Simulating the construction of conceptual space architecture to explore the potential of combined asteroid mining and space-based 3d manufacturing

Vermeulen, Angelo C.J.; Goldoust, Farshad; Sirenko, Mikhail; Hallak, Daniela; Lutkewitte, Brennan; Husárová, Lenka; Long, Kelvin F.; Brazier, Frances

IAC-19.D1.14

Simulating the Construction of Conceptual Space Architecture to Explore the Potential of Combined Asteroid Mining and Space-based 3D Manufacturing

Angelo C.J. Vermeulen[a*], Farshad Goldoust[b], Mikhail Sirenko[b], Daniela Hallak[c], Brennan Lutkewitte[d], Lenka Husárová[e], Kelvin F. Long[f], Frances Brazier[a]

[a] *Systems Engineering and Simulation, Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, 2628 BX, Delft, the Netherlands,* a.c.j.vermeulen@tudelft.nl, f.m.brazier@tudelft.nl
[b] *Engineering and Policy Analysis, Faculty of Technology, Policy and Management, Delft University of Technology, Delft, Netherlands,* f.goldoust@student.tudelft.nl, m.sirenko@student.tudelft.nl
[c] *Management of Technology, Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, 2628 BX, Delft, the Netherlands,* daniela.hallak@gmail.com
[d] *Technische Universität Berlin, Department of Aeronautics and Astronautics, Marchstraße 12, 10587 Berlin, Germany,* btlutkewitte@gmail.com
[e] *DLR Gesellschaft für Raumfahrtanwendungen mbH, Münchener-Str. 20, 82234 Wessling, Germany,* lhusarova49@gmail.com
[f] *Stellar Engines Ltd., Wellington Office, Reading RG7 2BT, United Kingdom,* star@sel.space
* Corresponding author

Abstract

Space-based manufacturing is considered a crucial next step for the further development of human settlement in space. There are vast quantities of building resources distributed throughout space, with asteroids among the most apparent candidates for large-scale mining and resource provision. In this presentation, we present a hybrid simulation model in which building materials extracted from asteroids are used in a differential 3D manufacturing process to create expanding modular space architecture. This work is part of the larger research programme E|A|S (Evolving Asteroid Starships) in which concepts for self-developing and evolvable interstellar spacecraft are being created by the DSTART team at Delft University of Technology. A high-level 'factory model' has been created that simulates the different steps of an entire production chain. The functions of the core disjunct components of the model range from mining, processing, storage, and 3D printing to biological life support and habitation. The model's backbone consists of a heuristic based on a decision tree that handles multiple incoming production requests. Architectural production is needed to cope with (1) population growth of the inhabitants, and (2) the need for replacement of modules due to space weathering caused by particle impact and structural fatigue caused by high-energy cosmic radiation. The simulation model combines DEVS (discrete event system specification) and DESS (differential equation system specification) approaches and includes an abstract animated visualization. The model allows the user to keep track of material flows, bottlenecks and production efficiencies. In a series of simulation experiments three parameters are varied: (1) system properties (including aspects such as processing speed and storage capacity), (2) resource availability (by varying the chemical composition of the asteroids), and (3) production demand (which depends on population dynamics and the need for module replacement). These experiments are designed to increase understanding of the performance of the envisioned system under different conditions. In this paper, the results of these different simulation experiments are described and compared. The relevance for the larger project goals of E|A|S are discussed, and conclusions are drawn for future research on evolvable space architecture concepts.

Keywords: Space architecture; Asteroid mining; 3D printing; Self-replication; Modeling; Discrete event simulation

1. Introduction

1.1 E|A|S (Evolving Asteroid Starships)

The hostile environment of interstellar space and its unpredictable impact require a new approach to spacecraft design, one that differs radically from current paradigms in aerospace engineering. In the E|A|S (Evolving Asteroid Starships) project a design solution is proposed in which a starship is attached to a C-type asteroid and whose architecture

consequently grows and evolves over time. The starship mines resources of the asteroid, while at the same time using the asteroid as a shielding structure against frontal impacts (Fig. 1). The extracted raw materials are used for the gradual expansion of the starship's architecture and cultivation of an onboard regenerative ecosystem enabling long-duration exploration. The expansion of the architecture is carried out by self-replicating mobile 3D printers. [1]
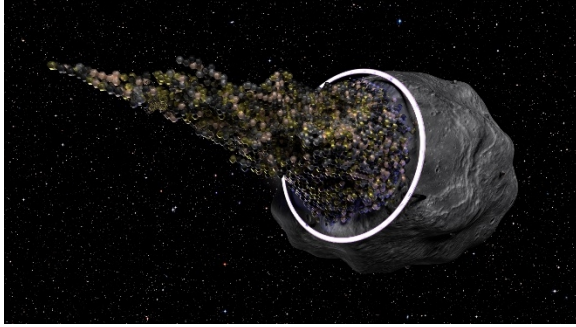
Fig. 1. Artist impression of the E|A|S (Evolving Asteroid Starships) concept. 3D modeling by Nils Faber.

1.2 Asteroid mining

Asteroid mining is not a new concept, but in recent years, it has been gaining more and more recognition as a viable endeavor. Asteroids contain many valuable minerals and materials, such as rare metals, within grain matrices of metal oxides, sulfides, and silicates [2]. As the mining of these materials could be lucrative, new companies are planning to bring this concept to fruition. Beyond containing valuable rare metals, asteroids also contain materials that could be utilized in the space environment. Such materials include organic material and water for biological needs or aluminum and copper for infrastructure applications, among others [3]. Because of the presence of these materials, asteroid mining is a critical element within the E|A|S concept. The asteroid is mined according to the needs of the growing and evolving starship as it travels through interstellar space. The mined materials are used for the manufacturing of mobile 3D printing robots and all necessary module types (habitation, biological life support, shielding, mining, processing, manufacturing, storage), and for providing all the biological needs of the starship.

The general concept of mining an asteroid is summarized in the next few steps [4]:

1. Comminution: reduction in particle size through crushing/grinding.
2. Screening: separation of desired size of material using differences in density.
3. Concentration: separation of desired mineral from waste/gangue possibly using gravity concentration, magnetic/electrostatic separation, or froth flotation. De-watering may also be required following these procedures.
4. Further refinement through hydrometallurgical, electrometallurgical, and pyrometallurgical techniques.

The exact method, however, does depend on the asteroid's properties, such as the composition and density. Depending on the method, asteroid mining might also require inputs of water, catalysts, gasses, organics, etc. The different potential mining methods draw from existing Earth mining processes and consist of drilling, blasting, cutting and crushing. One such method could be a machine similar to a snow blower, attached to the surface, collecting loose rubble by using a spinning blade to fling the material through a chute and into a high-strength bag. Both chemical and physical means could be used to extract the individual materials, depending on their properties. "Water can be extracted by heating the solid material, capturing the vapor and then distilling it; electrolysis of molten silicates would produce oxygen, iron and other alloys; and a method called the Mond process could be used to extract nickel." To determine the best method, meteorites are used as a testing ground for many of the mining experiments [5]. Dorington and Olsen offer a detailed discussion on the mining requirements for asteroid ore extraction using surface mining techniques [6].

1.3. Space-based 3D manufacturing

Over the past decade, significant research has been done on using regolith as a resource for 3D manufacturing architectural structures on the Moon or Mars. Diverse manufacturing procedures have been proposed are currently being researched. NASA's 3D Printed Habitat Challenge offers a good overview of different examples [7]. Apart from structures that are built on planetary surfaces, 3D manufacturing systems are also being developed for in-space manufacturing such as Archinaut by Made in Space [8], SpiderFab by Tethers Unlimited [9], and a carbon composite in-orbit manufacturing system by Magna Parva/Kleos Space [10].

1.4 Interstellar radiation and dust

Currently, the E|A|S project looks at missions to the nearest stars, between 4 and 8 light years (ly) from the Sun, such as the Alpha Centauri star system. The distance the starship needs to cover in our solar system dwarfs in comparison to the distance it needs to travel outside of it. Therefore, the environment that we're focusing on lies past the heliosphere. Galactic cosmic rays (GCR) represent the main source of radiation outside of the heliosphere. Their presence sharply increases past the heliopause [11]. Conventional aluminum shielding is not enough to protect the population onboard the starship, as even now the radiation dose the astronauts on the ISS experience is dominated by GCR [12]. Astronauts on the ISS are protected from GCR by the Earth's magnetic field, as well as by solar activity. The higher the solar activity, the lower the GCR dose. However, the interstellar medium (ISM) through which the starship is expected to travel will not

provide such protection. The only thing that is certain is that the ISM is isotropic [13]. Another important aspect of the ISM are dust particles. Dust grains beyond 50AU (0.00079 ly) are most probably larger than 1 μm [14]. However, despite their size, they might still significantly damage the starship because of high impact velocities. Their densities are known for the Local Interstellar Cloud (LIC) where the Sun is located. That density is 7.5×10^{-15} cm^{-3} [14]. It is important to note though, that only two probes have reached the edge of the heliosphere (Voyager 1 and 2) and that very little is known about interstellar space in general. The densities for the G cloud for example, where Alpha Centauri is located, can only be estimated. The real values will probably still differ and can only be established once that location has been reached and in situ measurements can be made.

1.5 Interstellar weathering
   Space weathering occurs on all objects in space. However, it is not fully understood how weathering affects C-type asteroids [15]. The weathering is caused by radiation and dust particles. When dust particles impact the starship, they increase the temperature of the material which can then cause mass loss due to erosion [16]. Erosion is also caused by the high impact energy of larger dust grains [16]. It is believed that the overall impact and significance of erosion will change depending on the mass of the asteroid chosen for the starship. The heavier the asteroid, the lower the relative impact of erosion damage on the starship. It is believed that erosion could potentially only occur for larger dust particles impacting the asteroid. However, further calculations on dust particle escape velocity need to be conducted to say that with certainty. Once it is known what size of dust particles cause erosion, the Benedict calculation method [16] can be used to calculate the magnitude of mass loss of the material.

1.6 The imperative of bioinspired engineering
   Creating a generation starship for long-duration interstellar travel is a challenge with a deep level of uncertainty:
   - Actual radiation levels and along the interstellar trajectory are not fully known at the start of the mission. Moreover, very little is known about the long-term impact of GCR on shielding and structural materials.
   - The actual distribution and density of dust particles and dust grains is equally not fully known.
   - The asteroid composition is also a factor with a lot of uncertainties (different elements that are present, variable and heterogeneous element concentrations, width of element

concentration ranges). Even with an in situ probe or high-resolution spectral data, it is impossible to know the complete and exact distribution of chemical species of an asteroid. Therefore, expected ranges of various species can allow for the modeling of such uncertainty. For example, based on observations of meteorite samples, asteroids can have up to 2% mass of organic matter [17], up to 20% water [18], and up to 2.4% of aluminum species [3].
   - The population dynamics of the biological life support system (microorganisms, algae, crops) and the crew are also difficult to predict. Ecosystems are dynamic and fluctuating systems [19]. And even when complemented by technological control mechanisms, artificial ecosystems might still display unexpected behaviors because of their complex nature [20]. Moreover, the long-term impact of the interstellar medium on the functioning of the different species and the ecosystem within a starship, is entirely unknown.

Designing a solution for a challenge with such an overall deep level of uncertainty is a complex problem. No top-down planning approach can handle this. A complex problem requires a complex solution: a responsive, flexible and robust system that can stay operational in a large variety of (unexpected) circumstances. In other words, we need a complex adaptive system (CAS). Not that complex is not synonymous with complicated [21]. However, a CAS cannot be built as such, it needs to be built starting from a simple system. We can accomplish this by using morphogenetic engineering [22]. In this approach, the desired system gradually emerges out of the interaction of construction agents. As such, the engineering focus shifts much more to the agents' attributes and behaviors, and less to the final result. Emergence is defined as follows [23]: "Emergence is the expression of novel properties, functions and behaviors of a system that are not observed in subsystems and their components. Emergent behavior can arise through the application of simple rules. Although hard to predict, emergence allows a system to optimize and adapt in real time, each new state building upon the previous one." In our starship concept we choose to operationalize such emergence through morphogenesis and evolution. Morphogenesis points to the fact that the starship grows and shapes itself during its journey using a self-replicating 3D manufacturing system. The self-replication approach guarantees an increasing production capacity to keep up with an exponentially increasing population of inhabitants (ecosystem and crew). Evolution indicates the capacity to reconfigure

the topology of the starship's modular architecture. It is precisely such a bio-inspired engineering approach (employing morphogenesis and evolution) that enables the spacecraft to handle the deep level of uncertainty that characterizes interstellar exploration.

This paper only addresses the growth process of the starship. The history of self-replicating goes back to John von Neumann's seminal work on universal constructors in the 40s [24]. In 1982, NASA published an extensive report on automated space systems that included a detailed conceptual study for a self-replicating lunar factory [25]. The current study explicitly builds on that report and uses some of its conceptualization schemes. Overall, there's been very limited theoretical research on the use of self-replication for interstellar exploration. Freitas published a series of papers on a self-replicating probe for interstellar missions [26]. The goal of the current paper is to discuss the preliminary results of a computer simulation that has been created to explore different scenarios of a gradually expanding generation starship.

2. Methods

2.1. Discrete event simulation

According to White and Ingalls [27]: "[…] models are simplified abstractions, which embrace only the scope and level of detail needed to satisfy specific study objectives." In this paper we demonstrate a proof of concept for the starship concept described above. The self-replicating mining and architectural production system have been conceptually encoded into a discrete event system specification model. As Zeigler [28] puts it: "A discrete event system specification (DEVS) is a structure:

$$M = <X, S, Y, \delta int, \delta ext, \lambda, ta>$$

Where X is the set of input values, S is a set of states, Y is the set of output values. At any time, the system is in some state, s. If no external event occurs the system will stay in state s for time $ta(s)$. Notice that $ta(s)$ could be a real number, as one would expect. But it can also take on the values 0 and ∞."

From a range of alternative modeling formalisms, DEVS enabled us to make a model with sufficient granularity, easy encoding and encapsulation, fast evaluation, and a capability of efficient handling of numerous model entities at the same time. First, a simple conceptual model was programmed in Python. Based on this core model, we developed a more detailed model in Simio. This is an academic/commercial software package that provides solutions for the design, emulation, and scheduling of complex systems.
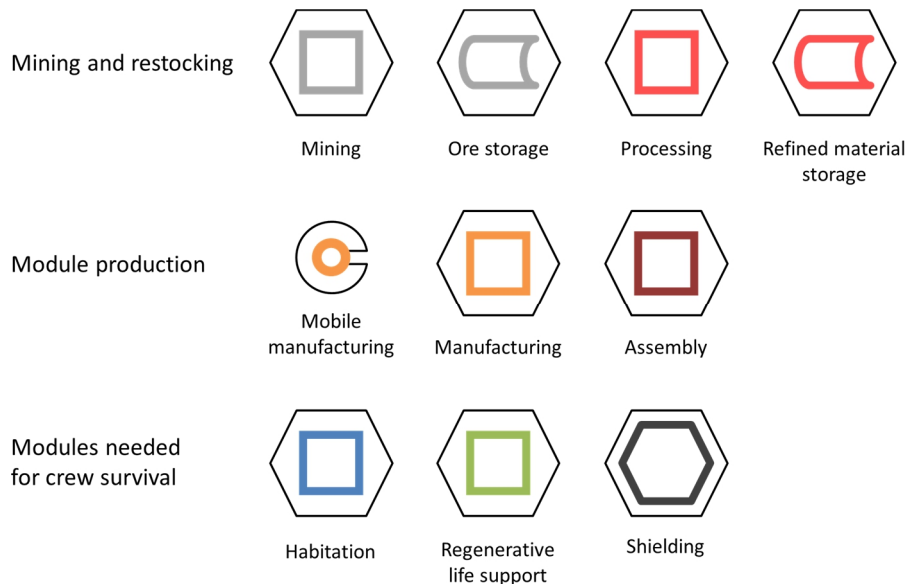

Fig. 2. Module typology currently used in the E|A|S (Evolving Asteroid Starships) project. The top row represents the mining and restocking chain. Whenever a storage module is (partially) emptied, it will get restocked by activation of the mining or processing modules. The middle row represents the module production chain and the bottom row represents the types of modules needed to keep a human crew alive.

2.2 Basic simulation architecture

The model consists of two main active factory chains that are connected to each other by a primary-secondary relationship. The first chain consists of asteroid mining, processing and storage (top row in Fig. 2). The second chain consists of mobile 3D printers and manufacturing modules coupled to an assembly module (middle row in Fig. 2). The mobile printers create architectural shells, while the manufacturing modules create the equipment for a module defining its function (e.g. habitation). The population is allowed to expand and this dynamic that constantly requires the production of more habitation modules. The interaction between these two main dynamics is the main driver of states (Fig. 3). Human reproduction pushes the system to higher module occupancy (population density), while module production pulls the system back towards lower module occupancy values. As illustrated in Fig. 4 we ran our analysis under the assumption of population desired occupancy equal to six and factory desired occupancy equal to five. This small difference is enough to steer system in an oscillatory fashion that keeps the dynamic running.
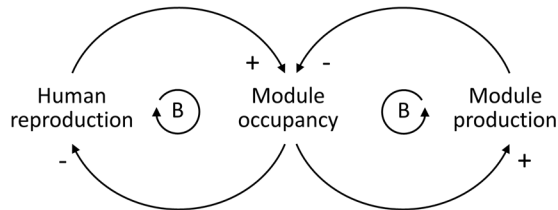

Fig. 3. Causal loop diagram representing the feedback between human reproduction and module production.
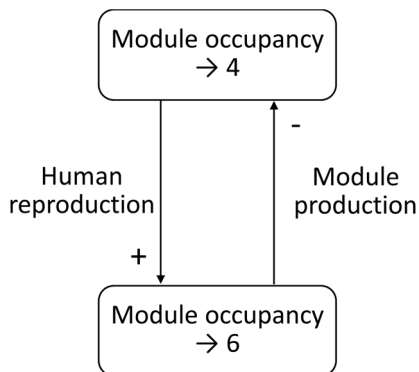

Fig. 4. Differential target system of human reproduction and module production used as an oscillating driver of the system.

2.3 Stochasticity

As mentioned above, deep space is associated with deep levels of uncertainty. In order to project uncertain nature of the environment and reciprocal uncertain responses of the factory, we assigned stochastic function to our design parameters including process times and inter-arrival of the entities. It's important to note that the model is only in a proof-of-concept stage right now. It's merely an approximation of reality to serve the purpose of our analysis. A short explanation of the distribution function will be represented below.

2.4 Activity flows

The main logic of entity (material) flow is illustrated in Fig. 5 and 6. As mentioned, population dynamics triggers the required token to activate the architecture sub-model. A decision must be made to check if the module occupancy state variable is over a desired level. Then the token may proceed to the next steps. On the other hand, the mining sub-model always at each time step checks the state of available refined material, ready to feed mobile printers and manufacturing modules. The criteria have been set to keep the refined material storage full. In theory this simple design as explained keeps the system responsive to the population dynamic.

2.5 Population dynamics

Population dynamics has a simple design too. We employed a simple logistic growth to the population. It consists of two main parameters which could influence the population state over time. First is a coefficient which indicates what percentage of the population would decide to procreate. The second parameter is an expectation constancy which indicates the maximum occupancy state that is desirable for the population. It also puts a cap on the population growth, otherwise the population growth would be unrealistic. The simple mathematical model we employed will be represented in more detail at section 3.

2.6 Self-replication

System-wide self-replication has been implemented by enabling each module type (Fig. 2) to send out a replication request. In our conceptual design, each module could ask for a replica whenever it doesn't meet the capacity requirements for the rest of the system. In other words, we implemented a decentralized bottle-neck detection mechanism through self-reporting by each and every module. This is possible because each module has an understanding of the state of its own queue. Then at each round, based on the highest number of requests,
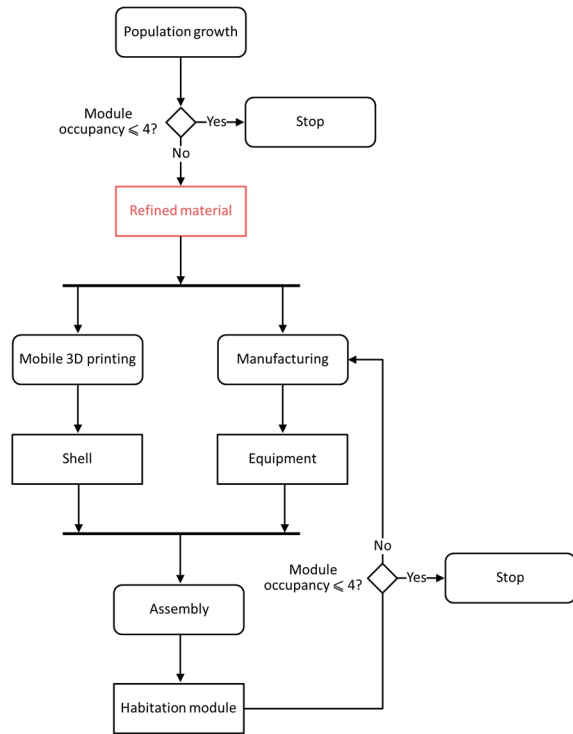
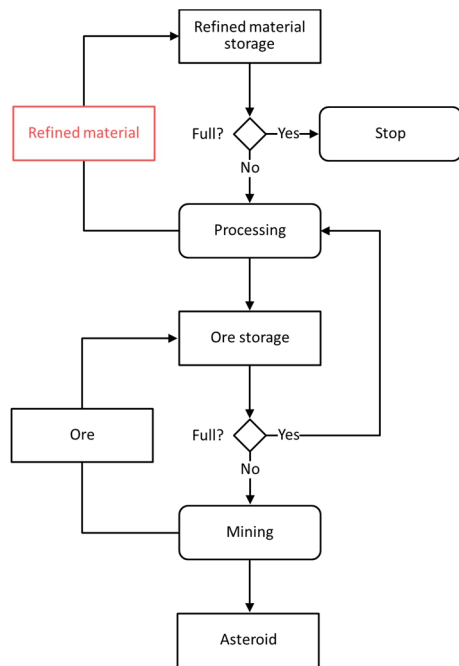Fig. 5. Activity diagram of the module production part of the factory.

Fig. 6. Activity diagram of the mining and restocking part of the factory.

an extra module will be granted. However, this problem could also be handled through many alternative policies which is a topic open for exploration in further research.

2.7 Preliminary experiments

Based on the main objectives of this system design – self-balancing and self-organization – verifying the responsiveness of the model to different trends of the crew population is a fundamental test. For this purpose, we injected variance to the population dynamics through a variable population growth coefficient. Also, to include unforeseen environmental factors and inherent system variability, the same stochastic behavior was used in all processing times. We ran experiments for 100 runs, each time using three major different self-replication policies. First, a system without self-replication, as reference. Second, a system with a binary comparison logic decision making policy. And third, a system with a built-in sorting algorithm as decision maker. An overview of all tested scenarios can be found in Table 1.

In policy I, within each chain of the model (mining-restocking on one hand, and module production on the other hand) a ranking of the modules is created according to how many requests for replication they sent out. Subsequently the two top ranking modules within each chain are compared, and the one with the most requests is selected to be reproduced. In policy II, a different built-in sorting algorithm ranks all module types according to the number of requests they sent out, and the top one gets selected.

Table 1. Overview of the different simulation scenarios that were tested. Self-replicating policies I and II indicate different methods that are used to select which module type gets reproduced first by the module production system. All 9 scenarios were run for both 20 and 100 years. Each simulation was run 100 times.

Self-replication	None	Self-replication policy I	Self-replication policy II
Reference experiment	1	2	3
Increased stochasticity	4	5	6
Decreased ore purity	7	8	9

3. Calculation

Since this whole analysis is a proof of concept to illustrate the effectiveness of self-organization as a response to complexity, we will only focus on the most relevant aspects here. In this section we present the population dynamics approach and we lightly touch upon random probability distributions in the model.

3.1 Population dynamics equation

Population dynamics consists of a formal logistic growth with a cap parameter to make it realistic and avoid an uncontrolled population explosion:

$$P(t_{n+1}) = P(t_n) + \delta * [P(t_n) / \Phi]$$

and

$$\Phi = H * \mu$$

Where H is the number of habitation modules in the system at time-step t_n and μ is the maximum number of habitants in a module or maximum occupancy. δ is the population growth dynamic coefficient. We may consider it as an indication of individual decision to either reproduce in the next time-step (year) or not. Also, it indicates in a linear manner what percentage of the population are going to add to the population in nine months (delay). Φ is the feedback mechanism inherited into the mathematical model of the population.

3.2 Stochasticity

To indicate uncertainty, we added random behavior to the different processes. Gaussian normal or log-normal distributions are the most appreciated distributions to describe full uncertainty about a continuous physical phenomenon. But they have a big disadvantage which is the infinite tail of them. Most of the time the probability of an occurrence farther than $\pm 3\sigma$ is negligible. Since the model might run hundreds of times for a specific scenario, the chance of extreme case occurrence is not negligible any longer. Another bell-shaped distribution could be a truncated Gaussian. In our design, since numerical

accuracy is not the case, we simplified a normal distribution to a triangular distribution with three easy adjustment parameters: minimum value, maximum value and mode of distribution. We used symmetrical triangular distribution where mode is equal to mean.

4. Results

Three variables are being presented in Fig. 7-10. Total population size is the entire population in the starship at the end of the simulation (after either 20 or 100 years). Average module occupancy is the average number of people living in a habitation module inside the entire starship. Average module production time is the time it takes to manufacture both an architectural shell and its interior equipment plus the assembly time of both.

The data in Fig. 7 clearly illustrate the impact of the presence of a self-replicating system. The populations reach higher levels, the occupancy is lower, and the module production time lowers. There is however no clear difference between the two different policies (scenario 2 and 3). The results over 100 years are very similar (Fig. 8), with the exception of a lower module occupancy.

Increasing stochasticity did not seem to have any effect and the simulation results look almost identical to the reference experiment (Fig. 9).

Lowering the ore purity did have a clear impact on the population size with lower values (Fig. 10) for all scenarios in comparison with the reference experiment. Module occupancy initially decreased to higher values after 20 years, but stabilized around the same values as in the reference experiment after 100 years. In all scenarios module production time decreased.
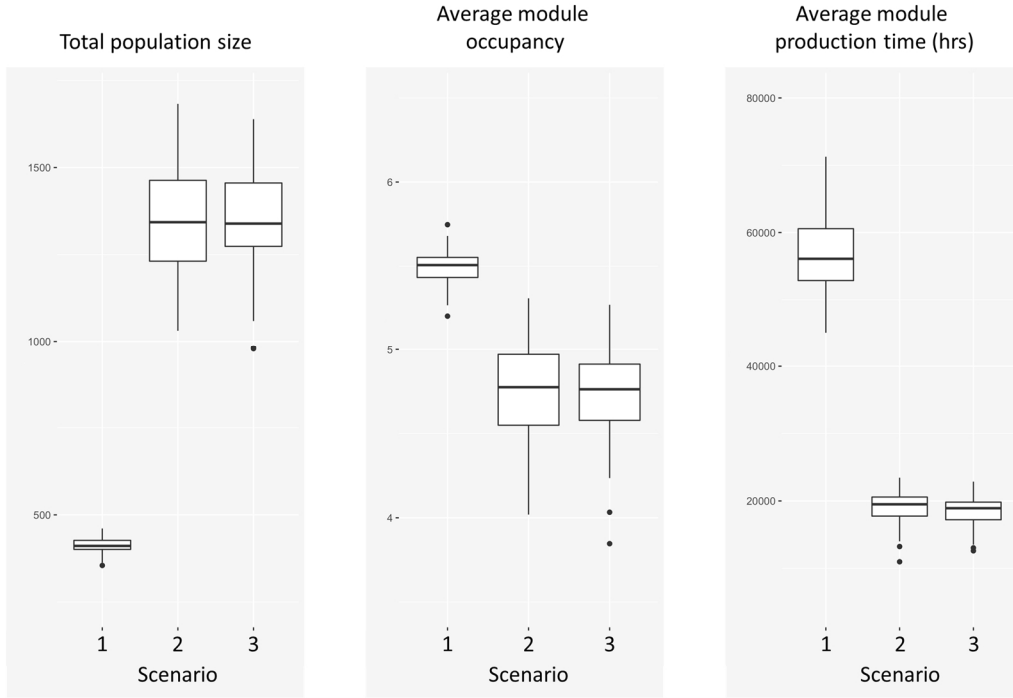
Fig. 7. From left to right: population size, occupancy and production times for a habitation module in scenarios 1, 2 and 3. In the first scenario, the system does not self-replicate. In the second and third scenario there is self-replication, but it is governed by two different sets of policies (explained in section 2.7). The simulations were run over a virtual timespan of 20 years, and the results are based on 100 simulation runs for each scenario.
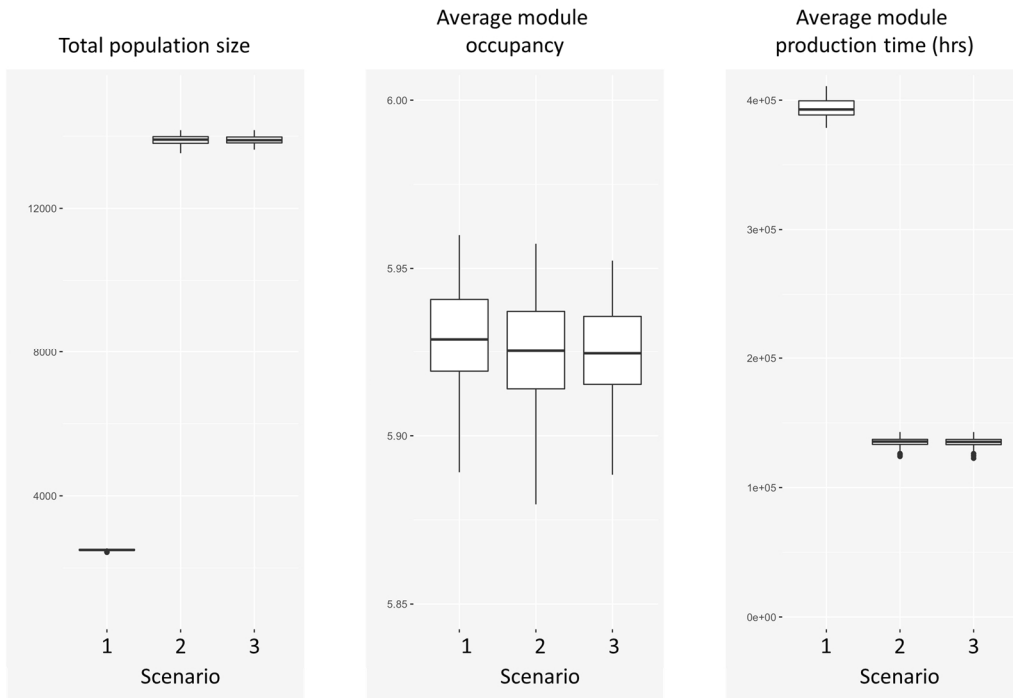
Fig. 8. From left to right: population size, occupancy and production times for a habitation module in scenarios 1, 2 and 3. In the first scenario, the system does not self-replicate. In the second and third scenario there is self-replication, but it is governed by two different sets of policies (explained in section 2.7). The simulations were run over a virtual timespan of 100 years, and the results are based on 100 simulation runs for each scenario.
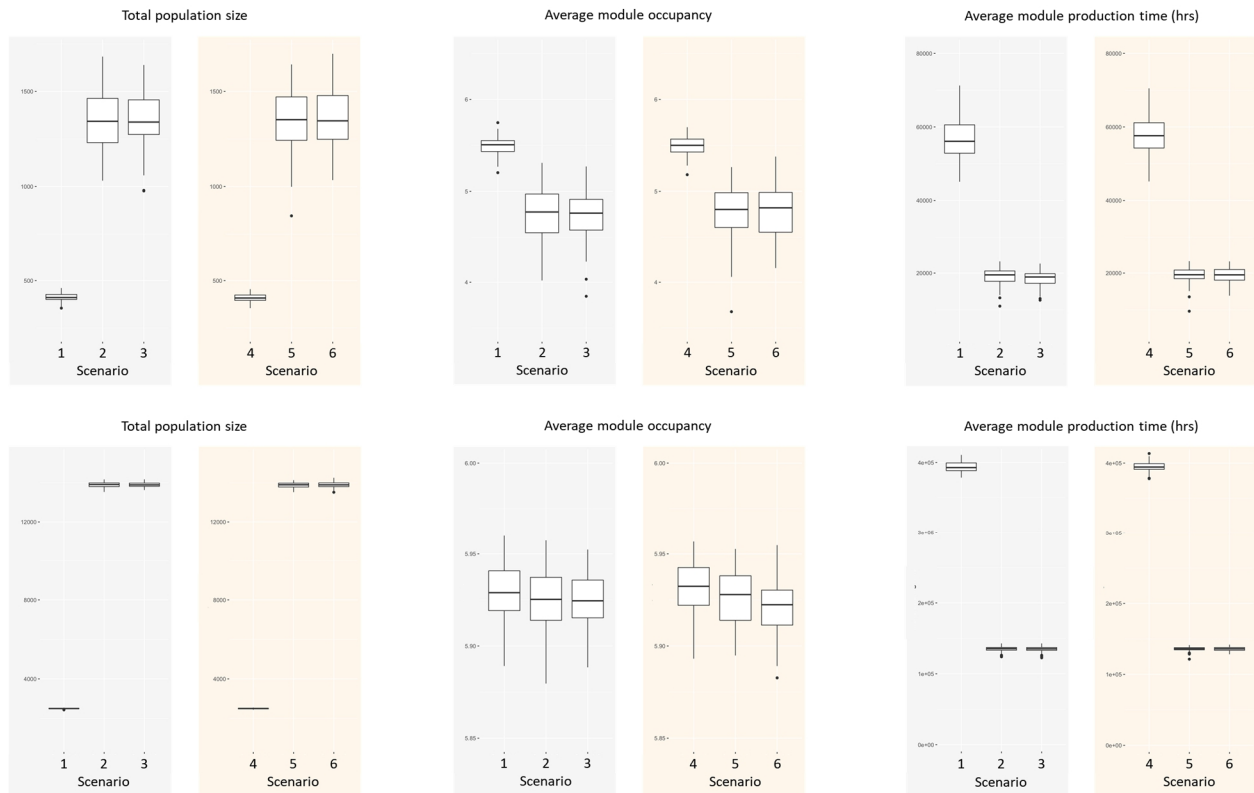
Fig. 9. Population size, module occupancy and module production time in the experiment with increased stochasticity in all processes (in both the mining and restocking chain and the module production chain, scenarios 4-6). The grey graphs are the same as in Fig. 5 and 6, and are used as reference (scenarios 1-3). The top and bottom rows are the results after virtual timespans of respectively 20 and 100 years.
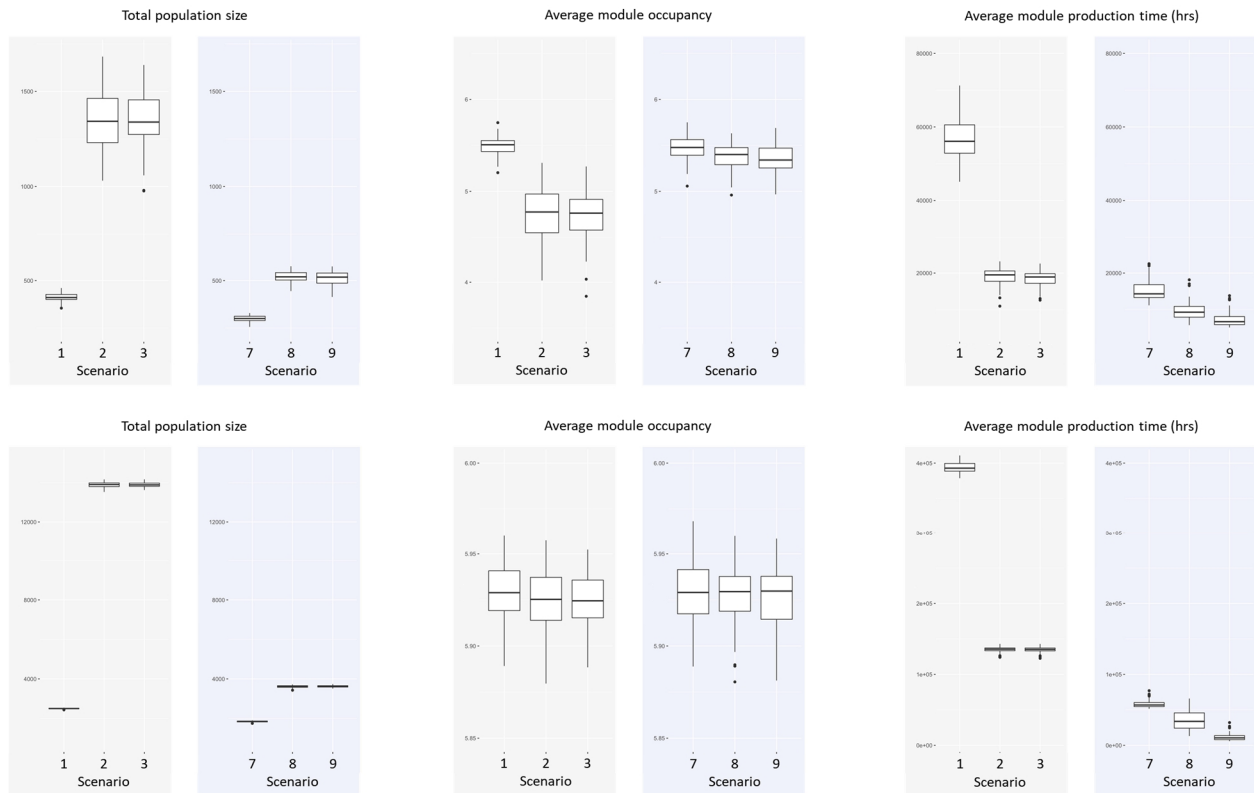
Fig. 10. Population size, module occupancy and module production time in the experiment with decreased ore purity (only 25% compared to the reference experiment, scenarios 7-9). The grey graphs are the same as in Fig. 5 and 6, and are used as reference (scenarios 1-3). The top and bottom rows are the results after virtual timespans of respectively 20 and 100 years.

5. Conclusions

The main conclusions of this study can be summarized as follows:

- The concept of a growing, self-replicating and self-regulating architecture is implemented into a working DEVS model.
- Differential targeting is successfully used as system driver.
- The result is an emergent and robust design that continuously responds to consequences of uncertainty which includes process stochasticity and variable ore purity.

Based on the current results, the next steps of this research involve:

- Adding other modules: biological life support, shielding.
- Investigating the impact of the interstellar medium and integrate module wear and recycling.
- Comparing the consequences of using different self-replication policies (e.g. different prioritization schemes).

Acknowledgements

The authors want to thank Martijn Warnier, Igor Nicolic and Alessandra Menicucci from Delft University of technology for their valuable input and feedback.

References

[1] A.C.J. Vermeulen, M. Sirenko, A. Papic, J. Kiem, A. Theys & F. Brazier, Evolving Asteroid Starships: A Bio-Inspired Approach for Interstellar Space Systems. 69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018.

[2] Jet Propulsion Laboratory, Small-Body Database Browser, https://ssd.jpl.nasa.gov/sbdb.cgi, (accessed 06.10.19).

[3] S.D. Ross, Near-Earth Asteroid Mining, California Institute of Technology, Pasadena CA, 2001.

[4] G. Alotaibi, J. Boileau, H. Bradshaw, R. Chalex, J. Chun, B. Criger (…) P. Zagorski, ASteroid mining, Technologies Roadmap, and Applications (ASTRA), International Space University Space Studies Program, Strasbourg, 2010.

[5] S. Shaw, Asteroid Mining, 21 August 2012, http://www.astronomysource.com/tag/rare-earth-metals-from-asteroids, (accessed 06.10.19).

[6] S. Dorrington, J. Olsen, Mining Requirements for Asteroid Ore Extraction, IAC-17-D4.5.2, 68th International Astronautical Congress, Adelaide, Australia, 2017, 25-29 September.

[7] NASA, Centennial Challenges: 3D-Printed Habitat Challenge, 4 June 2019, https://www.nasa.gov/directorates/spacetech/centennial_challenges/3DPHab/index.html, (accessed 27.10.19).

[8] Made in Space, Archinaut, http://www.projectarchinaut.com, (accessed 27.10.19).

[9] NASA, SpiderFab, https://www.nasa.gov/content/spiderfab, (accessed 27.10.19).

[10] Magna Parva, In-Space Manufacturing Prototype, https://magnaparva.com/2015/12/01/in-space-manufacturing-prototype, (accessed 27.10.19)

[11] S.M. Krimigis, R.B. Decker, E.C. Roelof, M.E. Hill, T.P. Armstrong, G. Gloeckler, D.C. Hamilton, L.J. Lanzerotti, Search for the Exit: Voyager 1 at Heliosphere's Border with the Galaxy, Science 341(6142) (2013) 144-147.

[12] F.A. Cucinotta, M.H.Y. Kim, V. Willingham, K.A. George, Physical and biological organ dosimetry analysis for international space station astronauts. Radiation Research 170(1) (2008) 127-138.

[13] A. Menicucci, personal communication, 24.09.19.

[14] J.T. Early, R.A. London, Dust grain damage to interstellar laser-pushed lightsail, Journal of Spacecraft and Rockets 37(4) (2000) 526-531.

[15] T. Nakamura, C. Lantz, S. Kobayashi, Y. Nakauchi, K. Amano, R. Brurnetto (…) T. Matsumoto, Experimental Reproduction of Space Weathering of C-Type Asteroids by He Exposure to Shocked and Partially Dehydrated Carbonaceous Chondrites, 82nd Annual Meeting of The Meteoritical Society, Sapporo, Japan, 2019, 7-12 July.

[16] A.R. Martin, Project Daedalus: bombardment by interstellar material and its effects on the vehicle, Journal of the British Interplanetary Society Supplement (1978) S116-S121.

[17] M. Sephton, Organic Geochemistry of Meteorites, in: H.D. Holland, K.K. Turekian (eds.), Treatise on Geochemistry, second ed., Elsevier, Amsterdam, 2014, pp. 1-32.

[18] M. Elvis, Prospecting Asteroid Resources, in: Asteroids: Prospective Energy and Material Resources, V. Badescu (Ed.), Springer, Heidelberg, 2013, pp. 81-129.

[19] C.S. Holling, Resilience and Stability of Ecological Systems, Annual Review of Ecology and Systematics 4 (1973) 1-23.

[20] B. Imhof, P. Weiss, A.C.J. Vermeulen, The world in one small habitat, in: R. Armstrong (Ed.), Star Ark, Springer, Switzerland, 2017, pp. 287-296.

[21] D.C. Mikulecky, The emergence of complexity science coming of age or science growing old, Computers and Chemistry 25(4) (2001) 341-348.

[22] R. Doursat, H. Sayama, O. (Eds.), Morphogenetic Engineering: Toward Programmable Complex Systems, Springer, Berlin, 2012.

[23] P. Gruber, J. Vincent, A.C.J. Vermeulen, T. Speck, Aspects of Life, in: B. Imhof, P. Gruber (Eds.), Built to Grow: Blending architecture and biology, Birkhäuser, Basel, 2016, pp. 21-27.

[24] J. von Neumann, Theory of Self-Reproducing Automata, first ed., University of Illinois Press, Champaign IL, 1966.

[25] R.A. Freitas, W.P. Gilbreath, Advanced Automation for Space Missions, NASA Conference Publication 2255, 1980 NASA/ASEE Summer Study, Santa Clara CA, US, 1982, 23 June - 29 August.

[26] R.E. Freitas Jr., A Self-Reproducing Interstellar Probe, Journal of the British Interplanetary Society 33 (1980) 251-264.

[27] K.P. White Jr., R.G. Ingalls, Introduction to Simulation, 2009 Winter Simulation Conference, Austin TX, US, 2009, 13-16 December.

[28] B.P. Zeigler, H. Praehofer, T. Kim, Theory of Modeling and Simulation, second ed., Academic Press, Cambridge MA, 2000.