Nüwa, a self-sustainable city state on Mars – development concept, urban design and life support

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Mars is one of the current targets for human space exploration. The first settlement will most likely include a small group of explorers, but with time, it is reasonable to assume that a city on Mars might grow and become a reality. *Nüwa* is a project of the Sustainable Off-world Network (SONet), a network of interdisciplinary and international professionals, dedicated to the development of sustainable human settlements beyond Earth. This project focuses on engineering and architecture, but also on sustainable growth planning of a society on the red planet. The design consists of five cities, with 200,000 inhabitants each. Different locations strategically selected ensure in-situ resource utilization. The city concept is based on a tunneling system on cliffs. The design of a big city in the harsh Mars environment poses several challenges and is a complex and broad task. Further research in all fields is required. This paper focuses on three aspects of the design: development concept, urban planning and Life Support. The city needs to provide a safe environment for the inhabitants, but also provide all required services and a practical and enjoyable place to live. This imposes challenges to the resilience of the system and the availability of resources as well as construction methods suitable for installing the desired infrastructure. The Life Support System consists mainly on biological elements, and its integration within the city is crucial, as it provides oxygen, water and food. Finally, the size of the city requires a sustainable growth plan, regarding materials and energy. As a result of this study, a first order of magnitude of the local resources to be incorporated per inhabitant is estimated, setting the baseline values for key quantities to be considered in future studies.

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Nomenclature

AI	=	Artificial Intelligence	*LSS*	=	Life Support System
CU	=	City Unit	*MEP*	=	Mechanical, Plumbing & Electrical
ISS	=	International Space Station	*SONet*	=	Sustainable Off-world Network

I. Introduction

Humanity has proven its ability to explore the Solar System and live permanently in Low Earth Orbit. A number of probes have been exploring the Solar System for decades, some of which even reached interstellar space[1]. The International Space Station (ISS) has demonstrated that permanently maintaining and occupying an orbital space station for more than 20 years is also viable[2]. These endeavors are, however, not self-sustainable as they still partially rely on supplies from Earth. Therefore, the next challenge is to ensure humans are able to live in another world in a sustainable and independent manner. Given current technologies, the most viable options for human settlements are the Moon, some asteroids and Mars[3]. From these, Mars seems the best fit to attempt a self-sustainable settlement, as it has some conditions which are similar to those on Earth (*e.g.,* very similar day length), it is relatively close, and it contains the basic elements needed to support a human settlement[4].

Nüwa is a concept design for a self-sustainable settlement on Mars prepared by the Sustainable Off-world Network (SONet) for the Mars Society competition 2020[5]. SONet is an interdisciplinary network of professionals in the public and private sector, enthusiastic about space, comprising aerospace engineers, biologists, architects, mining engineers, geologists and more. SONet aspires to link these disciplines to successfully develop concepts for sustainable human presence in space, but also looking beyond space applications. If starting a society in space is possible, Earth problems can be solved as well[6].

The Mars Society announced the competition in February 2020. It asked for designs of a 1Million inhabitants city-state on Mars (with the possibility of using more than one location). The city (or cities) had to be "self-supporting to the maximum extent possible", "be able to both produce essential bulk materials (...) and fabricate them into useful structures". Participating teams were asked "to design an economy, cost it out and show that after a certain initial investment in time, money and effort, that it can become successful"[5]. The competition attracted 175 teams from all over the world. The SONet project, *Nüwa*, ranked top 10 and was invited for a presentation at the finals in October 2020[7,8].

The result of the *Nüwa* project is an integrated design of a development plan, including the production of raw materials and essential products, and the manufacturing of almost all goods on Mars, as well as a full political and societal concept detailing the economic model, education, recreational capacities, and even solutions for birth and death of the citizens of *Nüwa*. This paper briefly describes the *Nüwa* concept (Chapter II), and focuses on three main aspects: its basic development model (Chapter III), the urban planning approach (Chapter IV), and the Life Support System (Chapter V). More information regarding the *Nüwa* design, including some systems not mentioned in this paper can be found in the project report[9].

II. The *Nüwa* concept

Nüwa, in Chinese mythology, is the mother goddess held responsible for the creation and protection of humanity. The project *Nüwa* aims to develop a settlement on Mars, to create and protect the first society in the red planet. Mars is a harsh environment, and not yet fully explored. This chapter aims to highlight some of the main characteristics of the *Nüwa* concept before going into detail on the development concept, urban planning and Life Support Systems (LSS) in the following chapters.

A. Constrains and assumptions

Mars' gravity is not too dissimilar to that on Earth, approximately 1/3 of it, and its solar day is only about 2.7% longer than Earth's[4]. Unlike other Solar System planets, Mars can provide the raw materials required to support a human settlement. Besides the carbon-rich atmosphere, Mars is also rich in water, mostly as permafrost and in clays, vital to sustain life and source of hydrogen. Oxygen and silicon are also abundant on Mars's surface[10,11], and Curiosity Rover has found biologically useful Nitrogen[12]. Phosphorus, Chlorine and Sulfur are within other critical elements found in Mars. In addition, various of these elements are likely to be concentrated in high-grade ores by the effect of ancient volcanic and hydrologic processes[10].

The design of a Mars settlement will be highly influenced by Mars environmental conditions. Mars atmosphere is mainly composed by Carbon Dioxide (CO_2), containing almost no Oxygen (O_2) and its pressure on the surface is less than 1% that of Earth. The combination of a thin atmosphere and a lack of magnetosphere exposes the surface of Mars to much higher levels of radiation and cosmic rays than that of Earth. Mars receives less irradiation from the Sun than the Earth, 590 W/m^2 and 1000 W/m^2 respectively[13]. Additionally, its orbital eccentricity results in broad differences between the irradiation received at the aphelion (furthest distance from the Sun) and the perihelion (closest distance to the Sun), which translates in a temperature range of 170-240 K at mid latitudes. These low temperatures make it impossible to find water in liquid form. In addition, there is a non-negligible flux of micrometeorites that reach its surface and sand storms can last for weeks[14,15,16].

All these factors and the constraints imposed by the Mars Society competition set the frame for the design. In addition, some assumptions and design principles needed to be adopted. The main are (1) this is a development plan using local resources, so except for the initial deployment phase, the settlement's growth should be self-sustainable (using local resources and manufacture only —which protects the design from problems on Earth), (2) the design should be resilient and it should use current science and existing (or almost existing) technologies, (3) the timeframe for the growth of the settlement is arbitrarily set to 50 years which is a reasonable time-scale for the growth of cities also on Earth, and (4) the city must be an attractive place to live.

For the development model to work, all the material cycles and costs must be designed following standards of circular economy and avoiding any energy losses. That is, once a material is integrated into the system, it shall not leave it, and materials with low embodied energy are the preferable choice when possible. With these principles, a safe and good living standard for the population must be maintained and mechanisms for individual and collective improvement granted.

B. Interdisciplinary design

The aim of this project goes beyond envisioning the infrastructure required for a Mars city, from an architectural and engineering point of view. As previously mentioned, self-sustainability and creating an attractive place to live are key elements on the design. Therefore, the entire process includes different disciplines, for example geology (regarding Mars available resources), material science and engineering (obtaining and processing these resources), orbital mechanics (transportation between Earth and Mars), biology (living organisms in the system). Besides those technical disciplines, socio-economical aspects are also very relevant. Education, political and economic organization have also been considered, among other aspects in the design of *Nüwa*. Further information on energy supply, communication, ground transport, social welfare infrastructure, culture and education, manufacture, chemical transformation, among others, can be found in the *Nüwa* report[9].

Figure 1. View of Nüwa. *This side view shows the cliff wall with several living compartments ("light" points in the wall) and the infrastructure in the valley. Credits: ABIBOO Studio / SONet.*

C. Construction inside the cliffs of Mars

One of the most characteristic features of this project is the construction of the city excavated in the cliffs, Figure 1. This architectural solution, discussed in more detail in Chapter IV, provides structures that protect inhabitants from the radiation on Mars, ensure indirect access to sunlight, protect from potential impact from micrometeorites, and solve the atmospheric pressure difference between the inside and the outside of the buildings.

From the urban point of view, building inside the cliff offers large advantages versus building underground in other locations, such as lava-tubes or craters. Thanks to the geological composition of a cliff, it is possible to create a denser three-dimensional urban net, reducing substantially the space and the resources required for transporting humans, life-support systems, and goods inside the city. A dense urban net is very important for a large settlement as it saves space and resources in the infrastructure required to connect the different areas in the city.

Additionally, excavating a city in Martian cliff walls is a safe solution since the high geological density guarantees good structural behavior and, in addition, Mars does not show relevant seismic activity[17].

D. Location – Multiple cities concept

In Mars, there is a trade-off between accessible water and access to Solar energy. The closer to the pole, the more accessible the underground water (permafrost) is, but the lower the energy influx. There are also regions that are rich in water bearing clays at mid-to-equatorial latitudes. In addition to this, the *Nüwa* approach requires the presence of cliffs with strong consolidated rock for the human dwelled spaces (the requirement on the slopes can be reduced, but not the strength of the ground to avoid large overheads in structural materials). With the current available data from Mars, it is not possible to select a precise optimal location. A detailed analysis of published data, has allowed the selection of potential targets, which should be analyzed in more detail in the future.

This project proposed five different locations. Considering five cities allows access to resources located in different places and offers redundancy for the inhabitants on Mars, should a problem occur in one location. The first proposed settlement is *Nüwa*, the capital, located in a region called Tempe Mensa, which stands in the middle of a riverbed at the shore of the ancient Martian ocean. In this location, the primary source of water would (initially) be clays, but frozen aquifers might be available at a few tens of meters below ground. The presence of past water circulation through the area also provides good prospects of mineral deposits and concentration of metal ores. A second urban center should also be developed within the first general area, to both optimize key resource extraction, and improve resilience against urban center wide incidents. A third location for a city could be in the Vallis Marineris area, which also has abundant cliffs, evidence of past water circulation and satellite confirmed presence of iron rich deposits (water might be too deeply buried for efficient extraction in a first settlement). To enable large-scale development of the city, a settlement close to the pole is also desirable to mass extract the necessary amounts of water from surface ice. This polar city would require further technology development since it is likely to require well-developed nuclear power generation system. The fifth city could be located in any other region with key strategic resources and/or peculiar landscape possibilities (*e.g.* rim of Olympus Mons).

III. Development concept – sustainable growth

Placing a city on Mars requires considering how it should be developed over time. Moreover, given the harshness and difficulties of the environment, the development itself shall be a key element of its nascent economy. For example, it is rather inefficient and unrealistic to assume that a large number of machines can be deployed at a certain point and that those machines would linearly build the city. As it happens on Earth, the larger the community (or economy), the more productive it becomes. Reinvesting surpluses in development infrastructure will allow a faster growth.

A. Growth model

For this project's model, a production and, therefore, a growth rate, proportional to the number of inhabitants is assumed, once a certain level of infrastructure complexity is achieved, and following the principle of self-development[18]. The requirement on the production rate can be set by estimating how many resources need to be collected, processed and how much infrastructure needs to be deployed to include one citizen to the city, which we call a City Unit (CU). The definition of the development process first requires generating an inventory of components in each CU (*e.g.* square meters per citizen, number of hospital beds, services). This required-CU needs to be mapped into Martian resources first, and then into operational requirements, such as energy and resource extraction rates. On top of this, maintenance cost (at least in terms of energy) to keep the city alive, even if there is no growth, need to be added. This process requires the development of all systems and subsystems in the city, including among other the LSS and the urban development.

Following this approach, the development is defined by Equation 1, where N is the number of citizens (or CUs), T is a characteristic time-scale, and N_i is the number of CUs imported from Earth. This equation can be trivially integrated and produces an exponential growth, Equation 2. N_0 (the initial population) and the time-scale T are parameters to be fixed by the boundary conditions. For all practical purposes, it is sufficient to assume that the import rate N_i is smaller than N_0 by about one order of magnitude, and represents the imported goods necessary to repair or assemble key systems in the first years of development.

$$\frac{dN}{dt} = \frac{1}{T}N + \frac{1}{T}N_i \qquad (1) \qquad\qquad N(t) = (N_0 + N_i)\, e^{t/T} - N_i \qquad (2)$$

Figure 2 shows the resulting city growth, following this exponential law. Using the constrains assumed in the previous section as boundary conditions, an initial population $N_0 = 1{,}000$, and a final population $N(t = 50\ yr) = 10^6$, the typical time needed to grow the population by a factor *e* can be found. By direct substitution of this values in Equation 2, we find T ~ 8 years, which is also equivalent to a population doubling time of 5.5 yr, with a weak dependence on the precise value of N_i. This growth rate requires each existing CU (and citizen) to contribute to the construction of 0.12 CU per year. Those CU consist of infrastructure, tools and materials that are constantly circulating within the city and, as happens on Earth, they will degrade overtime and will require maintenance. Assuming that each CU needs need to be fully renovated every 20 years (this would be a requirement for any machine or infrastructure of the city), 0.06 CU/yr need to be added to the construction rate, leading to a minimum production rate of 0.126 CU/yr per citizen.

This growth model is accompanied by a robust and scalable Earth-Mars transportation system, capable of guaranteeing the flow of immigrants to sustain Nüwa's development, which can be found in the report[9].

The growth model leads to three natural development phases shown in Figure 2. In phase 1, the imports still dominate over the local growth rate. After a certain time (about a decade), the exponential curve would need to take over (phase 2). Finally, the exponential growth needs to stop to avoid having a lot of useless development infrastructure once the target final population is achieved (phase 3). In this third phase, the activity can shift from development to a more diversified economy (*i.e.* services to improve welfare).

The three phases would also benefit from evolving organizational structures. In phase 1 the development and work need to be highly organized and efficient (population is still small) possibly resembling the operations of a large company or a remote Earth base. Once entering the second phase, local citizens should be able to decide on local governance matters, and a system of rules specifically adapted to the Martian city reality. Especially in the third phase, and with the lower pressure into the development sector, the economic activity should further diversify thus producing a rich self-developing Martian society and culture, and a fully developed quasi-independent government.

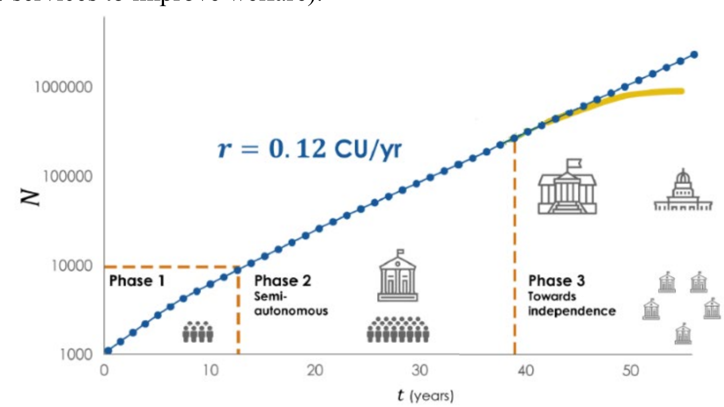

Figure 2. Time-line of *Nüwa*'s growth *as presented in Eq. 2 model together with important political organizational milestones.*

This growth model is over simplistic, but it is a first step to produce a conservative zero-order approximation of what to expect, and plan accordingly. The city can survive and grow as long as the design ensures a growth rate larger than the decay time of a CU. Improvements and refinements to the model should include more sophisticated scaling laws for CU production. An example could be assuming $\frac{dN}{dt} = \frac{1}{T}N^{\alpha}$,with $\alpha > 1$ due to economies of scale, and the role of experience and local innovation[19]. Further evaluation of a more complex growth model would be required in a more detailed future study.

B. Resources from Mars

If a city is supposed to develop autonomously and self-sufficiently, all its systems, parts, living organisms, buildings, and services need to build from local resources only. However, a seed infrastructure still needs to be deployed first. Defining how to exactly deploy this seed infrastructure is very important but it is out of the scope of the current exercise, which focusses on the growth from this initial seed up to the 1M inhabitants. To assess the feasibility of the design, an inventory of all the physical assets that need to be incorporated to the infrastructure for adding a person to the city is required. We implicitly assume a circular economy, where all incorporated materials remain in the system. The design of such industrial, human and biological ecosystem is out of the scope of this study. However, to facilitate this at the inventory level, we assume a minimal diversity of metals and other materials to the bare minimum. These include in order of most consuming to less: food production areas, living quarters and city infrastructure, energy production and distribution and welfare state facilities (including public buildings, hospitals, parks, etc.). The budget also includes biomass, air, water and nutrients required to sustain each human under the assumptions given in the LSS chapter. At very high level, the practical approach to derive this inventory can be summarized in 3 steps:

- Step 1: List all required items and estimate material costs based on Earth manufacturing and construction standards.
- Step 2: Map each of the Earth materials into the Martian equivalent ones. Minimizing material diversity allows improved reusability, recyclability and greatly reduces manufacturing complexity. This mapping should also resource collector machines that can be summarized as: pumps for atmosphere capture (CO_2, and other gases) and mining hardware (road headers and surface miners), and match their number to the required amount to meet the target growth rate of 0.126 CU/yr. A budget of average power needed to process all materials using the reference tables[20], needs to be included. Processing power overheads due to additional difficulties of working on a harsher environment than on Earth also need to be taken into account at this point.
  Key different processes adapted to Mars are those needed to start carbon-based value chains, such as conversion of CO_2 into syngas (Reverse Water Gas Shift reaction) and methane (Sabatier process) into more complex hydrocarbons. Water electrolysis shall also be used to produce hydrogen to be used in numerous value chains as well. Molecular oxygen is always produced as a byproduct of H, C, and metal smelting, so huge surpluses of it are always obtained. Metal extraction would mainly consist of iron processing and smelting using thermal reduction with Hydrogen (which is not consumed), thus minimizing the use of specialty metals (Aluminum, Titanium, Copper or Tungsten needed in smaller amounts).
- Step 3: Addition of reforming, manufacturing and finishing energy overheads using estimates for light, medium and heavy industry and imposing the production rate of 0.126 CU/yr per citizen.

Since the energy infrastructure also requires energy and materials to build-up itself, this process needs to be solved iteratively as illustrated in Figure 3. For *Nüwa*, the end result of this iterative procedure results on a total power consumption for CU of 117 kW, which includes the LSS power needs to support the humans (about 37 kW). Despite this number is subject to large uncertainty (it strongly depends on key processes such as metal smelting, and polymer, semiconductors and advanced organics manufacturing) it is a key indicator of the difficulties of operation in Mars compared to Earth (the value on Earth is approximately 10 - 30 kW). It is also important to remark that the procedure can be updated and implemented in other situations as technologies evolve and more realistic operational costs are obtained via experiments and demonstrators. A summary of the most relevant resources and work materials is given in Table 1.

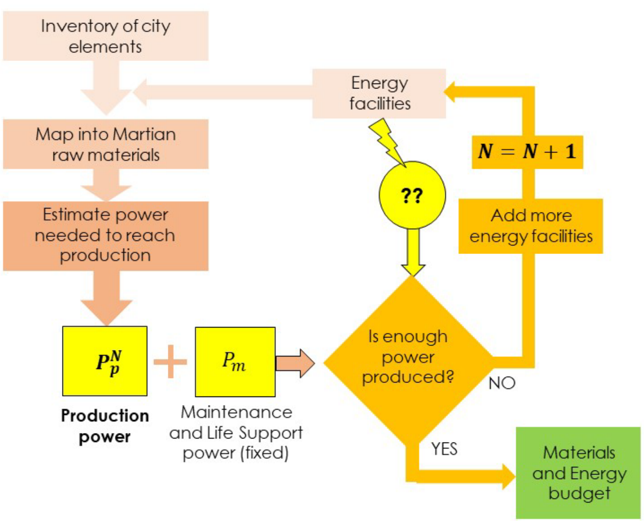

Figure 3. Iterative Materials and Energy budget estimation process.

Table 1 *Nüwa* main materials, both raw and transformed.

Raw material	Tons/CU
H_2O (from clays)	84
CO_2 (from atmosphere)	114
N_2 (from atmosphere)	2.2
Ar (from atmosphere)	3.1
O_2 (by-product)	(126)
Rock (mined)	300
Clays (mined)	1000
Transformed material	**Tons/CU**
Gravels and concrete	311
Simple mineral derivatives	36
Iron and steel	60
Polymers and organics	36
Speciality metals	7.8
Advanced materials	8.9

IV. Urban planning

The urban design, as previously explained, includes five cities, with *Nüwa* as their capital. Each city accommodates about 200,000 people. Aside from *Nüwa*, the rest of the cities follow the same urban strategy, such as Abalos City, located in the North Pole to leverage the access to ice, or Marineris City, located in the most extensive canyon of the Solar System. The solution, a city excavated in the cliffs, is a flexible and scalable model that could be easily applicable in many other Martian surface areas. The city of *Nüwa* is on the slope of one of the Martian cliffs with abundant water access, located at Tempe Mensa. A steep terrain offers the opportunity to create a vertical city inserted into the rock.

As mentioned in Section II.C, the construction inside the cliffs protects inhabitants from radiation and micrometeorites, and provides indirect sunlight. It also solves the pressure and temperature differences between the inside and the outside. Figure 4 shows a conceptual section of the cliff, which contains: the wall, the valley and the mesa.

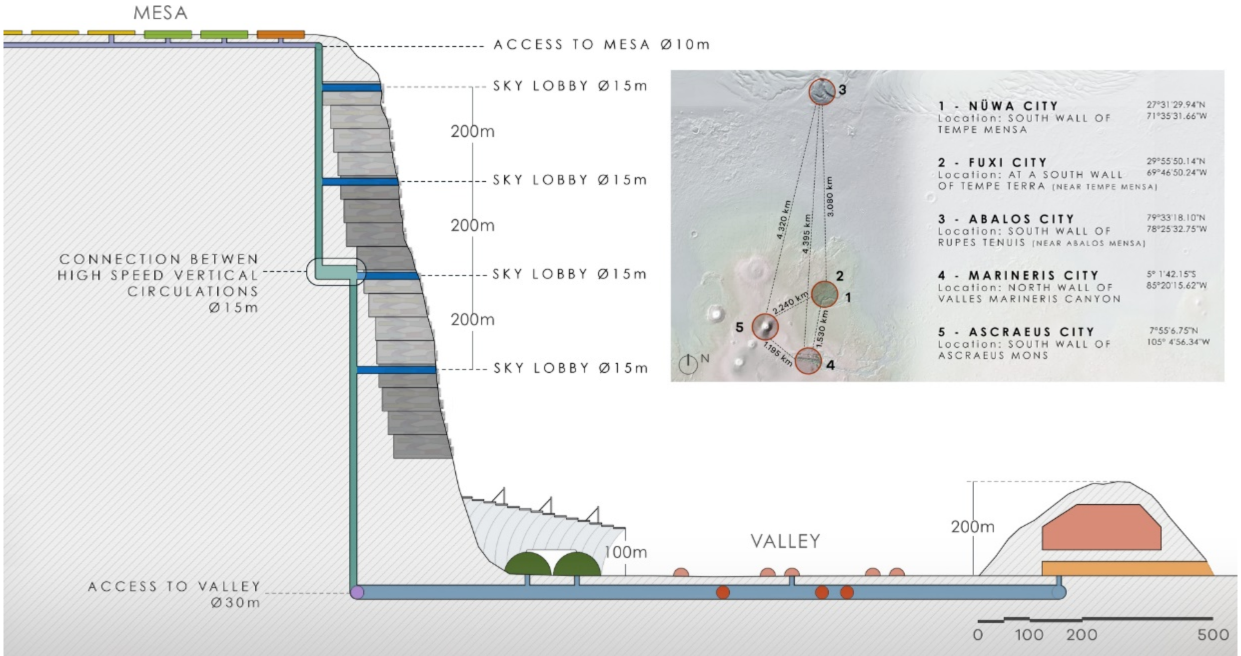

Figure 4. Conceptual section of the cliff, and location of the five cities proposed

A. The wall

The "Macro-buildings", with a total volume of 125,000,000 m^3 per city, are excavations inside the rock of the cliff. These constructions, implemented after tunneling, are modular and include residential and work activities, linked together by a three-dimensional network of tunnels. Each Macro-building accommodates 4,440 people and is self-sufficient for the day-to-day activities on Mars.

The modules that create these buildings include tunnels of 10 meters in diameter and 60 meters long, with two floors. There are three different residential and three work modules, providing a highly flexible and scalable opportunity by recombining the modules as needed, as it can be seen in Figure 5. By giving this standardization, the design ensures scalability and reduces complexity, costs, and construction schedules. All modules include green areas and urban gardens, spaces dedicated to art, and condensation areas, called "Snow-domes", that help dissipate heat and clean the air. The urban gardens are small community parks with animals and bodies of water designed to provide physical and psychological well-being. To create an emotional linkage with Earth, the design team has included vast, artificially created natural spaces in *Nüwa*. They are named "Green-domes", and there are two types: those that allow human presence and act as parks, and those that include experimental vegetation in an environment with a purely Martian atmosphere. As each macro-building is self-sufficient, the population in *Nüwa* can grow as needed. The first colony can be as little as 4,440 people and it can grow while the rest of the city is built. The city is expected to be completed after 50 years, when its population will reach 250,000.

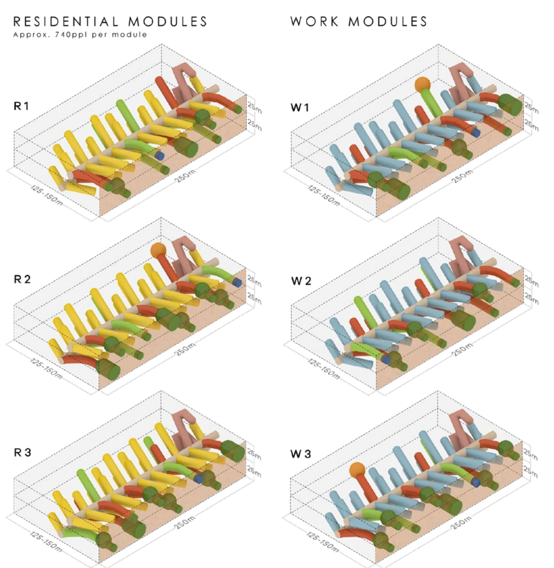

Figure 5. Typical modules in a "Macro-building".

The "Macro-buildings" on the cliff are connected by high-speed elevator systems, similar to skyscrapers on Earth. This infrastructure also connects the bottom of the cliff with the top, and has intermediate stops at the "Sky-lobbies" that connect the "Macro-buildings" with a separate elevating system.

B. The mesa and the valley

The highest point of the cliff is the Mesa. This vast plain contains the infrastructure dedicated to manufacturing, food production, and energy generation. At the foot of the cliff, large pavilions have been located for social interaction in the Valley. These pavilions have been designed with translucent skin to offer views of the landscapes of Mars. These domes are protected from external radiation by large overflying canopies. The material from the cliff's excavation is dumped (*i.e.* directly reused) on top of such roofs as radiation shield. This strategy avoids waste management at a large-scale. In the valley, there are also specific structures to house hospitals, schools and universities, sports and cultural activities, shopping areas, and train stations that communicate with the space shuttle. An artificial mountain created with additional material extracted from the excavations acts as a visual frame for the city and to decrease the fluctuations of temperature. It includes auxiliary energy systems, storage, and parking spaces for rovers and intra-city trucks.

C. The activities and built areas

In addition to buildings to live, work, educate, and facilitate social interactions, a human settlement on Mars also requires structures to fulfill the essential functions of air, water, and food production. In *Nüwa* and its adjacent cities, all the architectural constructions include additional safety aspects to regulate the internal atmospheric pressure and offer refuge zones for emergency cases. Several common spaces act as firebreaks and shelter for citizens until rescue units' arrival in case of an emergency. Air showers have been placed at each "Macro-building" entrance to clean and sterilize as health protection measures. Artificial Intelligence (AI) will also play an essential role in *Nüwa*'s building standards to help maintain optimal conditions and minimize risks.

Table 2 shows a broad estimation of the floor area and volumes per person of different infrastructure of the city.

These values are obtained by measuring the diversity of spaces in the city, which have been planned based on the *Nüwa* architectural team experience and the restrictions of building inside the rock (e.g. a certain distance between tunnels is required).

Some of the spaces in the city are suitable for humans while others require special equipment. The total built-up area of the city is 55.6 million m^2, which is equivalent to 278 m^2 per person, where 162 m^2 are related to spaces suitable for humans and the rest are for supporting areas. As a qualitative reference, the ISS has an habitable volume of 65 m^3 per person (for the usual crew of 6)[21].

Table 2. Built-up areas and buildings volume in *Nüwa* (Total population 200,000 people).

	Floor area (m^2/person)	Volume (m^3/person)
Volume of spaces suitable for humans in Nüwa		
Macro-buildings (in the wall)	150	625
High-Speed Elevator System + Sky-lobbies (in the wall)	0.625	125
Tunnel-Gardens (Valley)	1	10
Galleries & Arcades (Valley, underground)	12.35	115
Pavilions (Valley)	1.25	22.5
Low-Impact Industrial Buildings (Mesa)	3.75	37.5
Space Shuttle hub (nearby crater)	0.4	2.5
Volume of spaces not suitable for humans in Nüwa		
MEP domes & Snow-domes (in the wall), MEP Pavilions	22.5	225
Energy Buildings (Mesa) (Area for solar panels not included)	1.5	15
Agricultural Buildings (Mesa)	75	450
High-Impact Industrial Buildings (Mesa)	5	50
Storage and Support Buildings (Valley, artificial mountain)	5	12
TOTAL:	278.4	1689.5

On Earth, Manhattan, with a peak of 2 million people per day, has an approximate of 260 million m^2, including buildings, related civil infrastructure, and outdoor breathable areas, like streets and parks. Therefore, a highly dense urban development like the "Big-Apple" can be associated with an approximate of 130 m^2 per person. This area does not include all the required spaces for agriculture, industrial, and energy production. On Earth, the surface occupied by these spaces would be substantially higher than the 116 m^2 per person required in *Nüwa* and are usually not situated within the urban areas. For example, for agricultural purposes (both for direct human consumption and livestock), over 6,000 m^2 per person are used on Earth[22].

Vertical mobility within the city is carried out through high-speed elevators. Additionally, a system of buses and light-trains provides intra-city horizontal transport. These intra-city transportation systems are electric and within pressurized spaces. A network of train stations connects to the space airport, located at a nearby crater. The mobility between different Martian cities is provided by buses or trains that travel on paved roads.

Nüwa and adjacent cities exponentially accommodate their population. After an initial short period of capital investment and supply from Earth, this urban development on Mars maintains and grows by its own means and in a sustainable manner. All the materials required for constructing the city are obtained on Mars by processing Carbon and other minerals, and as a result, steel, and its derivatives, are extensively used for the construction systems in *Nüwa*.

V. Life Support System

The Life Support System is in charge of providing all required resources for human survival and it takes care of the human produced wastes. To ensure a sustainable city on Mars, all waste products will be treated to produce fresh new resources.

A. Life Support requirements

On average, every human requires 0.186 kg/day of O_2, 1.5 kg/day of food, about 10 kg of water per day (2.5 kg potable water for drinking and food preparation and, the rest for hygiene purposes)[23]. That means that for 1 million people living on Mars 820 t of O_2, 1,500 t of food and 10,000 t of water will be required per day. Humans will produce waste products, which include about 1 kg/day of CO_2, and solid (feces) and liquid waste (urine, condensate, sweat). Which will need to be collected and processed.

Current LSS onboard the ISS use physico-chemical technologies, which are able to recycle 90% of water and recover 42% the O_2 from the CO_2 astronauts produce[24]. Food is fully produced on Earth and brought to the station. Future missions, such as a Moon base or an exploration mission to Mars are likely to include some biological technologies to complement those existing technologies. A 1-Million-city-on-Mars LSS might look much different to those ISS technologies, relying mostly on biological systems.

The design of *Nüwa* is at a very initial phase, thus the goal of this chapter is to explain the LSS concept and provide some rough estimates on the system sizing, based on published experimental data. As the design advances, a more detailed analysis, including system simulations will be required.

B. Life Support concept

The LSS concept for *Nüwa* is summarized in Figure 6. It includes several living organisms to ensure a full closure of all LSS-loops, including atmosphere, food, water and waste management.

Crops and microalgae are in charge of producing 50% and 20% of the food respectively, while processing CO_2 into O_2 and taking part in the water processing system. Both crops and microalgae grow in the agricultural modules, Figure 7, the atmosphere of which is independent from the living compartments. That allows the use of a CO_2-rich atmosphere (3,000 ppm). Together with the use of hydroponic systems and adaptive LED-lighting, this ensures a highly efficient cultivation. The LED can ensure that the plants obtain the required lighting for efficient growth at all phases, independently from solar irradiation, which on Mars is considerably lower than on Earth. The system will require 37 kW per person. With these conditions, a surface of about 100 m^2 per person for crop production, and 250 L microalgae reactors are required according to current experiments. [25,26,27,28]

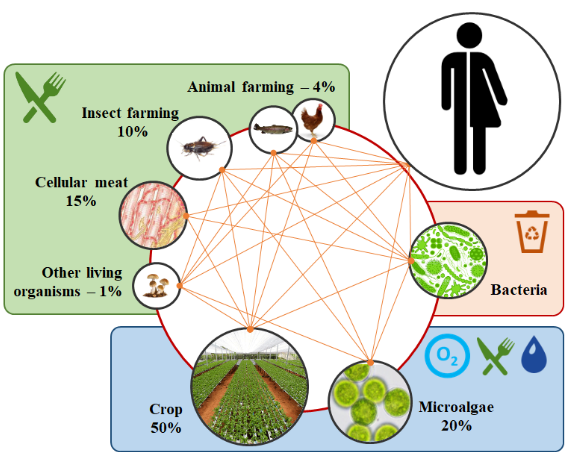

Figure 6. *Nüwa*'s Life Support System concept. *Percentages represent the food contribution of each element.*

Figure 7. Agricultural modules.

In the living compartments CO_2 is collected, together with water, through cold precipitation. This is achieved by expanding the pressurized air into large, but closed volumes exposed to the surface of the planet, the "Snow-domes". The expanding gas goes through a turbine producing mechanical energy, losing heat, and its temperature further drops (Joule-Thomson effect). As a result, CO_2 and air humidity freeze into snow that falls to the bottom. Other gases (O_2, N_2, and Ar) do not become liquid, and can be re-injected into the system with a compressor (using energy from the turbine) to the pressurized environment. The CO_2 can then be transported to the agricultural modules, while the water goes to the water management system.

Besides crops and microalgae, other living organisms will complement the diet. Several potential animal and insect farming species have been considered to provide a first estimate of surface and resources required. Insects, even if they are not widely introduced in western diets, are highly efficient. Typical values for insects are that 80% of insect mass is edible[29,30], while for fish and other farm animals, such as chickens, cows or pigs, the amount of edible mass is reduced to an average of 55%[31]. Insects consume less than 3,000 liters of water for each kilogram of meat produced, while farm animals will consume between 5,000 and 16,000 liters[29]. Animals are expensive to grow and maintain compared to crops or algae, but they provide a positive psychological effect and can serve as a buffer in the system. Due to the small amount of daily consumption considered (4%), the required surface for land farming is estimated to be less than 0,5 m^2 and the volume for fish production less than 600 L.

Cellular meat production should provide about 15% of the daily food consumption. Although this method of meat production is still not implemented in our daily life, several companies are currently working on that and it is reasonable to think that in the project timeframe the technology would be fully developed. It is estimated that, to produce 240 g/day, 3.31 m^2 system will be required[27]. Other living organisms, such as mushrooms should also be considered to ensure a balanced diet.

Finally, several bacteria will be in charge of processing both the solid and liquid waste. The system should be composed of several types of bacteria, to be able to break the waste products into the elements required for the LSS, e.g. nutrients for the algae and crop. A first rough estimation, based on published data[25,32], shows that a volume of 1.6 m^3 and 3.5 kW per person will be needed.

C. Life Support integration

The LSS cannot be an independent system but it needs to be integrated with the city architecture, since it is required everywhere. Several green areas are placed within the city, which partially contribute to air regeneration. Animals and insects will also be placed in the human living areas, distributed among the city. The vegetation and animals act as buffers of organic matter as well. A "Snow-dome", for water and CO_2 collection is placed in every module, i.e. 12 in each "Macro-building".

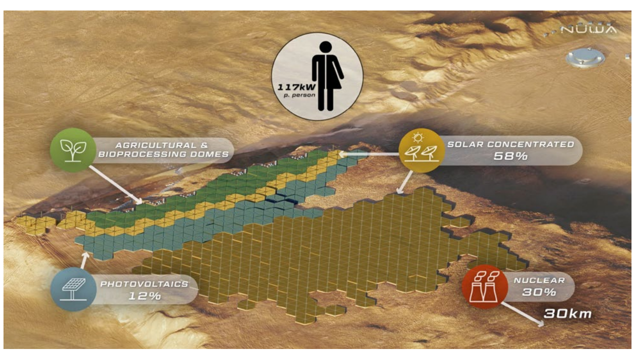

Figure 8. View of the mesa, with the agricultural and power modules.

The agricultural modules, Figure 8, are located in the mesa and composed of 27 hexagons, providing 16 km^2 of build surface. Each hexagon is divided in several modules, with two floors each. The lower level is fully LED-dependent, while in the upper level sunlight could complement the LEDs. This distribution ensures a crop cultivation surface of 100 m^2 per person and space for the algae and bacteria reactors still providing some safety margin.

Thanks to the reduced atmosphere (not breathable for humans), the pressure difference with the exterior is very low and the structure can be much simpler.

The LSS infrastructure requires per person about 110 m^2 surface, 37 kW, 8,000 kg of water, 100 kg of nutrients and 240 kg of O_2 (to fill the atmosphere of breathable compartments). In the mesa, several solar panels and collectors (2,700 m^2 per person), as well as a nuclear reactor, ensure the provision of all the power (117 kW) needed per person.

VI. Conclusions

Nüwa is high-level development plan for a sustainable 1 Million-people settlement on Mars, designed by SONet for the Mars Society Competition 2020. It consists of five cities built in the cliffs of Mars. The project considers engineering, architectural, socio-economic and political aspects, among others. This paper focuses on three main aspects: development concept, urban planning and Life Support System.

The City Unit concept represents the infrastructure required to add one citizen into the city. Under our assumptions and the boundaries set by the competition, each citizen should contribute to 0.126 CU/year, which sets the constrains on the resource extraction and power consumption rates.

For *Nüwa*, high amounts of energy are needed to guarantee human survival: 37 kW per inhabitant only for life and a total of 117 kW to keep up the target development rate. In developed countries on Earth ~11 kW are typically used per person. Energy consumption is proportional to the amount of work that needs to be executed/supervised per person, which points to a key need for the development of a Martian city: to take standardization, automation and AI into account at design level across all economic activities. On the other hand, the overall material budget per person obtained for the *Nüwa* design is comparable to Earth's (about 800 Tn of minerals for a person living 70 years in a developed country, without taking into account the mining of the water).

Nüwa needs the ability to cope with potential future uncertainties, i.e. it needs to be resilient. In the design, resilience is improved by redundancy, i.e. no basic function is covered by a single solution, and by careful design, considering a range of approaches and their performance under distinct plausible futures. This approach is not limited to the physical elements, but in the economic aspects as well. Some examples of how specific design decisions help improve its overall resilience have been mentioned in this paper.

The design of *Nüwa* foresees the construction of the city excavated in the cliffs of Mars as a solution to several environmental and human factor constraints. Compared to other underground possibilities, excavating in the cliffs, allow for a denser three-dimensional urban net, which is crucial given the size of the cities. The concept includes "Macro-buildings" with living and working compartments inside the wall, bigger facilities in the valley, and required support infrastructure in the mesa. Buildings are modular to be able to isolate specific sections in case of an accident, providing resilience as well. The city includes a surface suitable for humans of 162 m^2 per person.

The LSS tasks are fulfilled by a combination of living organisms. Crops, algae, insects and cellular meat production are the main food sources. Farming animals and vegetation are only included in small amounts in the living areas for their physiological effects and to act as a system buffer. The LSS design proposed in this project is only a first conceptual design. Although the systems planned are currently available and used on Earth, further questions need to be answered in a more detailed study. For example, the selection of the crops or insects, how can long-term stability be guaranteed, how will the use of medicines by humans influence the water recycling, etc. The LSS Infrastructure requires per person about 110 m^2 surface, 37 kW, 8,000 kg of water, 100 kg of nutrients and 240 kg of O_2.

The project *Nüwa* has been the first step in studying the feasibility of developing sustainable Mars settlement for 1 Million people. It provides a first estimation of the systems required, looking both at the raw materials as well as the energy needed to process them. The results obtained, in terms of materials and energy, and the consideration of technologies (either in use or currently under development) suggest that such a settlement should be technically feasible. However, further research is required, and several critical aspects, such as long terms effects of radiation, reduced gravity, and practical implementation of a circular economy, still need to be analyzed in more detail before such a settlement can become a reality.

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