49th International Conference on Environmental Systems
7-11 July 2019, Boston, Massachusetts ICES-2019-158

Self-Sustainable Smart City Design on the Red Planet

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The author of this paper created a design process and design plan for a 1000 person Mars colony for the 2019 Mars Society contest. Particular attention was given to In-situ resource utilization and civil engineering, critical factors for constructing a substantial infrastructure for an almost completely self-sufficient colony. However, it is not possible to produce everything needed on Mars. To make the colony and its habitat self-sustaining and expandable as rapidly as possible, it is necessary to study multiple development schedules to determine the optimal weight of cargo per flight to be sent from Earth and the timing of when to send them, as well as, what should be produced on Mars to reduce the total resources needed. Therefore, our Mars colony development model created for analyzing the development schedule takes into consideration total mass transported from Earth to Mars, total resource mass obtained on Mars, the total energy required, and the total cost required. We determined the most feasible option would be using approximately 200,000 m^2 of habitable area on Mars for a colony consisting of eight greenhouse domes with basement habitats built with resources found on Mars and brought from Earth.

Nomenclature

A	=	surface area, m^2
h	=	convection heat transfer coefficient, W/m^{2}K
BFR	=	Big Falcon Rocket
CFRP	=	carbon fiber reinforced plastic
CNF	=	cellulose nanofibers
DSN	=	deep space network
ECLSS	=	environmental control and life support system
EZ	=	exploration zone
HAB	=	habitat
ISRU	=	In-situ resource utilization
ISS	=	International Space Station
LED	=	light emitting diode
LEO	=	low Earth orbit
LSS	=	life support system
MCD	=	Mars colony development
MEV	=	manned electrical vehicle
SH	=	Super Heavy
ROIs	=	regions of interest
$m_c(t)$	=	transported mass for construction machine at Year t, i.e. Bulldozer and crane
$m_f(t)$	=	transported mass for production facility at Year t, i.e. 3D printer
$m_g(t)$	=	transported mass for greenhouse and LED at Year t
$m_h(t)$	=	transported mass for habitat at Year t
$m_m(t)$	=	transported mass from Earth for maintenance at Year t
$m_p(t)$	=	transported mass for power plant at Year t
$m_{re}(t)$	=	transported mass from Earth at Year t
$m_{rm}(t)$	=	produced mass on Mars at Year t, i.e. water
$m_{se}(t)$	=	transported mass from Earth for structure at Year t
$m_{sm}(t)$	=	produced mass on Mars for structure at Year t

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$m_{ISRU}(t)$ = transported mass for In-Situ Resource Utilization (ISRU) at Year t
$m_{LSS}(t)$ = transported mass for life support system (LSS) at Year t
$p_c(t_s)$ = power for construction, kW
$p_b(t_s)$ = power for biomass production, kW
$p_f(t_s)$ = power for manufacturing, kW
$p_h(t_s)$ = power for habitation, kW
$p_s(t_s)$ = power reduced by using sunlight directly, kW
$p_{LSS}(t_s)$ = power for LSS, kW
$p_{ISRU}(t_s)$ = power for ISRU, kW
Q_b = heat by hour, kWh
$\bar{Q}_{qt}$ = hourly average of Q_{qt}, kWh
$\bar{Q}_s$ = hourly average of Q_s, kWh
t = time, year
t_h = time when heat is calculated, hour
t_s = time when required power is calculated, s
T_a = temperature inside dome, K
T_s = temperature on dome surface, K
ε = thermal emittance of surface
σ = Stefan-Boltzmann constant, 5.670367×10^{-8} W m^{-2} K^{-4}

I. Introduction

A team of space engineers, a space architect, a science curator, and a medical student, and the author of this paper created a design process and design plan for a 1000 person Mars colony plan for entry into the 2019 Mars Society contest.[1]

In-Situ Resource Utilization (ISRU) and civil engineering are critical factors for constructing an infrastructure for a 1000 person colony. Water is an especially critical resource that colonists will need to produce on Mars: water is essential as a propellant for ascent vehicles, life support, and biomass production. To produce water, a substantial area of land containing icier water in the soil located less than 1 meter below the surface must be within 3 km from the processing equipment site. This area must also be accessible and minable by highly automated systems.[2] For biomass production, a low latitude location ideal for rich sunlight, with accessibility to water, and with no terrain features that cast shadows on light collection facilities is important for a self-sufficient colony.

Although all the materials needed on Mars are available on Mars, the equipment required to generate the resources must be brought from Earth. To make the colony and its habitat self-sustaining and quickly expandable, it is necessary to study multiple development schedules to determine the optimal cargo weight per flight and timing of the shipments to be sent from Earth and what can be produced on Mars to reduce the total resources needed. Therefore, the Mars colony development (MCD) model we created for analyzing the development schedule, takes into consideration total mass transported from Earth, total mass obtained on Mars, total energy required, and total cost (transportation cost) required.

II. Mars Colony Development (MCD) Model

We used the MCD model to build a development schedule that minimizes total transported mass required from Earth while taking into consideration the following constraints: resources, budget, time, transport capacity, and technology. The MCD model components related to mass consist of habitat, greenhouse and biomass production system, factory, life support system (LSS), ISRU, power plant, structure, maintenance, construction machinery, and resources. The calculation procedure in the MCD model is shown in Figure 1.

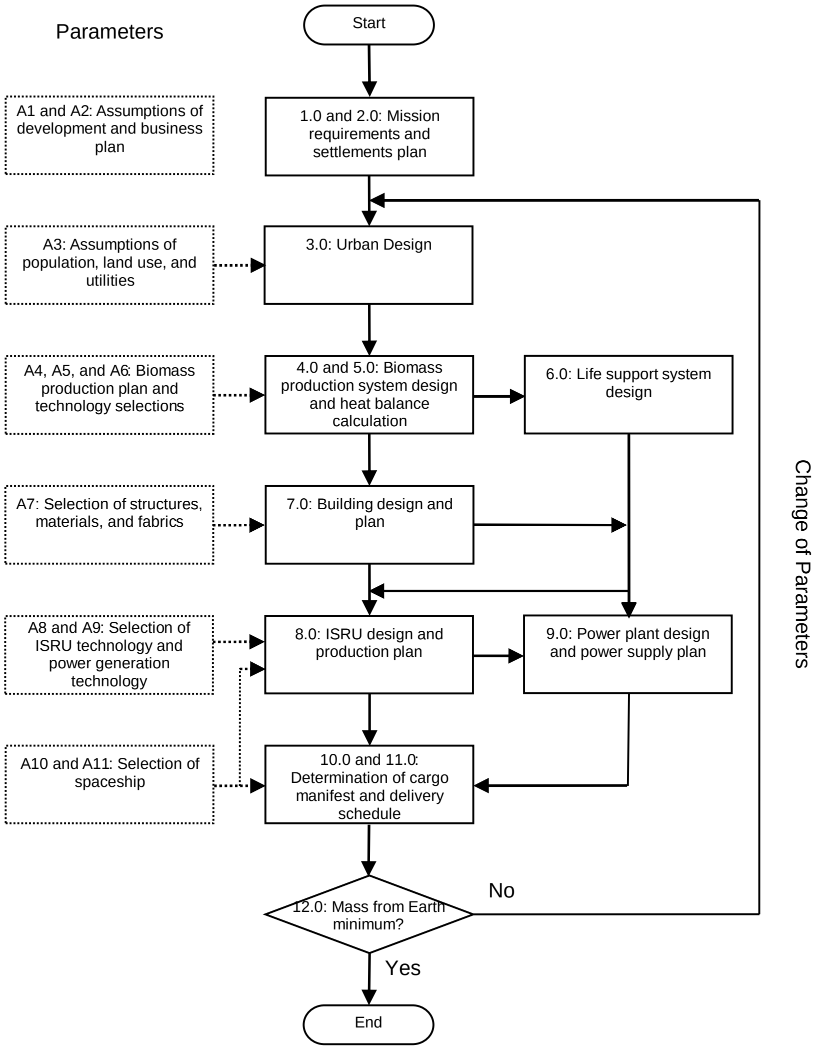


Figure 1. Calculation procedure in Mars colony development model.

Steps 1 and 2: The mission requirements, the initial settlement plan (yearly number of immigrants) (1.0 and 2.0) and design assumptions such as population, land use, and facilities (A3) shown in Table 2 are used for calculating the urban design (3.0).

Step 3: Biomass production system design (4.0) and heat balance calculations (5.0) are conducted based on the urban design (3.0), the biomass production plan (A4), and technology selection (A5). In addition, life support system design (6.0) is determined based on the biomass production system design (4.0) and life support system baseline assumptions (A6).

Step 4: Building design and plan (7.0) are determined based on the biomass production system design (4.0), and selection of structures, materials, and fabrics (A7).

Step 5: ISRU design and production plan (8.0) are determined based on the life support system design (6.0), building design and plan (7.0), selection of ISRU technology (A8) and power generation technology (A9). This step is also based on the selection of a spaceship (A11) in Step 6. In addition, the power plant design and the power supply plan (9.0) are determined based on the LSS design (6.0) and ISRU design and production plan (7.0).

Step 6: Cargo manifest and delivery schedule (11.0) are determined based on the ISRU design and production plan (8.0), selection of a spaceship (A11), and the power plant design and power supply plan (9.0).

Step 7: When the transported mass from Earth reaches its minimum mass target number (“Yes”), the procedure is no longer necessary. When it has not reached the minimum mass target number (“No”), the procedure returns to the urban design (3.0) in Step 2. The maximum mission duration is set at 50 years in this design.

The total mass of the Mars colony at Year t is calculated by adding the summation of subsystem masses year-by-year, usually Year t increases by 2 years as follows:

$$m_{mc}(t) = \Sigma\,(m_h(t) + m_g(t) + m_f(t) + m_{LSS}(t) + m_{ISRU}(t) + m_p(t) + m_{se}(t) + m_{sm}(t) + m_m(t) + m_c(t) + m_{re}(t) + m_{rm}(t)) \tag{1}$$

m_h, m_g, m_f, m_{se}, and m_{sm} are in proportion to the area. m_{LSS}, m_{ISRU}, m_p, m_m, and m_c are proportional to the number of equipment transported from Earth at Year t. m_{re} and m_{rm} are proportional to population or the requirement of construction.

The MCD components model related to required power (P_{mc}) at time t_s defined as Eq(2) consists of habitat (p_h), biomass production (p_b), life support system (p_{LSS}), ISRU (p_{ISRU}), manufacturing (p_f), construction (p_c), and energy from sunlight (p_s).

$$P_{mc}(t_s) = p_h(t_s) + p_b(t_s) + p_{LSS}(t_s) + p_{ISRU}(t_s) + p_f(t_s) + p_c(t_s) - p_s(t_s) \tag{2}$$

III. System Configuration and Conditions

This paper uses the following phases to describe the stages of development for the Mars colony:

- Phase 0 uninhabited construction phase
- Phase 1a inhabited phase without biomass production
- Phase 1b inhabited phase with biomass production in inflatable greenhouses, and
- Phase 2 manned phase with biomass production in greenhouse domes

The Mars colony system components are shown in Table 1.

Table 1. Mars colony system components.

1.0	Mission Authority
2.0	Driving Factors
3.0	Urban Design
4.0	Biomass Production
5.0	Thermal Control
6.0	Environmental Control and Life Support System
7.0	Habitat Structure
8.0	ISRU and Civil Engineering
9.0	Power
10.0	Communication
11.0	Interplanetary Transportation
12.0	Mobility Systems
13.0	Robotics and Artificial Intelligence
14.0	Sustainability and Supportability

1.0 Mission Authority

Mission authority consists of vision, goals, objectives, constraints, and stakeholders. The mission goal as defined in the Introduction is to develop a self-supporting Mars colony that is able to produce all the food, clothing, power, common consumer products, vehicles, and machines required for 1000 people with a minimum reliance on supplies from Earth. The constraints consist of resources, budget, time, transport capacity, and technology.

2.0 Driving Factors

The driving factors of a Mars colony consist of social factors and mission factors. Social factors consist of government (political system, laws), economy (business plans), financing, occupations, religion, culture, population composition (age, gender), and population growth rate (immigration rate, birth rate). Mars and asteroid resource development as well as tourism are incorporated into the Earth-Mars-Asteroid economic model (EMA model), which was developed to calculate the economic factors based on the WORLD II model (Dennis Meadows).[3] Mission factors consist of mission duration, concept of operations, location, and Mars climate/environment. We incorporated all mission factors into the MCD model.

3.0 Urban Design

Although the infrastructure, environment, utility, and transportation are described in 3.0 Urban Design in the plan to be submitted for the contest, it is not described in this paper.

4.0 and 6.0 Biomass Production and ECLSS

An International Space Station (ISS) type environmental control and life support system (ECLSS) that recycles air and water is used in Phase 1a. A fully closed ECLSS that produces biomass is used after Phase 1b. Biomass production is conducted by LED in Phase 1b and by a combination of sunlight and LED in Phase 2. The ECLSS and biomass production system baseline mass and power[11,12] are shown in Table 3. The total mass and power of the 1000-person colony are linearly scaled up from the baseline mass and power by 1000 times.

5.0 Thermal Control

The thermal control system was designed to collect, transport, and reject excess heat from the dome habitat and infrastructures. The environment of the internal dome keeps comfortable temperature and moisture for living or biomass production through the air circulation system. Indoor heat generated by daily life and production is transferred with water flows among habitats, greenhouses, and facilities. The calculation model of the heat balance of the dome is shown as follows.

The heat balance inside each of the greenhouse domes is calculated by assuming that the greenhouse temperature is kept controlled at 300 K. The convection heat loss, Q_c, and heat loss due to radiation, Q_{rs}, are expressed as follows:

$$Q_c = (T_s - T_a) \times A \times h \tag{3}$$

$$Q_{rs} = (T_s^4 - T_a^4) \times A \times \varepsilon \times \sigma \tag{4}$$

$$Q_{qt} = Q_c + Q_{rs} \tag{5}$$

Incident energy, Q_s (W), from the Sun at time t_h (0 - 24) is expressed as follows: [13]

$$\text{if } \theta_h = 2\pi(t_h/24) > 0 \ Q_s = 400 \times (-\cos(\theta_h) \tag{6}$$

$$\text{else } Q_s = 0$$

where 400W/m^{2}K of maximum sunlight reaches the Mars surface in clear weather.

Heat by the hour, Q_b (kWh), is calculated as follows:

$$Q_b = \bar{Q}_s - \bar{Q}_{qt} \tag{7}$$

For example, it is assumed that when a dome's surface is A = 26,533m^2, the heat Q_b is -1.45x10^8 (kWh/day) =3.88x10^7 - 1.84x10^8.

7.0 Habitat Structure

Because the mass of building material to build structure is much larger than other subsystems, the selection of the type of structures and materials will affect the total Mars colony mass budget. Several modules sent from Earth will be used in Phase 1. Domes will be constructed by using cutting edge lightweight material from Earth and resources on Mars in Phase 2. The basement habitats will be constructed with 3D printers. The greenhouse dome will be constructed on the habitat. Carbon fiber strand rods (CFSR)[7,8] will be used for restraining the expansion by internal pressure of the dome and cellulose nanofibers (CNF)[9] will be used for the membrane structure of the roof to minimize the transported mass from Earth.

The habitat of the first stage of colonization is based on reutilizing the Starship itself with nearby inflatable greenhouse structures for subsistence farming. Each starship's cabin provides 825 m^3 of habitable volume, and five starships (4,125 m^3) are needed to give as habitable volume per crew of 34 m^3 for long duration stay on Mars. Each greenhouse has 1,200 m^2 of cultivation area.

The domes are located along the steep, sloped northern edge of Endeavour crater, which provides natural protection from a portion of micrometeoroids and space radiation. The air-supported structure of the dome consists of an inflatable membrane of cellulose nanofiber (CNF) with hexagonal surface cells, supported by ultra-light and strong carbon fiber strand rods (CFSR) to restrain the expansion by internal pressure.[7-9] In order to give sufficient resistance to space radiation, each hexagon has a 50 cm-thickness cell of CNF to store water, mostly in solid form (given the outside atmospheric temperature on the Mars surface), with outer and inner cells of CNF filled with CO^2 as insulation layers.

For example, for a greenhouse dome constructed using CFSR, CNF and water, assuming that the total area is 101,400 m^2, the roof structure mass is 8,112 kg (80 g/m^2 multiplied by 101,400 m^2), the membrane mass is 1,622 kg (0.016 kg/m^2 multiplied by 101,400 m^2), and the water mass in hexagonal surface cells is 1,005,000 kg (Dome 1 is protected by 660,000 kg water, Dome 6 is protected by 346,000 kg water, and other domes are not protected by water).

The underground regolith concrete chamber modules are fundamental spaces for Martian urban city life. The honeycomb structure used for the complex of hexagonal module units draws upon the same structural geometry as the dome surface, minimizing usage of materials.

8.0 ISRU and Civil Engineering

Past Mars explorations have revealed the presence of water, carbon dioxide, metals, and other resources on Mars. We selected our landing site and habitation site based on the information from various presentations at the First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars in 2015. A single Exploration Zone (EZ) contains a landing site, a habitation site, and several Regions of Interest (ROIs) nearby, such as resource regions and science regions located within approximately 100 kilometers.[2]

Four characteristics are required for a Mars landing site from an engineering perspective: The site must be located between +/- 50 degrees latitude, have an altitude of less than +2 kilometers, have approximately 25 square kilometers of generally level terrain significantly devoid of landing hazards, and contain no thick deposits of fine-grained dust.

Our three primary objectives: a low latitude, a low altitude, and existing water resource. These were identified as the criteria for selecting our Mars colony landing site.

- A low latitude gives longer hours of daylight, more sunlight energy, and higher temperatures than a high latitude. In addition, it can reduce propulsion requirements at launch, using Mars's rotation for added acceleration.
- A low altitude has a high-density atmosphere, which can be used for aerobraking during descent and landing. It can also improve the shielding effect against radiation.
- A large area was selected to provide substantial production land located near water, and easily accessible by automated systems.

Based on the requirements, we choose the Endeavour Crater[2] at 3º South of latitude and 43º West of longitude from forty seven EZs, where it can be used as a gateway from Earth or to Earth. The ISRU baseline mass and power[4-6] when it is located at Endeavour Crater is shown in Table 4.

9.0 Power

Required power consists of power used for habitation, biomass production systems, life support systems, ISRU, and construction machines. Sunlight is directly used in addition to LED for biomass production. Solar energy in Mars orbit is 590 W/m^2; net solar energy produced on Mars is assumed to fluctuate between 0 to 400 W/m^2. Primary power is provided by nuclear power stations installed nearby habitation sites. It is assumed that all power is provided by the nuclear power stations during the night and sandstorms. The baseline power requirement is estimated by using the space nuclear design 4,000 kg/100 kW. For example, it is assumed that the power plant mass is $4{,}000/\sqrt{(10{,}000/100)} = 40{,}000$ kg, the mass of 200,000 kg is required for 50 MW by using scaling rule of a nuclear reactor.[10]

10.0 Communication

The communication system enables surveying and navigation, relays communication signals, and supports prospecting decision-making with a constellation of 15 small remote sensing satellites, providing uniform coverage of the entire Martian surface. The constellation system with its satellites assures optimal ISRU excavation locations for construction and research. The ground stations can communicate with Earth via the Deep Space Network (DSN) and directly with the entire navigation network. The surface infrastructures use wireless communications between habitats, mobile surface systems, and other infrastructures.

11.0 Interplanetary Transportation

The SpaceX Big Falcon Rocket (BFR) consisting of a Super Heavy (SH) and a Starship is used for delivering passengers and cargo to Mars.[14] Its transportation capability is 100 mT per flight to Mars surface. People and cargo are delivered to Mars every two years at the best possible time to travel to Mars. The Starship for returning to Earth is operated from Phase 1b. Its required fuel is produced by ISRU on Mars surface.

12.0 Mobility Systems

Manned and unmanned rovers are used for construction starting in Phase 1 and tourism starting in Phase 2. Construction robots that can be controlled remotely are utilized from the initial development phase. The mass and power assumptions of the cargo carrier, hauler, small manned electrical vehicle (MEV), excavator with bulldozer, crane rover, and 3D printer are shown in Figure 2.

13.0 Robotics

90% of biomass production in the greenhouses and manufacturing in the factories is automated. The mass and power required for automation are included in the MCD model. The details are described in the plan, but not described in this paper.

14.0 Sustainability and Supportability

Sustainability and supportability for the Mars colony consists of logistics systems, maintenance system, and repair system. The logistics systems consist of a production system, a recycle system, and a storage system. The maintenance system consists of a defect detector system and a spare parts production system. The repair system consists of only a repair parts production system. The production system, recycle system, and storage system are incorporated in the MCD model.

Table 2. Assumptions and conditions.

Items	Phase 1a	Phase 1b	Phase 2
Habitation area[10,15], m^2/person	25	25	100
Biomass production area[10,15], m^2/person	-	50	100
Power for living[15], kW/person	10	10	10
Power for food production[16], kW	-	25	25
Mass of power plant[10], kg/kW	40	40	40
LSS			
Water consumption for living, kg/person-day	10	30	100
Water produced by crops, kg/person-day	-	100	100
Oxygen[11], kg/person-day	0.84	0.84	0.84
Food[11], kg/person-day	2.51	2.51	2.51
Recycling ratio	0.9	0.99	0.99
Structure and system mass			
Mass of shield module[11], kg/m^3	-	133.1	-
Mass of unshield module[11], kg/m^3	-	-	9.16
Mass of dome (CNF and CFRP)[7,8,9], kg/m^2	-	-	1.064
Mass of LED[11], kg/m^2	-	7.5	3.75
Mass of biomass production system[11], kg/m^2	-	12.5	1.25
Ceiling height, m	3	3	10

Table 3. LSS mass and power baseline.[11,12]

Subsystems	Phase 1a			Phase 1b - Phase 2b		
	Fixed mass, kg	Logistics, kg	Power, kW	Fixed mass, kg	Logistics, kg	Power, kW
Air	846	28	1.41	653	28	1.32
Food	0	4073	0.00	321	149	0.00
Thermal	390	19	1.28	390	19	1.28
Waste	115	0	0.01	348	0	0.00
Water	1062	2206	1.36	141	3	0.00
EVA	196	757	1.00	196	757	0.00
Accommodation	35	3024	0.00	115	2131	0.63
Total, kg/6 persons	2644	10108	5.06	2164	3087	3.24
Total, kg/person	441	1685	0.84	361	514	0.54

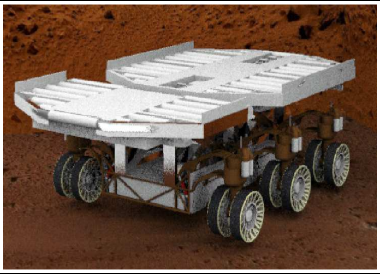
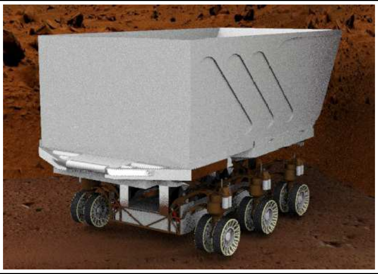
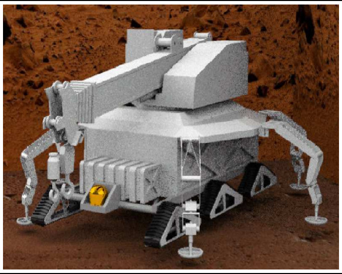
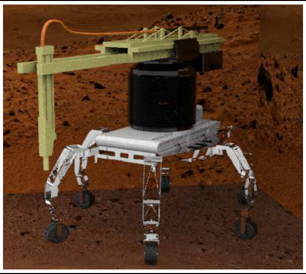
Table 4 (a). ISRU mass and power baseline.[6]

Processes	Unit feedstock rate	Mass, kg	Power, kW
CO_2 acquisition	1 kg/hr of CO_2	50	1.2
Sabatier conversion	1 kg/hr of CO_2	12.5	0.16
Water electrolysis	1 kg/hr of water	11.2	2.4
Liquefying O_2	1 kg/hr of O_2	35	1.1
Liquefying CH_4	1 kg/hr of CH_4	85	3
Regolith excavation and water extraction	1 kg/hr of water recovered	700	8

Table 4 (b). 1000 Mars colony ISRU mass, power, and unit.

ISRU	Mass, kg	Power, kW	ISRU unit
CO_2	958	50	0.24 mT x 4
H_2O	84,643	967	14.1 mT x 6
N_2	958	23	0.48 mT x 2
O_2	2,088	158	0.42 mT x 5
CH_4	1,200	37	0.24 mT x 5

Figure 2. Construction machine mass and power baseline.

		
Cargo Carrier[17]	Hauler[17]	Small MEV[17]
1.5mT, 8kW	2mT, 8kW	4mT, 10kW
		
Excavator with Bulldozer[18]	Crane Rover[19]	3D Printer[20]
4mT, 66.1kW	20mT, 30kW	6mT, 30kW

IV. Simulations and Design Results

The initial settlement plan and assumptions as shown in Tables 2 3, and 4 were used for calculating the Mars colony development plan. The population, area, power, total mass, mass transported from Earth, and ISRU production mass were calculated every two years. The cargo manifest from Earth and the delivery schedule were designed to produce resources, power, and biomass for the colony on Mars. Additional facilities and power for resource development and tourism were included in Phase 2.

In this paper, to what level of difficulty resource excavation would impact ISRU design and how sunlight irradiance value by sandstorms would impact the power system design were analyzed in view of minimizing cargo shipments from Earth. Our settlement scenario made by the MCD model is shown in Table 5. The population including 2% of natural growth of population, exceeds 1000 people at Year 36. The habitation areas, greenhouse areas, total mass, mass transported from Earth, and required power are 100,600 m^2, 107,400 m^2, 11,526 mT, 2,347 mT, 42,465 kW when sunlight cannot be used, and 20,921 kW when 100% of sunlight can be used respectively at Year 36.

The cargo manifest and launch manifest satisfying our settlement scenario as shown in Table 5 are shown in Table 6 and Table 7. There are five unused ships on Mars between Year 0 and Year 6 consisting of two crew spaceships and three cargo ships for habitat use in Phase 1 as shown in Table 7.

A cost comparison between the reusable spaceship and the single-use spaceship, used for transporting the cargo of the manifest, is shown in Table 8. The costs consist of Starship development, Starship production, tanker production, crew launch to Mars from Earth, cargo launch to Mars from Earth, and launch to Earth from Mars. The number of spaceships and the number of launches were determined to satisfy the necessary cargo volume for a reusable Starship and single-use Starship based on the cargo manifest.

The operating plans for both reusable and single-use modes are shown in Figures 3 (a) and 3 (b), respectively. Given the large amount of O_2 and CH_4 used to produce fuel for a cargo Starship returning to Earth, over a finite period of time, the operation plan must take into consideration a constant level of production volume. A reusable Starship to return crew to Earth is operated every two years after Phase 1b. As many as seven Starships will be accumulated on Mars for 2 years in Year 12 and Year 16. To reduce their number, the scale of ISRU and number of power plants would need to be larger in order to produce the required fuel. The number of Starships carrying cargo would also increase for shipping ISRU and power plant hardware. Starship operation, and in particular launches, have the biggest impact on mass transported from Earth.

The change in population is shown in Figure 4 (a). Though 100 people arrived at the Mars colony after Year 16 in Phase 2, only 72 people stay permanently in the colony. 2% natural growth of the population was assumed after Year 16.

The total mass required for the Mars colony is shown in Figure 4 (b). The solid circle (●) shows the Mars colony total mass by means of reusable Starships. The solid square (■) shows mass transported from Earth by means of reusable Starships. The empty circle (○) shows the Mars colony total mass by means of single-use Starships. The empty square (□) shows mass transported from Earth by means of single-use Starships. For reusable Starships, both the Mars colony total mass and mass transported from Earth are larger than for single-use Starships because the ISRU mass increased for producing fuel for returning the reusable Starships. However, the total cost for reusable Starships is less than that for single-use (ratio of single-use to reusable = 1.2 (=1.99/1.68) as shown in Table 8).

The production mass of H_2O, CO_2, and N_2 by ISRU is shown in Figure 4 (c). H_2O production for generating oxygen and CH_4 (methane), which are used as fuel for returning the ship back to Earth, drastically increases after Year 10 in Phase 2.

The evolution of power consumption is shown in Figure 4 (d). The solid square (■) shows required power on a sunny day. The solid triangle (▲) shows required power during a dust storm or at night (i.e. No sunlight). The solid circle (●) shows available power. It is sufficient to supply power required for photosynthesis in the case of no sunlight.

As the water extraction rate decreases and/or the distance to the mine increases from the ISRU sites, the mass ratios of ISRU and the power plants increase as shown in Figure 5. Power 2 shows twice the distance from the mine compared to Power 1. ISRU 2 shows twice the distance from the mine compared to ISRU 1. The power plant mass increased as the power consumption increased due to a longer distance trip, but the ISRU mass did not.

When the water extraction rate decreases from 1 (10% water content) to 0.2 (2% water content), a wider area of land must be excavated and the masses of ISRU and the power plants increase. The ISRU 1 and ISRU 2 mass ratios for regolith excavation and the land required for the water extraction process became approximately 4.3 times larger.

The Mars colony site plan is shown in Figure 6. 8 Greenhouse domes, 5 inflatable greenhouse modules, 2 crew Starships, 3 cargo Starships, ISRU, power plants, and roads are shown here. 5 Starships for habitation and 5 greenhouse modules are installed in Phase 1b, and 8 greenhouse domes (lower level contains habitats; upper level contains greenhouses) are constructed in Phase 2. The components and specifications are shown in Table 9. The final mass budget is shown in Table 10. 84% of total mass at the final stage in Phase 2 was structural mass. 5% of the structural mass which cannot be produced on Mars, was transported from Earth. All mass for power plants, biomass production systems, LED, life support systems, and construction machines were transported from Earth. Finally, 20% of total mass was transported from Earth.

Table 5. Cumulative numbers in settlement scenario.

Phase	Year	FY	Population	Habitation, m^2	Greenhouse, m^2	Total mass, mT	Mass from Earth, mT	Total power (0%), kW	Total power (100%), kW
0	0	2034	0	0	0	165	165	1,284	1,284
	2	2036	0	0	0	211	211	1,563	1,563
1a	4	2038	12	300	0	314	303	2,660	2,660
1b	6	2040	24	600	1,200	545	475	4,487	4,247
	8	2042	48	1,200	2,400	977	836	8,334	7,853
	10	2044	72	1,800	3,600	1,220	1,008	9,210	8,488
	12	2046	120	3,000	6,000	2,265	1,252	10,916	9,713
2a	14	2048	168	16,800	18,675	3,430	1,376	12,622	8,876
	16	2050	243	24,300	31,350	4,327	1,480	15,288	8,999
	18	2052	319	31,900	31,350	4,714	1,569	18,009	11,720
	20	2054	397	39,700	44,025	5,610	1,660	20,781	11,950
	22	2056	476	47,600	56,700	6,511	1,752	23,589	12,215
	24	2058	557	55,700	56,700	6,893	1,816	26,487	15,113
2b	26	2060	640	64,000	69,375	8,210	1,963	29,437	15,521
	28	2062	724	72,400	82,050	9,132	2,057	32,423	15,963
	30	2064	810	81,000	82,050	9,509	2,096	35,499	19,040
	32	2066	898	89,800	94,725	10,502	2,244	38,627	19,625
	34	2068	987	98,700	107,400	11,445	2,340	41,790	20,245
	36	2070	1,006	100,600	107,400	11,526	2,347	42,465	20,921

Table 6. Cargo manifest.

Year	ISRU					Power	Buildings		Construction machines				
	ISRU H_2O	ISRU CO_2	ISRU N_2	ISRU O_2	ISRU CH_4	Power plant	Green-house	Dome	Cargo carrier	Small MEV	Excavator with bulldozer	Crane rover	3D printer
	13.4mT	0.21mT	0.21mT	0.7mT	0.21mT	40mT			2mT	4mT	4mT	20mT	6mT
0	1	1	1	1		1			2		3	1	
2										2	3	1	1
4	1			1									
6	1	1			5		1			2			2
8	3	2		3			1						
10			1			1	1						
12							2	1					
14								1					
16								1					
18								1		2			
20						1							
22													
24								2		2			
26						1		1					
28													
30										2			
32						1		1					
34													
36													

Table 7. Launch manifest.

Year	Crew ships *1		Cargo ships *2		Unused	Stacked ships on Mars	
	Earth to Mars*3	Mars to Earth	Earth to Mars*3	Mars to Earth	ships on Mars	Reusable	Single-use
0	-	-	2	0	2	0	0
2	-	-	1	0	1	0	0
4	1	0	1	0	1	1	1
6	1	0	2	1	1	2	3
8	1	1	4	0		6	4
10	1	1	2	2		6	6
12	1	1	3	2		7	9
14	1	1	2	2		7	11
16	1	1	2	2		7	13
18	1	1	1	2		6	14
20	1	1	1	2		5	15
22	1	1	1	2		4	17
24	1	1	1	2		3	18
26	1	1	2	2		3	20
28	1	1	1	2		2	22
30	1	1	1	2		1	23
32	1	1	2	2		1	25
34	1	1	1	2		0	26
36	1	1	1	1		0	27
Total	17	15	31	28	5	-	-

*1 Super Heavy (1st stage) and Crew Starship (2nd stage). The empty mass: 85 mT, payload to Mars surface: 100 mT, cabin volume: 825 m^3, and propellant mass: 1,100 mT (CH_4: 240 mT and O_2: 860 mT)

*2 Super Heavy (1st stage) and Cargo Starship (2nd stage). The empty mass: 85 mT, payload to Mars surface: 100 mT, 1000 m^3 pressurized volume and 88 m^3 unpressurized volume, and propellant mass: 1,100 mT

*3 Tankers (2nd stage) are used in LEO for flights from Earth to Mars

Table 8. Cost comparison between the reusable Starship and the single-use Starship.

	Unit price (a)	Reusable		Single-use	
		(a) x (b)	Number (b)	(a) x (c)	Number (c)
Starship development	5.0.E+09 $	5.00E+09	1	5.00E+09	1
Starship production	3.4.E+08 $/ship	4.36E+09	13	1.01E+10	30
Tanker production	3.4.E+08 $/ship	5.70E+09	17	3.35E+09	10
Crew launch cost - Earth to Mars *1	7.0.E+06 $/launch	3.57E+08	51 (17x3)	3.57E+08	51 (17x3)
Cargo launch cost - Earth to Mars *2	7.0.E+06 $/launch	1.09E+09	155 (31x5)	1.05E+09	150 (30x5)
Launch cost - Mars to Earth *3	7.0.E+06 $/launch	3.01E+08	43	1.05E+08	15
Total cost, $		1.68E+10		1.99E+10	

*1 A Starship is refueled by two tankers in LEO. 17 spaceships land on Mars.

*2 A Starship is refueled by four tankers in LEO. 31 or 30 spaceships land on Mars. *3 No refuel in Mars orbit.

Table 9. Mars colony components and specifications.

Components	Numbers	Specifications
HAB	5	2 Crew Starships and 3 Cargo Starships are used for habitat, and the total volume is 4,125m^3 (825 m^3 x 5).
Greenhouse	5	Area 6,000 m^2 (1,200 m^2 x 5), volume 18,000 m^3 (3,600 m^3 x 5), Inflatable
Greenhouse dome	8	Radius of the Domes 1-8: 65 m, 80 m, 65 m, 120 m, 80 m, 100 m, 100 m, and 65 m, upper contains greenhouse, lower contains habitat
Power plant	5	Nuclear 10 MW, 40 mT
ISRU	4 6 2 5 5	ISRU CO_2, mass 0.24 mT, power 12 kW ISRU H_2O, mass 14.1 mT, power 161 kW ISRU N_2, mass 0.48 mT, power 11 kW ISRU O_2, mass 0.42 mT, power 32 kW ISRU CH_4, mass 0.24 mT, power 7 kW
ECLSS	1000	In transit: Mass 519 kg/person Phase 1b: Mass 441 kg/person, Power 0.84 kW/person Phase 2: Mass 361 kg/person, Power 0.54 kW/person
Biomass production system	1000	Phase 1b: Mass 7.5 kg/person, Power 25 kW/person Phase 2: Mass 3.75 kg/person, Power 25 kW/person
Construction machine	2 10 6 2 3	Cargo carrier, mass 1.5 mT, power 8 kW Small MEV, mass 4 mT, power 10 kW, 6 rovers for tourism Excavator with bulldozer, mass 4 mT, power 66.1 kW Crane rover, mass 20 mT, power 30 kW 3D printer, mass 6 mT, power 30 kW

Table 10. Mass budget.

Subsystem	Final mass in Phase 2, mT (a)	a/b	Mass from Earth, mT (c)	c/a
Structure	9,650	0.84	471	0.05
Power plant	200	0.02	200	1.00
Greenhouse	209	0.02	209	1.00
LED	448	0.04	448	1.00
ISRU	530	0.05	530	1.00
LSS	363	0.03	363	1.00
Construction machine	126	0.01	126	1.00
Total	11,526 (b)	1.00	2,347	0.20

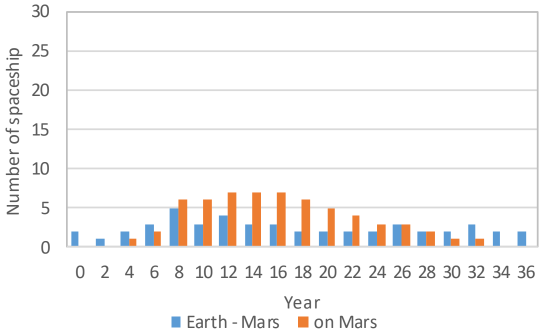


Figure 3 (a). Number of Starship in reusable operation.

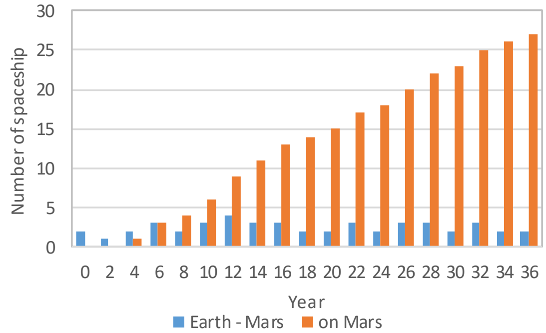


Figure 3 (b). Number of Starships in single-use operation.

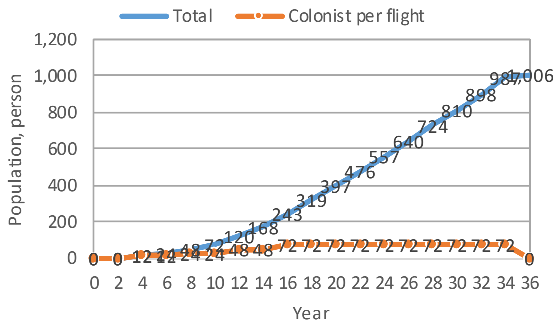


Figure 4 (a). Change in population.

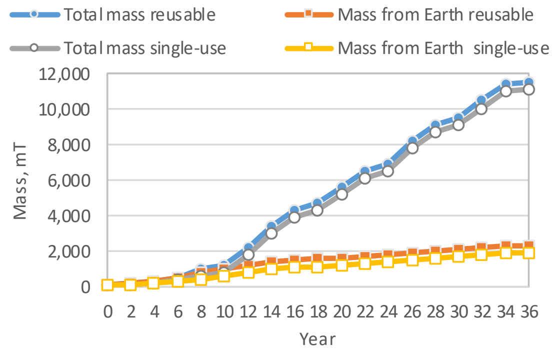


Figure 4 (b). Cumulative mass of Mars colony.

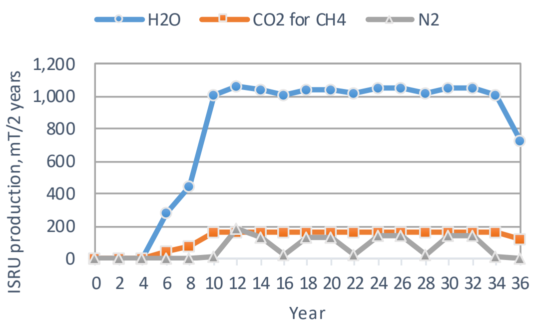


Figure 4 (c). ISRU production mass in reusable operation.

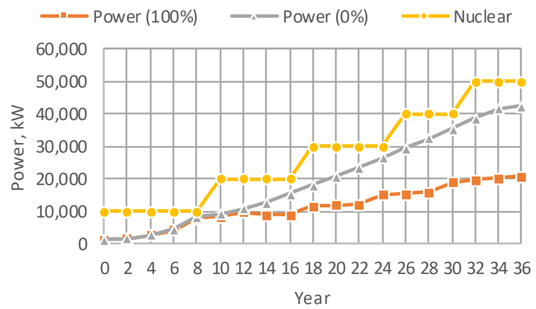


Figure 4 (d). Change of power consumption in reusable operation.

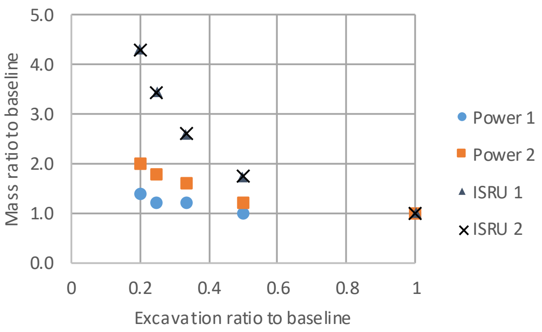


Figure 5. Mass ratio of ISRU and power plant.

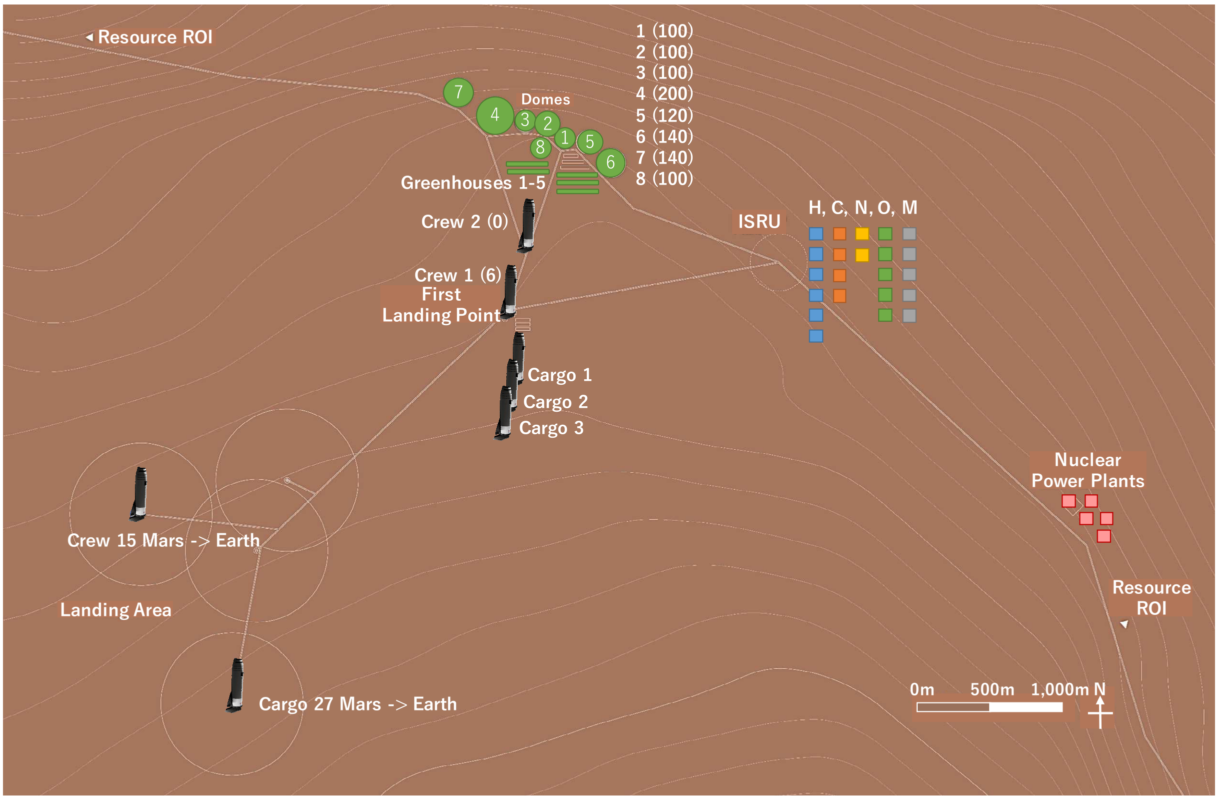


Figure 6. Mars colony site plan.

V. Conclusion

In this study, the MCD model was developed to analyze a Mars colony development schedule that took into consideration mass transported from Earth, resources on Mars, total energy, and total cost (transportation cost). The population is expected to exceed 1000 people at Year 36. The habitation areas, greenhouse areas, total mass, mass transported from Earth, and required power when sunlight cannot be used and required power when 100% of sunlight can be used at Year 36 are 100,600 m^2, 107,400 m^2, 11,526 mT, 2,347 mT, 42,465 kW, and 20,921 kW, respectively. Levels of difficulty in resource excavation and their impact on ISRU design was analyzed in view of minimalizing the number of cargo shipments from Earth. Wider areas of land must be excavated when water extraction rates decrease and the masses of ISRU and number of power plants naturally increase. ISRU mass for regolith excavation and land for the water extraction process becomes multiple times larger. The available power supply is sufficient enough to provide power on a sandstorm day or at night. It can supply the power required for photosynthesis when there is no sunlight.

The year 2400 Mars colony prediction:

In 2400, 431 years will have passed since 1969, when the first human beings landed on the lunar surface. 117,000 people will be living on Mars[21] as well as 3,000 people on the moon and asteroids. The Mars colony named "Arche Thales" will become a space oasis for people working in the Mars-Asteroid Development Public Corporation, providing food, water, machine maintenance, fuel, medical services, and entertainment. The construction of the first Mars colony at Endeavour Crater will commence with the use of robots in 2034. The first 12-person colony will begin living on Mars in 2038. A mission of colonists will be sent to Mars every two years. Infrastructure on Mars will be set up to support the first gateway city. When the first 72-person non-professional colonist group arrives in 2050, the population will rise to 243 people. After that, more immigrants will continue to arrive every two years and the population will exceed 1000 people in 2070. The MCD model makes this kind of story feasible.

References

[1]The Mars Society, Mars Colony Prize, http://marscolony.marssociety.org/, accessed Feb. 27, 2019.

[2]Bussey, B. and Hoffman, S. J., Human Mars Landing Site and Impacts on Mars Surface Operations, *2016 IEEE Aerospace Conference*, 2016.

[3]Meadows, D. H., Randers, J., and Meadows, D., *Limits to Growth*, Chelsea Green Pub Co, 2004.

[4]Gerald, S. B., In-Situ Resource Utilization on Mars - Update from DRA 5.0 Study, *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, AIAA 2010-799, 2010.

[5]Rapp, D., et al., Preliminary System Analysis of In Situ Resource Utilization for Mars Human Exploration, FY04 Report, JPL D-31341, Oct. 25, 2004, revised Jan. 25, 2005.

[6]Rapp, D., *Human Missions to Mars: Enabling Technologies for Exploring the Red Planet*, Praxis Publishing Ltd., 2008.

[7]Nippon Paper Group, Cellulose nanofibers (CNF): cellenpia, https://www.nipponpapergroup.com/products/cnf/, accessed Feb. 27, 2019.

[8]Asahikasei, Nanoleaf, http://www.asahi-kasei.co.jp/fibers/nanoleaf/, accessed Feb. 27, 2019.

[9]Komatsu Matere Co., Ltd., CABKOMA Strand Rod (CFSR), https://www.komatsumatere.co.jp/cabkoma/en/, accessed Feb. 27, 2019.

[10]Mole, A., Baseline Design for a Mars Colony, http://marscolony.marssociety.org/MARSColonyi2.pdf, accessed Feb. 27, 2019.

[11]Hanford, A. J., Advanced Life Support Research and Technology Development Metric - Fiscal Year 2005, NASA/CR-2006-213694, 2006.

[12]Hanford, A. J., Advanced Life Support Baseline Values and Assumptions Document, NASA, CR-2004-208941, 2004.

[13]Appelbaum, J., and Flood, D. J., Solar Radiation Mars, NASA TM-102299, 1989

[14]SpaceX, https://www.spacex.com/mars, Starship and super heavy, accessed Feb. 27, 2019.

[15]O'Neill, G. K., et al., *Space Resources and Space Settlements*, NASA SP-428, 1979.

[16]Kozai, T., *Sunlight Plant Factory - Sustable Design of Advanced Plant Factory*, ohmsha, Tokyo, 2009.

[17]Zakrajsek, J. J., Exploration Rover Concepts and Development Challenges, *First AIAA Space Exploration Conference*, AIAA-2005-2525, 2005.

[18]Komatsu Ltd., https://home.komatsu/en/, accessed Feb. 27, 2019.

[19]Tadano Ltd, https://www.tadano.com/, accessed Feb. 27, 2019.

[20]3DPRINT.COM, https://3dprint.com/189228/cazza-3d-print-construction-robots, accessed Feb. 27, 2019.

[21]Miyajima, H., et al., Mars Colony Design - Self-Sustainable Smart City Design on the Red Planet, *Mars Colonies: Plans for Settling the Red Planet*, Mars Society, 2019.