master programs at Politecnico di Milano, also in collaboration with MIT Media Lab, the other related to deeply focused workshops at Digital Futures and Parametric Architecture web-based platforms.

## 2. Space Architecture Education

Architecture in Space is the result of the combination of various disciplines, such as space sciences, engineering, robotics, industrial design, ergonomics, medicine, psychology, and, last but not least, art [1]. Space Architecture as a discipline connects the design of living and working environments in space and on planetary bodies, such as the Moon and Mars and other celestial bodies. Therefore, it includes space vehicles, orbital space stations, planetary habitats, and analogs facilities [2-3].

Teaching Space Architecture means combining engineering thinking with criteria related to habitability and human factors, as within architecture and industrial design. In a Space Architecture studio, students advance and develop their projects for human missions and habitat facilities aimed at optimizing human safety, performance and comfort under extreme, isolated and confined conditions of space habitation [4].

## 3. Didactic experience at Politecnico di Milano

The course "Architecture for Human Space Exploration" (AHSE) has been offered to both Bachelor and Master students belonging to the School of Architecture, Urban Planning and Construction Engineering at Politecnico di Milano since A.Y. 2020-21.

Therefore, the course is open to all students from Architecture Built Environment Interiors, Architecture and Urban Design, Building Architecture and Architectural Engineering.

### *3.1 AHSE at Politecnico di Milano A.Y. 2020-21*

During A.Y. 2020-21, the AHSE course was devoted to the design of a resilient and sustainable infrastructure for human missions on the Moon and Mars. This new design challenge required a novel holistic design approach, given the strong multi-disciplinarity of the space architecture domain.

Students were challenged to design in teams within a cross-disciplinary environment at different scales, from urban to architecture and interior design, and build on the knowledge and technologies developed for space applications. Challenging both space and terrestrial architectures to consider the relationships between human activities and the resources which support them.

Indeed, students conceived architectural solutions for the Moon and Mars that advanced thinking about terrestrial concerns on Earth (Fig. 1). The challenges in solving how a human settlement might evolve in the extreme conditions of space enables more intelligent methodologies for terrestrial utilization and promises to directly impact how we approach challenges on Earth, while meeting the UN Sustainable Development Goals of Agenda 2030 [5].

The AHSE course Syllabus (Table 1) covered different areas of expertise, including a computational design introduction and multi-objective optimization algorithms to learn how to manage the complexity of having several requirements and objectives to solve for.

Table 1. AHSE course Syllabus overview.

| | Main learning objectives |
|---|---|
| 1 | Introduction to Space Architecture and its multidisciplinary approach. |
| 2 | Planning human and robotic missions. Introduction to environmental constraints, mission definition and Concept of Operations. |
| 3 | Introduction of Technology Readiness Level for Aerospace missions. |
| 4 | Analog and terrestrial simulators for human long-term space missions |
| 5 | NASA Artemis Accords and the vision of a lunar base by 2030. |
| 6 | Space Law introduction to build infrastructures and use in-situ resources (ISRU) on other celestial bodies. |
| 7 | Fundamentals of the history of Space Architecture. Detailed analysis of iconic space infrastructures: Apollo Spacecraft, Salyut Space Station, Skylab Space Station, MIR, ISS. |
| 8 | Criteria for a sustainable surface habitat for human space missions. Overview of space architecture advanced concepts for the Moon and Mars. Class I, II, III for habitats in space. |
| 9 | Introduction to radiation protection in space: radiation protection fundamentals, design criteria |

and solutions.

10 Introduction to computational design applied to space architecture across scales, from masterplan to habitat and interior design.
11 Fundamentals of Multi-Objective Optimization: a numerical problem. Multi-objective optimization algorithm for structural design and radiation shielding of space habitats. Visualization of optimal solutions on the Pareto Front.
12 Human activities definition for long-term space mission. Form-finding optimization of different functional diagrams and habitability requirements
13 Autonomous robotic manufacturing in space, leveraging the exploitation and use of ISRU. Topology optimization of shell structures in ISRU.
14 Design of autonomous food production systems minimizing the use of resources.
15 Fundamentals of Human Factors design principles and psychology for isolated, confined, and extreme (ICE) environments. Design of proper HCI interfaces to enhance.
16 Design of proper HCI interfaces to enhance human experience in space. Augmented human performance through wearable technologies.
17 Sustainability by design in space. Fundamentals of Sustainable Development Goals. Lessons learned from Space Architecture back to Earth.

The 91 international students have been subdivided in 16 different groups and asked to develop a series of concepts to settle on the Moon and Mars by maximising the use of ISRU [6] and integrating a "sustainability by design" methodology. The use of computational design tools and multi-objective optimization algorithms resulted to be extremely useful in the form-finding design process.

Table 1. Projects developed during AHSE course, A.Y. 2020-21

| | Moon | Mars |
|---|---|---|
| Team 1 | Demeter | |
| Team 2 | | Mission Mars |
| Team 3 | | Chryse Planitia |
| Team 4 | | MARS-BA |
| Team 5 | | Ice-Drop |
| Team 6 | Chrysalis | |
| Team 7 | | International Mars Station |
| Team 8 | | Modern and Primitive |
| Team 9 | | Mars Future Colony |
| Team 10 | We are Back! | |
| Team 11 | | New Roots |
| Team 12 | | FLEXY-MA |
| Team 13 | | SYCON |
| Team 14 | Trabantenstadt 4.0 | |
| Team 15 | MOONHIVE | |
| Team 16 | In-Fold | |

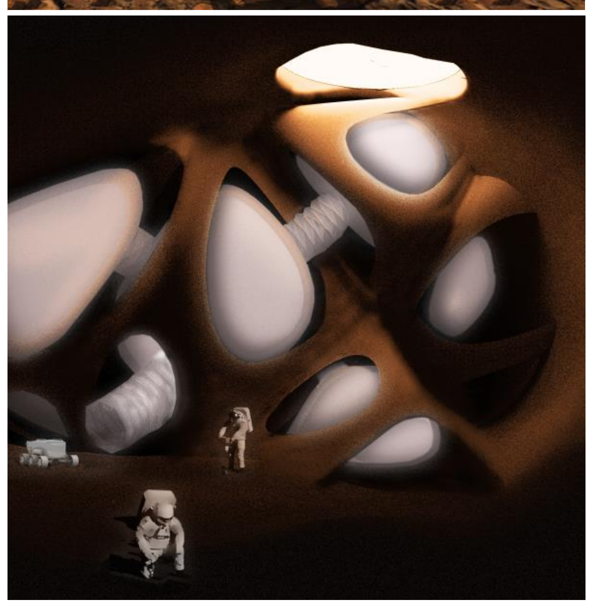

Fig. 1. AHSE course A.Y. 2020-21, lectured by Prof. Valentina Sumini and T.A. Vittorio Netti. Projects by Team 8 and Team 11.

During the several projects reviews, students have been exposed to an international audience of faculty, astronauts, experts and space architects affiliated to international space agencies and other universities worldwide.

*3.2 AHSE at Politecnico di Milano A.Y. 2021-22*

The structure of the course was indeed similar to the previous A.Y., however, the scope of the design included an overall project across scales, from interior design to the masterplan. The outcomes of AHSE course were intriguing space architecture systems that enabled a sustainable human presence on the Moon and Mars, envisioning as possible timeline respectively 2030 and 2050.

The projects solved for: design criteria of space architecture; masterplan design of the settlements; optimal use of ISRU; Human Factor Design principles for integrated design solutions; complexity management through integrated design workflows and multi-objective optimization processes; autonomous robotic structures; Concept of Operation of the human mission; Life Cycle Assessment of the proposed architectural solution.

During the course a computational design approach [7] has been strongly encouraged and taught thanks to a series of dedicated lessons. Students became skilled in parametric design workflow, mainly coding in Grasshopper3D© and its plugins, in order to include real-time structural optimization in the overall design process.

The 119 international students were asked to engage in collaborative teamwork activities (Table 2) and critical thinking to share their knowledges, skills and experiences in order to successfully develop and deploy their projects (Fig. 2).

Table 2. Projects developed during AHSE course, A.Y. 2021-22

| | Moon | Mars |
|---|---|---|
| Team 1 | Hivebitat | |
| Team 2 | Lunar Ziggurat | |
| Team 3 | Lunar Worm | |
| Team 4 | | Prosperity |
| Team 5 | | Martian Formicary |
| Team 6 | | Mars Longevity |
| Team 7 | Lunar Habitat | |
| Team 8 | | Mission to Mars |
| Team 9 | Lunar Molecule Colony | |
| Team 10 | | Octopus Invasion |
| Team 11 | | Mars Base |
| Team 12 | Lunar Hotel | |
| Team 13 | | Mars Habitat |
| Team 14 | | Martian Egg |
| Team 15 | | Growing Roots |


Fig. 2. AHSE course A.Y. 2021-22, lectured by Prof. Valentina Sumini and T.A. Marta Rossi. Projects by Team 2, Team 5, and Team 11.

**4. International collaboration between Politecnico di Milano and MIT Media Lab**

The collaboration between Politecnico di Milano and MIT Media Las has been organized through the Webinar Series "Design Exploration: towards a Moon Architecture" (DEMA), organized and lectured by Prof.

Joseph Paradiso (MIT Media Lab Responsive Environments), Prof. Valentina Sumini (Politecnico di Milano and MIT Media Lab), Arch. Guillermo Trotti (Trotti Studio) that had the syllabus as shown in Table 3.

More in depth, about the scope of this DEMA Webinar Series, the focus was on the prospect that now humankind is on the verge of a massive exploration and exploitation phase on our closest celestial body and, as envisioned also by the NASA ARTEMIS Program, always "on behalf of all Mankind", as written in the NASA constitutive act [8], the idea of one or more permanent settlements on the Moon is currently under study.

Indeed, this is an effective challenge for our and future generations to design new shared infrastructure following the collaborative vision of the ISS experience, defining some kind of "master plan" for an inclusive and organized evolutionary settlement.

From an architectural perspective, this means the possibility of recalling in a completely new context the idea of an "ideal city," as devised so many times in the past, as in the Renaissance or, more recently, by Le Corbusier and Oscar Niemeyer [9]. Moreover, the extreme environmental conditions are a major technological challenge, but also an opportunity, of being free in front of a new kind of blackboard and chalk set.

Therefore, designing a resilient and sustainable infrastructure for human missions on the Moon is a new challenge that requires new conceptual design approaches.

In these DEMA webinars participants had the possibility to learn how to approach this new design challenge taking into account several expertise in various research fields and exploring strategies and solutions to settle on the Moon on a permanent basis.

The DEMA seminars covered the following topics: introduction to Space Architecture; history of Space Architecture (orbital habitats) and contemporary planetary advanced design concepts (static and mobile); planning a Human Space Mission; Habitation System and Habitability Requirements; fundamentals of In Situ Resources Utilization for construction; Human Factor Design principles for integrated design solutions; fundamentals of computational design methods for multi-objective optimized space architecture solutions; construction autonomy and self-deployment of habitable structures on the Moon; and sustainability of human space exploration.

Table 3. DEMA Webinar Series Syllabus

| | Syllabus | Organization |
|---|---|---|
| 1 | Intro Space Architecture | MIT Media Lab, Politecnico di Milano |
| 2 | Inspirational Talk | MIT, Trotti Studio |
| 3 | Mobile and Static lunar settlements | NASA JPL, SICSA |
| 4 | ISRU and Automated Additive Construction | ESA, University of Southern Denmark |
| 5 | Innovative Radiation shielding strategies | University of Bologna, UW-Madison, Redhouse Studio |
| 6 | Visions and Advanced Concepts | ICON, SOM |
| 7 | Human Factors Design and HCI | MIT Media Lab, SICSA, Université Paris-Saclay |
| 8 | System integration | |
| 9 | Living in space: astronauts' talks | ESA, NASA, MIT AeroAstro |
| 10 | Future of human space exploration | MIT Media Lab, MIT EAPS, Thales Alenia Space |

The DEMA Webinar Series has been open to both MIT and Harvard students, given its strongly multi-disciplinarity and counted about 80 participants, plus the about 119 students from AHSE course at Politecnico di Milano.

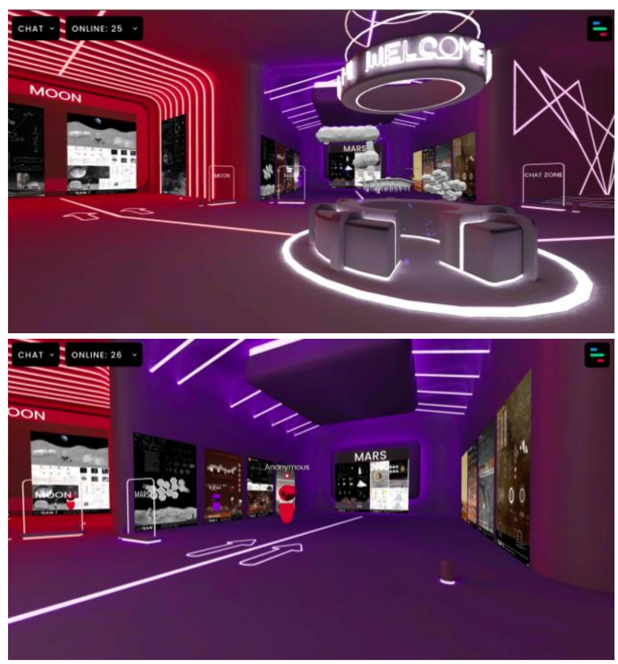


Fig. 3. AHSE VR Poster gallery (Accessible at: https://framevr.io/ahse )

The final AHSE project review has been accessible to all participants, including DEMA ones and all invited speakers. Finally, a VR Poster Session (Fig. 3) has been implemented to share an overview of the space architecture projects developed by Politecnico di Milano students during this collaborative didactic and research activity, and to promote an effective exchange of ideas and feedbacks.

The VR Poster gallery hosted real-time project presentations with a virtual Q&A session for each project.

## 5. Space Architecture Workshops

The didactic experience related to focused Space Architecture Workshops on web-based platforms, with a very limited number of teaching hours, has been challenging, since it combines the scope of designing a lunar or Martian settlement without having the possibility to extensively acquire all the required notions for each specific topic (environmental constraints, habitability requirements, mission planning, ISRU, etc). Indeed, the use of computational design tools [7] in these types of Workshops becomes even more important as it allows to explore multiple design options without having full knowledge of all design requirements and criteria for space architecture. Moreover, given the variety of students' backgrounds at different learning stages, it is extremely efficient to have an algorithmic aided design approach.

Teaching space architecture principles using computational design tools was possible since these types of software allow to feed crucial data into the model. For example, it is possible to control the gravity value and adapt it to the design needs, and parameters such as the internal pressure of a habitat and the tensile strength of materials can be managed. Therefore, during the process of showing these steps inside the software it was possible to explain the theory behind the values and the logic followed to build the model itself.

### *3.1 Digital Futures*

The "Explore Moon Architecture" Workshop for Digital Futures, organized in the framework of InclusiveFUTURES in June 2021, had as objective the design of a lunar settlement by using parametric tools. The EMA Workshop allowed students to build on the knowledge and technologies developed for space applications and explore innovative architectural design solutions of an integrated habitat on the Moon. The projects are based on the conditions unique to the lunar environment, such as reduced gravity, extreme thermal differentials, high-energy solar exposure, cosmic radiation, high velocity micrometeorite impact, abrasive-electrostatic regolith, zero atmosphere and constrained human living space and human factor design principles [10]. A computational design approach has been applied in order to perform multi-objective optimization and form-finding analysis to take into account human and environmental requirements for a lunar habitat. Using Grasshopper3D©, a graphical algorithm editor tightly integrated with Rhino's 3-D modelling tools [11], the students could explore new shapes and form-finding using generative algorithms. During the EMA Workshop also other plugins have been used in order to perform Multi-Objective Optimization analysis, like Octopus that allows the search for several goals at once, producing a range of optimized trade-off solutions between the extremes of each goal by introducing the Pareto-Principle for Multiple Goals.

Fig. 4. EMA Workshop - Digital Futures, organized and lectured by Valentina Sumini. Projects by P. Aashwinay, E. Angelaki, S. De Mio, S. I. Dimcea, S. Gupta, H. Kouchaki, J. Rodríguez P., D. Roy, M. Saifiz, M. Shehreen Baig, L. Tenorio, Y. Wang.

Another plugin that has been employed for the form-finding and structural analysis has been Karamba3D©, a parametric structural engineering tool which provides accurate analysis of spatial trusses, frames and shells. The students had the possibility to explore several optimal design solutions (Fig. 4), applying all the required loads to their space structures and developing interesting concepts for a lunar settlement.

*3.2 Parametric Architecture*

The "Mars Architecture" workshop for Parametric Architecture (PA), held from March 2022 until June 2022, intended to explore advanced concepts for a settlement on Mars, envisioning as a timeline 2050. Within the workshop students had the possibility to learn how to plan a long-term human mission to Mars and through Design Thinking activities brainstorming all possible requirements and design criteria to take into account for the project.

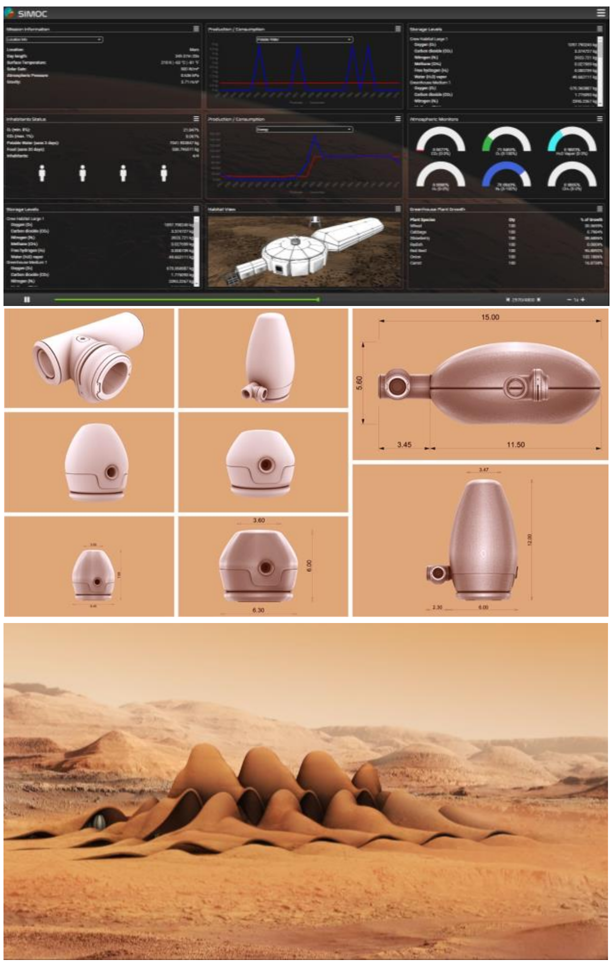


Fig. 5. Mars Architecture PA Workshop organized by Hamid Hassanzadeh and lectured by Valentina Sumini and Marta Rossi. Dune City project by Simina – Ioana Dimcea and Assem Attia.

The outputs of this cross-disciplinar activity became the inputs to run a SIMOC simulation [12]. SIMOC is a scalable, interactive model of an off-world community. The model is founded on published data derived from life support and closed ecosystem research at NASA and universities world-wide.

The users are invited to design a habitat that sustains human life through a combination of physio-chemical (mechanical) and bioregenerative (living plant) systems, selecting various combinations of crew quarters, greenhouse, food and plants, energy generation and storage, and mission duration.

The results of this simulation became the insight for the computational design models that each team had to implement for the project (Fig. 5).

The parametric design has been developed in Grasshopper3D© in integration with several other plugins in order to perform the form-finding and structural analysis of the pressurized modules and the inflatable membranes, the topology optimization of the radiation protection shielding, the optimization of interior functional distributions and, finally, the simulation of the membrane folding inside the payload fairing system of SpaceX Starship [13].

Regarding the form-finding and structural optimization of the pressurized the plugins Kangaroo, a Live Physics engine for interactive simulations, and Karamba 3D© have been used. The advanced topology optimization of the radiation shielding using ISRU on Mars has been implemented through Ameba© a topology optimization software based on Bi-directional Evolutionary Structural optimization (BESO) technology [14].

The adaptive design of interiors, in terms of functions and spatial distribution, has been implemented through a Grasshopper3D script entirely devoted to the parametric floor area segmentation and furniture design.

Finally, the simulation of the inflatable membrane folding has been performed through OpenNest, to verify the geometrical compliancy of the structure inside the rocket for the launch configuration.

## 6. Discussion

Common ground of all the outlined learning activities is the implementation of computational design tools that allows students from different backgrounds and learning stages to use a shared and universal language.

These community tools, mainly open source, have some fascinating aspects that entail a largely shared enthusiastic interest among young generations that consider these design activities a sort of a blank blackboard, where through new chalks they can envisage their future.

Associating the need to fulfill different design requirements for space applications with the use of really flexible computational design tools, covering a large spectrum of constraints, has been considered very powerful, towards a real democratization of space education.

Indeed, there are some aspects related to exporting human life out of our planet that must be primarily considered. Our life on Earth has driven us to a sustainability crisis that must be clearly avoided "by design" in our visions for the Moon or Mars. We have the chance for instance of designing human settlement "from scratch", in order to envision humanity's first effort in establishing an off-world society.

## 7. Conclusions

The springing up, the fast evolution and the constant growth in terms of resource investment capabilities of a strong "space economy" that is actually spreading all around the world and that aims at covering various aspects connected to the scientific and economic exploitation of Earth "outer space", the Moon at first but also Mars in perspective, make evident the need of the possibility of the development of a structured educational framework enclosing all the technological aspects outlined above as a subject of dedicated learning activities.

Several aspects in designing solutions and making things real are still actually covered through non-standard learning path that have been precious in a first pioneering phase, but we should prepare to train new generations of young scientists and technologists able to implements brand new ideas and solutions. The numbers and the really enthusiastic answers received in our experiences testify the need of more diffused and organised training path aiming at offering to the students the possibility of acquiring all the multidisciplinary knowledge required for the development of the original visions that will be implemented in our future.

## Acknowledgements

The authors would like to acknowledge the Politecnico di Milano grant for Innovative Didactic Pilot Projects that allowed the generation of the collaborative classroom with MIT Media Lab Webinar Series "Design Exploration: towards a Moon Architecture" held by Prof. Joseph Paradiso, Prof. Valentina Sumini, Arch. Guillermo Trotti during A.Y. 2021-22.

The authors would like to express their gratitude to all invited speakers, astronauts, MIT Space Exploration Initiative, AIAA Space Architecture Technical Committee, Parametric Architecture, Digital Futures and all students that enthusiastically participated to these didactic activities.

## References

[1] C. Adams, O. Arenales, M. Cohen, The Millennium Charter, space architecture workshop by AIAA DETC Aerospace Architecture Subcommittee, Houston, USA, 2002, 12 October.

[2] S. Häuplik-Meusburger, O. Bannova, Space Architecture Education for Engineers and Architects Designing and Planning Beyond Earth, first ed., Springer, San Francisco, 2016.

[3] A.S. Howe, B. Sherwood, Out of this World The New Field of Space Architecture, American Institute of Aeronautics and Astronautics, Inc., Reston, 2009.

[4] M.M. Connors, A.A. Harrison, F.R. Akins, Living Aloft Human Requirements for Extended Spaceflight, US Government Printing Office, Washington DC, 1985.

[5] United Nations, Transforming our world: the 2030 Agenda for Sustainable Development, 2015, https://sdgs.un.org/2030agenda, (accessed 01.09.22).

[6] R.P. Mueller et al., Automated Additive Construction (ACC) for Earth and Space Using In-Situ Resources, Proceedings of the Fifteenth Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (Earth & Space 2016), American Society of Civil Engineers (2016).

[7] A.J. Keane, P.B. Nair, Computational Approaches for Aerospace Design: The Pursuit of Excellence, John Wiley & Sons, Ltd, Chichester, 2005.

[8] NASA, National Aeronautics and Space Act of 1958 (Unamended),1958, https://history.nasa.gov/spaceact.html, (accessed 01.09.22).

[9] H. Nooraddin, City Centers as Urban Growth Cores, Journal of Economic and Sustainable Development. 7, 2222-2855 (2016).

[10] J. Boyer, Human Integration Design Processes (HIDP). Human Health and Performance Directorate, NASA/TP-2014-218556 (2014).

[11] M. Ericson, Review: Grasshopper Algorithmic Modeling for Rhinoceros 5, Journal of the Society of Architectural Historians, (2017) 76 (4): 580-583.

[12] National Geographic, SIMOC, https://education.nationalgeographic.org/resource/simoc, (accessed 01.09.22).

[13] SpaceX, Starship Users Guide, March 2020, https://www.spacex.com/media/starship_users_guide_v1.pdf, (accessed 01.09.22).

[14] Y Li, YM Xie (2021), 'Evolutionary topology optimization of spatial steel-concrete structures', Journal of the International Association for Shell and Spatial Structures 62:102–112.