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PARAMETRIC EQUATION FOR THE SETTLEMENT OF MARS

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Abstract

The colonization of Mars has been addressed by many authors but there is still a lack of methodology to determine its feasibility in terms of costs and logistics. We propose a new approach based on a mathematical model of the required payload mass per year that has to be sent to Mars to sustain the life of the settlers during the long period of development of the colony that precedes the self-sufficiency capability. As the required mass is highly dependent on the available working time of the settlers, it is suggested to transform the mass estimation problem into the estimation of the annual missing time to produce all objects needed for the daily life of the settlers. The annual missing time is calculated using five parameters. The first is the number of settlers. The second is the working time capacity per person. The third is an estimate of the total time per person and per year that is required to produce all objects needed for a single person. The fourth is called the sharing factor and is a function of the number of settlers. The fifth parameter allows the conversion of the annual missing time into an annual mass of payload.

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Keywords: Mars settlement, colonization, self-sufficiency, parametric equation

1. Introduction

Is the settlement of Mars feasible or not? In general, how to determine if the settlement in space or on another planet is feasible and at what conditions? Many authors try to address that problem and provide partial answers [1-6]. O'Neel addressed the problem of building a colony in space [3]. The total mass of what is to be sent to Earth orbit is so high that the feasibility seems very weak. For Mars, Zubrin explained that the presence of useful resources is a tremendous advantage [5]. Water can be extracted from the ice, carbon from atmospheric carbon dioxide, iron from hematite, silicon from sand, etc. The Mars Homestead project illustrates this strategy [9] Nevertheless, there is a long way to go to be able to transform these resources into consumables and complex objects such as cars, computers and robots. As a factory cannot be run with very few people, a successful settlement would obviously require numerous persons and a long term financial investment. But how many persons are needed to achieve full autonomy or close to full autonomy on the planet? And if the number of persons is very high, e.g. several thousand people, how many tonnes of payload would have to be sent from Earth to sustain the lives of the settlers during the transition period? The feasibility is clearly linked to that mass, especially if no significant improvements are made neither for interplanetary propulsion systems nor for the costs of building and launching rockets from earth [7,8]. We propose to assume these two constraints and to address the difficult question of the feasibility. In Section 2, a simplified parametric equation is presented. In section 3, interpretations of several colonization scenarios are proposed in order to provide estimations for the parameters of the equation. The relevance of the model is discussed in conclusion and several ideas are suggested to improve it.

2. Looking for a model

2.1 Methodology

Let us assume that a human organization is committed to the project of settlement on another planet. In order to reach that goal, two important issues have to be addressed: How long will it take to succeed (autonomy achievement) and what would be the cost per year? In first approximation, the cost depends on two parameters:

- The cost per kilogram of material or object to be sent to the planet
- The total mass that has to be sent to the planet per year.

We do not address here the cost per kilogram problem, we rather propose to focus on the total mass, which typically depends on two main parameters. The first one is simple, it is the number of astronauts. The second is hard to estimate, it is the mass of all needs except those that can be produced or created using in situ resources. Obviously, the total mass of needs grows with the number of astronauts, but the mass of objects or consumables produced on the planet also grows with the number of astronauts. Intuitively, as more and more tools and facilities can be shared when the number of astronauts increases, it is expected that the needs are quickly growing at the beginning of the settlement and are slowly decreasing when the number of astronauts becomes much higher. The problem is to be able to determine the exact shape of that evolution curve. We propose to address the problem in a mathematical way. Let n be the number of astronauts or settlers on the planet. The problem is to determine a function of variable n, called p(n), that computes the minimum payload mass that is required each year to sustain the lives of all persons. It is proposed here a two steps approach. First, a parametric model of that function is looked for and second, possible values for all parameters are suggested and discussed.

2.1 Proposed model

As a planet usually has numerous useful resources for humans, it is reasonable to assume that the minimum payload is achieved by sending only objects that cannot easily be produced on the planet using in situ resources. An important difficulty is to express what cannot easily be produced into mathematical terms. The ease to produce something generally depends on available tools, available energy and available human resources. However, without time constraints, energy production, human resources and the construction of new tools would not be a problem. Time can therefore be considered a key parameter of the model. In first approximation, the local production simply depends on the available working time of settlers. Nevertheless, as there are numerous acceptable living conditions and many different ways to produce objects and consumables, the optimal strategy is hard to find. One way or the other, a mathematical model should include parameters that would take this strategy into account. The problem can be formulated as follows (see equ. 1):

$$p(n) = k * n * \left(\frac{r}{s(n)} - w\right) \tag{1}$$

Where:

- w (in hours) is the individual working time capacity per year in average. This parameter may vary according to the type of work, the organization of the society, habits, etc. In modern societies, a person works approximately 2000 hours per year.
- r (in hours) is the minimum individual working time requirement per year and in average to produce on the planet all objects and consumables that are necessary to sustain the life of one person. It includes agriculture time to grow plants, industrial time to extract chemical elements from the atmosphere and ores from the soil in order to produce metals, plastics and then tools and complex objects, as well as medical time, teaching time, administration time, etc. As all objects have a limited lifetime, the working time also includes the time to create or build each object divided by the lifetime of the object. The working time therefore includes a percentage of the construction time of buildings, cars, and all complex objects that are assumed to be required for living in a decent way.
- s(n) is a function of n and is called the sharing factor. For instance, if for 4 astronauts, on average, each object is shared between 2 persons, s(4) = 2. It is expected that the number of shared objects will grow with the number of persons. For instance, a kitchen may be shared by four or five persons of the same family and an electric power plant may be shared by a thousand people. Importantly, for a high enough value of n called n_t, $r/s(n_t)$ equals w, which means that a threshold is reached, there will be enough people in the colony to produce everything. In other terms, the colony would potentially achieve full autonomy as soon as the number of persons exceeds n_t.
- Given w, r and s(n), the right part of the expression computes the time that is missing per person and per year to build all required objects to sustain the life of one person. It is multiplied by n to obtain the total missing time and by a coefficient called k to transform the missing time in tonnes.
- k is a mass coefficient. If the missing time is greater than zero, it is necessary to compensate by sending objects from the Earth. A difficulty is to convert a time in mass. This is the role of constant k. It is obviously not required to send all missing objects. It is possible to send only tools or to provide parts of the missing objects, with the objective of minimizing the total payload mass and therefore k. A method is proposed in section 3 to determine k.

3. Scenarios

In this preliminary study, we did not try to determine the exact values of the parameters. We propose a simplified analysis with numerous assumptions and simplifications, which differ depending on the chosen scenario.

3.1 Scenario 1: Modern society

In a modern society, there are numerous complex objects such as computers, robots and other high tech devices for agriculture, metallurgy, transportation, etc. In order to produce these objects, it is necessary to extract iron, alumina, silicon, copper, etc. from different ores, to master plastics production, to build metallurgy factories, microelectronics factories, and finally to produce and assemble complex objects such as computers, cars, robots, etc. in other dedicated factories. In this scenario, as many people have to work in the industrial and digital worlds, it is expected that r is very high and k very small. The following parameters are proposed:

- w=2000 hours
- r = 10^6 hours It means that 1 million hours of work would be required to produce all objects

and consumables needed for a single person per year.

- $s(n) = n^\alpha$ This is a simple way to consider the sharing factor. This function is interesting because it starts as expected with n equal to 1 whatever the value of α and it regularly increases with n but in less proportion, which is also expected. Intuitively, as for 2 persons more than 50% of all objects would be shared (house, car, life support system, facilities, etc.), it is assumed that α is higher than 0.5. For the sake of simplicity, we propose 3 values for α: 0.52, 0.54 and 0.6.
- k = 0.00001 It is proposed to determine k by looking at p(1), which is the expected payload for a single person. For n=1, the sharing factor is equal to 1, which simplifies the equation. A single person would not be able to produce numerous objects or consumables on the planet. As most objects would have to be sent from Earth, an estimate of the payload can be made by looking at the payload mass that is expected for the first manned missions to Mars, which is in the order of 30 tonnes for 3 astronauts and a stay of 1.5 year on the planet. For the sake of simplicity, it is proposed here to determine k such that p(1) would be equal to 10 tonnes given the set of parameters already fixed. In first approximation, k can therefore be set to 0.00001.
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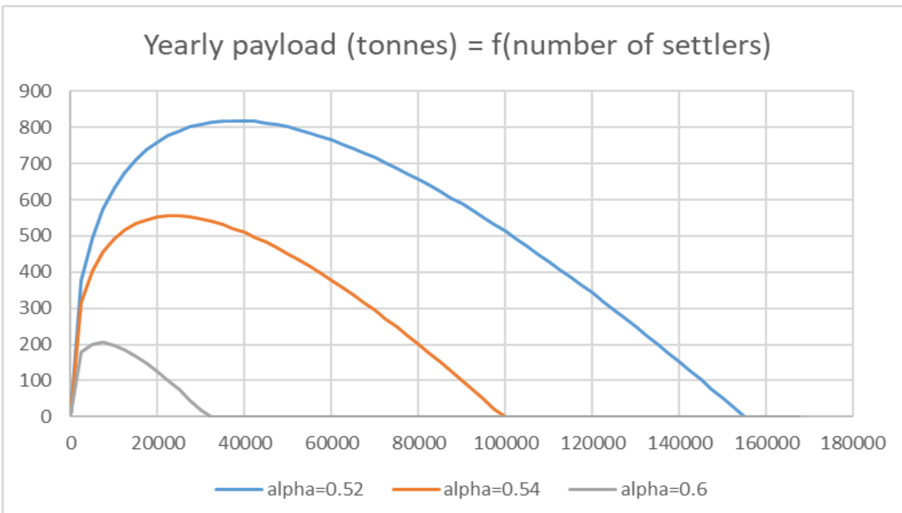

Fig. 1. Yearly payload for scenario 1.

The result is presented Fig. 1. According to our model, for α=0.54, approximately 100, 000 people are required in the colony to achieve full autonomy. Another important result is the peak payload requirement that is close to 800 tonnes and occurs when there are 20, 000 people in the colony. Sending 800 tonnes to Mars each year on average is probably a difficult challenge if there are no commercial exchanges. With current technologies, sending 100 tonnes to low Earth orbit is possible only with the heaviest launchers. With advanced interplanetary propulsion systems and provided that there are no strong time constraints to send the payload, 50 tonnes could probably be sent to the Mars using a single heavy launcher and an ionic propulsion system for the transfer to the other planet. As a consequence, at least 16 launches per year would be required to send 800 tonnes to the colony.

3.2 Scenario 2: Frugal society

Robots, modern cars and modern computers are not absolutely required for the survival of the colony. It is indeed possible to live on the planet using 20th century objects. For instance, in the years 1950-1970, there were already cars, planes and even rockets and spacesuits, but computers and robots were rare or very simple. With more simple objects, the productivity is impacted in many domains, but there are huge time savings due to the reduction of the needs: Without smartphones, robots and other complex objects that require miniaturized electronic components, numerous factories would not be needed any more. In addition, simple objects are in general more robust and maintenance is easier. Other working time savings per year are therefore also expected thanks to longer objects lifetimes. On the other hand, a loss in productivity and optimization suggests that the time to mass coefficient would be impacted. For this scenario, r is therefore assumed to be smaller and k higher than in scenario 1. The following parameters are proposed:

- w=2000 hours
- $r = 5 \times 10^5$ hours It means that 500,000 hours of work would be required to produce all

objects and consumables needed for a single person per year.

- $s(n) = n^{\alpha}$ Same role as scenario 1.
- $k = 0.00002$ This value is justified to maintain in first approximation p(1)=10 tonnes (see method in scenario 1). Productivity is less important and miniaturization is less effective. The mass conversion coefficient is therefore higher (assumed twice as high as in scenario 1).

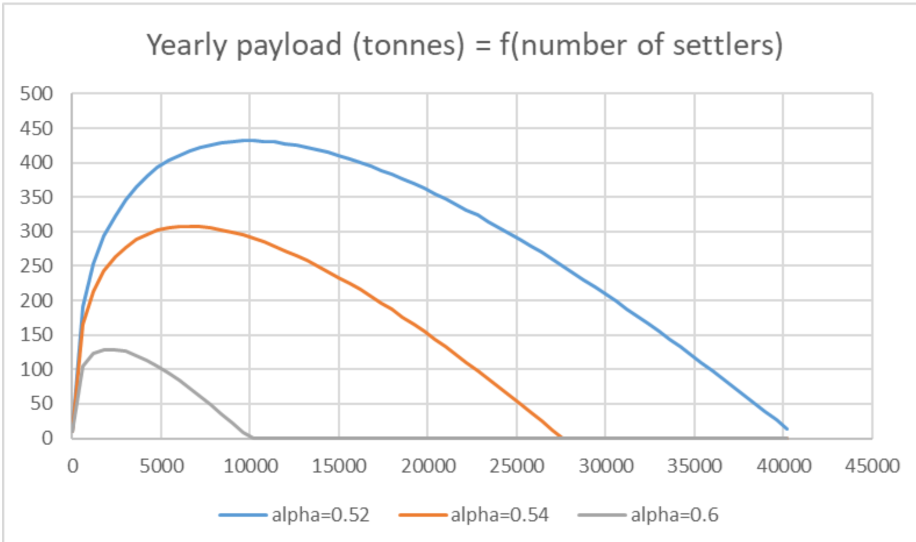

Fig. 2. Yearly payload for scenario 2.

The results are presented Fig. 2. Important simplifications of the problem have been made and the interpretation of the results remains a difficult task. However, assuming that the model is not oversimplified, the results suggest that it is preferable to avoid robots and other complex objects to reduce the period needed to achieve autonomy and also to minimize the peak payload requirements per year. With α=0.54, the peak payload mass would be around 300 tonnes per year when the colony reaches 27, 000 settlers. Although still a difficult challenge, this is much better than in scenario 1. If only 6 heavy launches were required per year, the colonization process would be close to affordability by a group of rich countries.

3.3 Scenario 3: survival

In this scenario, it is assumed that the number of settlers is fixed and the problem is to look for parameters that allow the survival of the colony, which is determined by p(n)=0. Interestingly, the time to mass conversion has no impact on the problem. The only variables are r and α and the equation is very simple (equ.2).

$$r = 2000 * n^{\alpha} \quad (2)$$

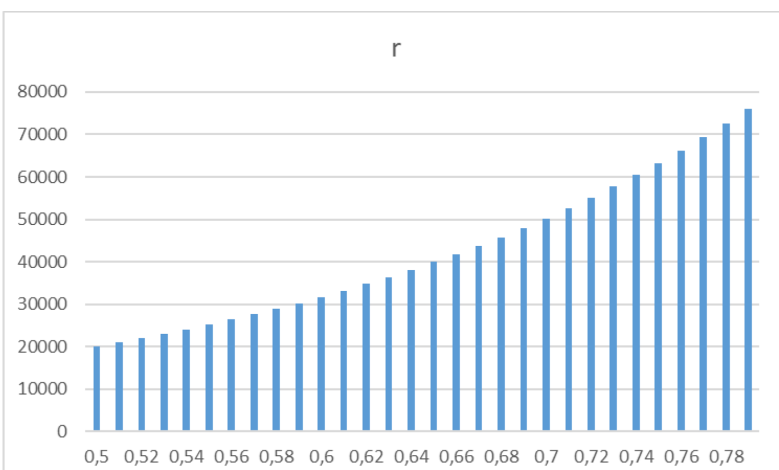

Fig.3: survival case, for n=100 settlers.

It is shown in Fig.3 that the survival of the colony for 100 settlers is possible only if two constraints are satisfied:

- a very low total working time requirement per person and year. The values are an order of magnitude lower than in scenario 1 and 2. Is that possible? Perhaps, but probably at the expense of good living conditions: People would probably have only very simple tools and would spend most of their time farming and extracting water and other important resources, with very low human resources for industry, medical acts, administration, etc.
- the sharing factor is very high, which means that a significant effort would have to be made to share all existing objects, as it could be expected in a big family or perhaps in a communist society, where all the food, the building, the vehicles and all facilities and devices would be shared among all persons.

4. Conclusion

Our model is very simple. We did not investigate much how to determine the values of w and s but it seems possible to provide estimates. For w, a bottom up approach is possible. The idea would be to fix an industrial strategy (for instance, all objects have to be made of iron or plastics) and to determine how much working time is required to implement all processes, from ores to object manufacturing, then to add the working time for life support, farming, education, medical acts, etc. For the sharing factor, it is also possible to list all objects and consumables and to determine for each of them if it is shared or not, and among how many settlers. A difficult question is how to take into account technological evolutions, development strategies, culture and human factors. Even if the model is very simple, it allows the discussion of different options with different parameters and provides conceptual insights into the difficult question of the feasibility. It is also important to notice that the model does not consider genetic constraints. Some authors tried to determine the minimum number of persons for survival according to the genetic variability [10]. It is suggested here that the strongest constraint is rather linked to the working time and the available human resources.

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