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Thermoeconomic Analysis of Martian Habitats

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Abstract

Martian habitats are pseudo-isolated systems, with strict requirements of mass, occupancy, and energy. A thermoeconomic can provide invaluable information to the viability and cost of possible habitat designs. The thermo-economic model can also be used to provide guidelines for optimisation and comparison between different habitat designs. This work creates a novel software to perform thermo-economic analysis of potential habitats at the Arcadia Planitia location on Mars. The analysis of the habitat system is split in three main categories which are life support systems (Oxygen/CO2 levels, food/water needs, waste, hydroponics), energy generation/consumption (electricity/heating, power sources) and human factors (physical/mental limits).

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1. Introduction

The futuristic plan for colonizing other planets and specifically Mars, has its own sector in the space industry and there is ongoing research on developing technologies to support humans on Mars [1]. There are several proposed designs for potential habitats that can accommodate life on the red planet. However, there is no standard method on comparing those proposed designs to decide which one is better or more suitable for each mission. The project aims to fill the gap in the industry, due to lack of a comparison tool between the habitats, by developing a comparing tool. The development of a software named "ARHS"[1] that it will perform such a comparison. The software will be validated with the use of pre-existing data by expeditions on the ISS and analogue astronaut missions. To do such compromisation the relevant assumptions had to be me made and most importantly the assumptions that gravity and radiation levels are almost identical to ISS. In the future, when the database of the software increases, it could potentially act as an optimising tool suggesting improvements to minimise the cost of the mission. The analysis of the habitats, independently of comparison or optimisation, requires a big amount of inputs. This ensures that all the affecting parameters have been identified and calculated, with the scope to provide the most accurate and reliable results.

1.1. Background

The thermoeconomic analysis of this study provides emphasis to the viability and cost of possible habitat designs that can accommodate humans for prolonged periods at the Arcadia Planitia location on Mars. This location, shown in Figure 1, offers a smooth surface for possible landing , as well as access to potential ice formations and shelters from solar radiation [2].

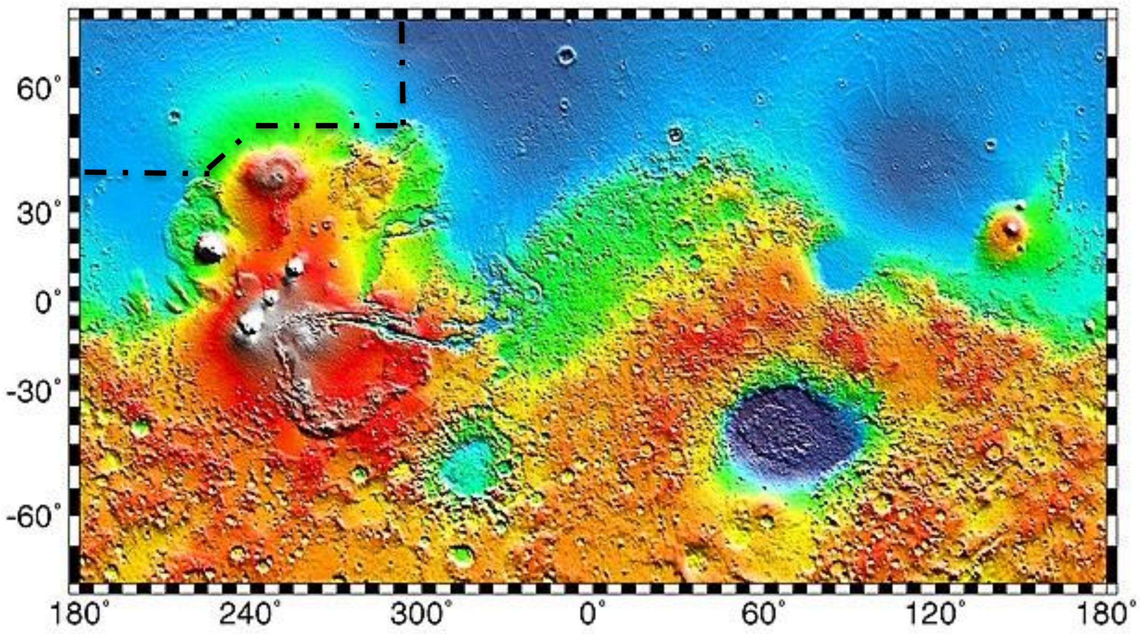

Figure 1: Global topography of Mars, the different colours indicate the different terrain of the location. Arcadia Planitia is located in the top left corner of the figure enclosed by the dotted lines [2].

The past few years there have been several design proposals for habitats on Mars especially from the NASA "eXploration Systems and Habitation (X-Hab) Academic Innovation Challenge" [3]. There are some implementations through the world with analogue habitats, simulating conditions on Mars in order to gather data for the life supporting systems for similar designs [4]. Despite its importance, thermoeconomic analysis barely appears in the literature, there are a few separated researches, but only on the one side of the analysis. For example, there are papers that they concentrated on the thermal analysis of habitats and don't consider the cost [5]. "ALLiSE" is the only known software in Europe which accommodates most of the thermodynamics parameters required for such research [6]. However, this software is focused on lunar habitats [7] rather than Martian due to Moon prioritization for European Space Agency (ESA) [8]. Exploring Mars is still important and there is an ambition that one-day humanity will inhabit the red planet [9] and that is why this project is important.

[1] ARHS is an Anglicisation of a Greek spelling of the word Ares (=Mars)

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1.2. Aim and Objectives

The scope of this paper is to illustrate the methodology and the approach followed, in order to achieve the objectives of the project:

I) Identification of parameters of the thermoeconomic analysis of Martian habitats.
II) Develop the software, with clear inputs and outputs.
III) Perform thermoeconomic analysis of designs, to validate the software.
IV) Proposal of energy source for each design based on the results from the analysis.
V) Provide comparison between designs, considering the cost.

1.3. Methodology

The thermoeconomic analysis is separated into the two sub-analyses, the thermal and the costing. The approach of this project is to tackle one analysis at a time, initiating from the thermal analysis which appears to be the most complex.

To perform the thermal analysis, the following separations had to be done to identify and select the parameters affecting it. This segmentation lead into two main sections; the three main categories and the three main classes. These categorisations and classifications are inspired by ESA [6]. The three main categories are:

1) *Life Support Systems* (LSS) (Oxygen/CO2 levels, food/water needs, waste, hydroponics).
2) *Power production/consumption* (electricity/heating, power sources).
3) *Human factors* (physical/mental boundaries).

The power generation is a rather separate part of the software, but the power consumption is inextricably linked to almost all the classes. The reason of this difference is because the power generation system it will be proposed to the user after the final consumption calculation, as it depends on the range of it. The human factors category constrains the LSS in such ways to ensure that life can be maintained in the systems. It controls, from the optimum temperature to the constrains of oxygen (O2) and carbon dioxide (CO2) level limitations. The tree classes: 1) Controllers 2) Flows 3) Systems. The analysis of them can be found in detail in the upcoming section of Project Development.

The economic factors will be introduced once the first sub-analysis is performed. The approach for this second analysis will be straight forward with the values allocated to each flow in Great Britain Pounds. The exchange rates that are used are: 1 £ = 1.2369 $ and 1 £ = 1.173 € which are the average exchange values of 2022 [10] [11].

Combining the two sub-analyses they form the thermoeconomic analysis which it will provide a value for the power demand of the mission. Then the software will recommend the most value for money power generation system. Finally, the software after processing different scenarios with different inputs and outputs, it will provide the user with a table sorting from the lowest to the highest value. Giving the opportunity to easily compare different missions based on all the aspects and find which inputs parameters are fit the budget of the user.

2. Project Development

The project is separated into two main sections: the categorization of the classes, the presentation of the main features and abilities of the developed software and software status

2.1. Classes

It was the proper separation of each influencing parameter of the Thermoeconomic analysis. Extensive research has been made up to the date of this report as deep understanding is required to ensure the correct link of different classes. the main classes are divided into the three main categories.

Flows: are indicated in the figures below as arrows. They can represent either flow of mass or flow of energy connecting the systems to either other systems or to controllers. All the possible flows can be located in Figure 2 and Figure 3 , were the arrow on the line indicate the direction of the flow. The three orange lines that they are dashed, mean that they require permission from the software to initiate flow. The thicker orange lines indicate the flow of energy to the hydroponics and crew systems as in some cases the energy is provided to the controllers and the controllers are altering the electricity to useful energy for the system. For example, for the hydroponics electricity is provided to the lightings and the lightings are used for the photosynthesis of the hydroponics. The blue thick arrows represent the flow of masses. In detail, it can be seen from Figure 3 that the cargo provide food, water and breathable air to the crew. Then the crew process them and provides back to resources the recovered urine, given by the composter. The crew extracts waste which includes feces and other biodegradable waste, such as wet wipes, which along with the CO2 and grey water are transferred to the hydroponics system. The grey water is a combination of the water used by

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the astronauts for any technical purpose in the habitat and by the dehumidification of the air. Once the hydroponics receive these inputs from the crew system along with the inputs from the resources and power, it provides back to the crew direct access to food and oxygen.

Controllers: which are constants of the system and do not affect the flows. The controllers are then split into two subcategories as it can be seen in Figure 2, the *Simple Appliances* which consume energy based on the input data and the *Life supporting systems* appliances which are constrains from the software, including the optimum temperature, humidity, O2, Nitrogen (N2) and CO2 levels.
The main difference is that the simple appliances are affected by the inputs whilst the others are not. Their common factor is that all of these appliances require a constant power that needs to be provided by the power source system.

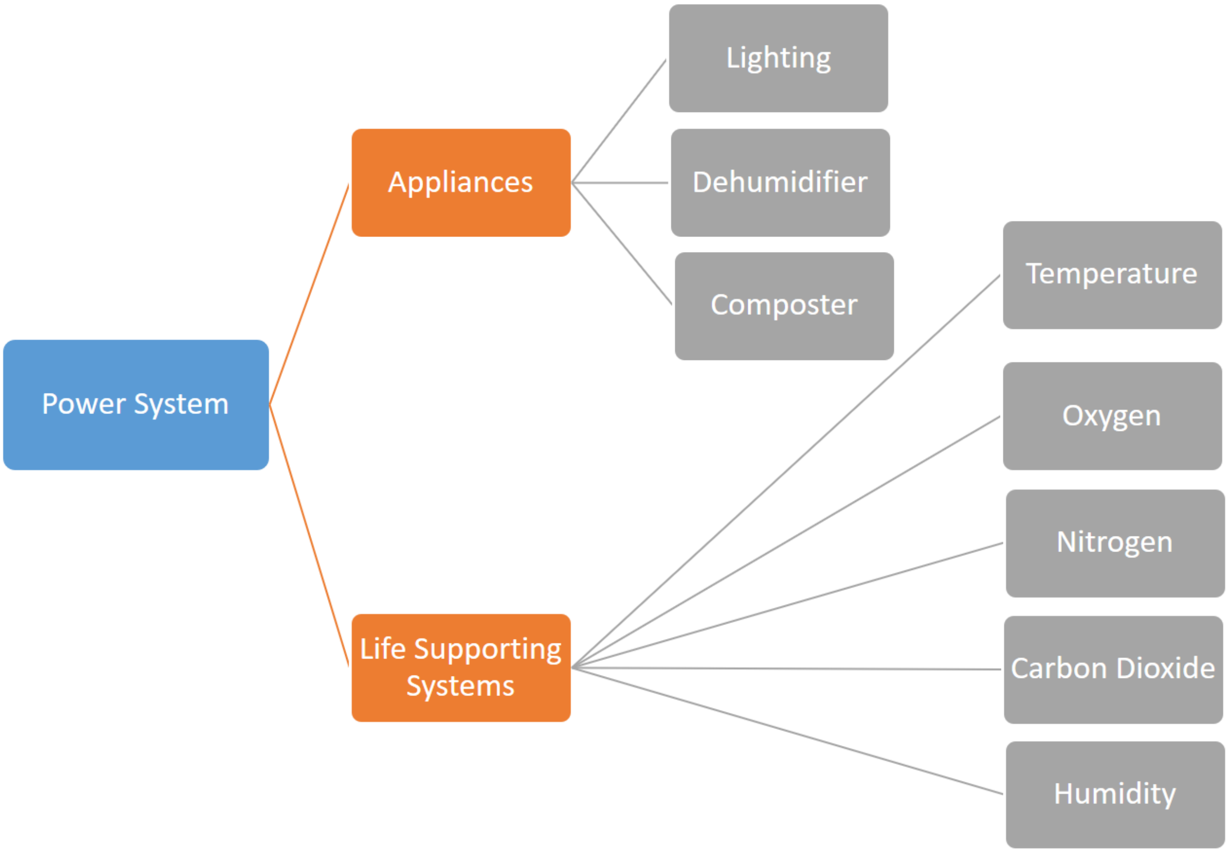

Figure 2: Schematic representation of the connections of the Power system and the controllers. Controllers are separated into 2 main categories.

Note: The composter is considered to include also the urine recovery system and the dehumidifier is providing grey water while ensuring that the humidity and temperature are at the optimum levels. Moreover, these are not the only appliances in the habitat, but they are the ones that are considered to have significant impact on the power consumption. The heating and cooking are embedded in the LLS appliances as they are necessary for survival.

Systems: are defined from their continuous interaction with other systems through the flows. Hence, they have “inflows” and “outflows”, see Figure 3. There are two type of shapes black rectangles and red parallelograms. The parallelograms are optional system and require permission by the software to operate, based on the outcome of the analysis. The black rounded corner rectangles indicate the main systems that they are continuously operating to ensure that life can be supported in the habitat.

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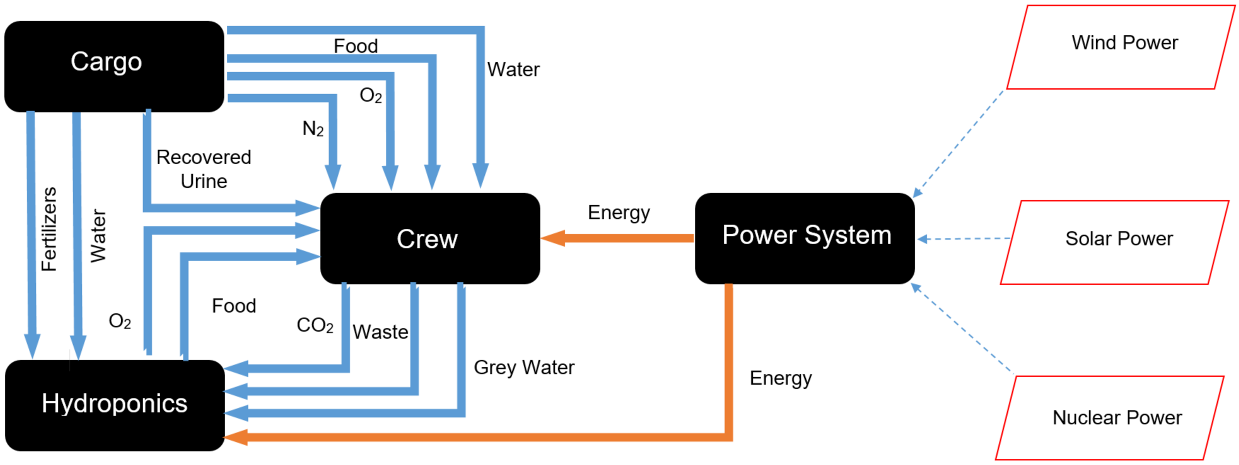

Figure 3: Schematic of representations of the three classes. The black rectangles represent the main systems, the red parallelograms the secondary systems. The blue arrows represent the mass flows and oranges arrows the energy flows, whilst the dotted lines represent again energy flows but are activated only on demand.

The most interactive and important system is the crew, which is defined by the number of days and the number of astronauts of the mission. Additionally, the hydroponics system requires as input the dedicated surface area available, the type of vegetables used for planting and the harvesting method. These inputs can be processed to define the requirements for both cargo and power system.

The software will evaluate the amount of power required for the habitat and based on the range of that value, it will propose the suitable power generation system. The current range of energies vary as follows; Wind power suitable up to 400 W [12], Solar power for levels of 400-600 W [13] and nuclear power can cover ranges from 500 W to 50 MW [14]. It should be noted that all these values are under conditions and assumptions, that they can theoretically be found on Mars [13]. Wind is suitable for low to medium power usage, solar for medium and nuclear power can provide all the ranges. Although, nuclear is significantly more complex to install and maintain, it is not weather dependent which can be a significant factor [14]. The main factor for selection of the most suitable power generation system will be the consideration of cost. A combination of wind and solar energy might be plausible for the optimized outcome.

2.2. Software

"ARHS" it is still in a premature state as it requires a lot of hours until its expected final result. The current status of the software is that it receives three main inputs and provides four main outputs. In the processes, it generates many intermediate parameters based on the literature review performed to allow accurate and representable outcomes.
The main inputs are:

- Number of Astronauts
- Number of Days
- Hydroponics
  - Surface area available for planting
  - Type of crops
  - Harvesting method

The software provides a catalogue of four choices for the plants that they can grow on a hydroponics system similar to the ones tested on the International Space Station (ISS) along with the options for a single or a multiple harvesting method and the user is required to choose. Then, based on literature intermediate parameters are calculated to provide the necessary outcomes. For example, the waste is calculated by the simple calculation provided by the literature [15]:

$$Waste = 0.156 * Number\ of\ Astronauts * \frac{days}{365} \quad \text{[Kg/mission]} \tag{1}$$

The 0.156 Kg of waste include 0.128 Kg of feces per day on average and anything else biodegradable that astronauts turn into waste. This is effectively the environmental footprint of humans on Mars as waste is non-recyclable nor reusable mass that is dumped on the planet. Similar calculations and references have been used for most of the flows to calculated all the in between parameters.
Object Oriented Programming was used to ensure the flexibility and ease of interactions between the systems by using the flows. The main outputs that "ARHS" provides are

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- Amount of water
- Amount of Nitrogen and Oxygen
- Food quantity
- Required budget

However, to reach these four main results, it generates a lot of intermediate parameters that help to connect the interconnected flows. Some examples of these non-primary results from the calculations are: the food required by the astronauts, the cost of it, the water demanded by the hydroponics, the amount of grey water generated, the exhaled carbon dioxide, the weight of the tools and seeds required, the waste produced by the crew, the amount of eatable greenery from the crops and many more. Example of some of these parameters can be better visualised in the Table 1 below. The first two rows indicate some possible inputs to the system and then the flows of two of the main systems, crew and hydroponics, are calculated. There are many more parameters that they need to be found before eventually leading to the four main outcomes stated above.

Table 1: Example of inputs and outputs from the system

	Days	**Astronauts**	**Hydroponics Area [m²]**	**Type of Crops**	**Harvesting Method**
Inputs	500	6	40	Red Russian Kale	Single
Intermediate Parameters	**Processing**				
Crew System	**Food [Kg/mission]**	**Cost of Food [£]**	**Waste [Kg/mission]**	**Grey water [Kg/mission]**	**Exhaled CO2 [Kg/mission]**
	5400	$2.16x10^8$	1.28	81000	13860
Hydroponics System	**Water for plants [Kg/mission]**	**Hardware required [Kg/mission]**	**Eatable greenery [Kg/mission]**		
	53.73	17	242.69		

3. Conclusion and Future work

The continuous technological advancements have increased the hopes for colonizing other planets and specifically Mars. This project will perform a thermoeconomic analysis on Martian habitat designs with the scope of generating a software tool that it can be used for the comparison of the habitats. The methodology and approach followed to tackle this gap in the industry was investigated in this report. The software is based on object-oriented code and is under development with clear strategy to fill the industrial gap.

The future steps for the software after its full development are well defined. The first step will be the extension of inputs, adding parameters such as the gender, age, body mass index and more personalised details of the crew, which they increase the accuracy of the comparison between different scenarios. Then the costing can be used as the factor for optimisation by the software. Simply, the cost of the resources along with the cost for the recommended power source will be evaluated compared to the duration of the mission and the amount of astronauts. If the outcome is not within the expected range then the optimization will take place to provide possible solutions, such as the recommendation of using plants that they can provide more food or require less water.

This project will be an added tool for the space experts to support the choice of a future habitat selections for Mars expeditions, by standardising and simplifying the required thermoeconomic analysis.

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