104f A Simulation-Based Optimization Approach to the Evolution of an Advanced Life Support System for Mars Base

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In this work, a Simulation-based Optimization (SIMOPT) approach is proposed to predict the evolution of a Mars base. The Mars base is an advanced life support system (ALSS). An ALSS is a set of technologies to regenerate the basic life support elements, i.e. oxygen, water and food during long-term spaceflight, whether in low Earth orbit, on the Moon, on Mars, or beyond. The most important aim of the ALSS technologies is to provide a habitat that ensures health, safety and maximum efficiency of crewmembers.

An ALSS is subject to a myriad of uncertainties because most of the technologies involved are still under development. The result is high levels of uncertainties in model parameters estimates, such as unit conversions, recovery rates or process efficiencies. Even for fully developed technologies, it is difficult to predict behavior due to the unknown and different nature of the environmental conditions (e.g. lower gravity of Mars) that will be encountered beyond Earth. Moreover, due to the high recycle rates within ALSS, the uncertainties are amplified and propagated within the system resulting in a complex problem.

As currently configured, the ALSS includes six subsystems. They are air, biomass, food, thermal, waste and water. The air subsystem stores and maintains the habitat atmospheric conditions by controlling pressure, overall composition and trace contaminants. The biomass subsystem produces, stores and provides raw agricultural products to the food subsystem while revitalizing air and water. The food subsystem receives harvested agricultural products from the biomass subsystem, stabilizes and stores them, and transforms them into a ready-to-eat form via food processing and meal preparation operations. The thermal subsystem is responsible for maintaining cabin temperature and humidity within appropriate habitatable bounds. The waste subsystem collects and conditions waste material from anywhere in the habitat, including packaging, humans, inedible biomass, and brines. The water subsystem collects waste water from all possible sources, recovers and transports potable water, and stores and provides recovered water at the appropriate purity for crew consumption, hygiene use and external users [1].

For each of the above subsystems, ongoing research is being conducted to identify, develop and test what are referred as 'ALS technologies'. Some examples of 'ALS technologies' are the Sabatier process, in which CO_2 is reacted with H_2 for CO_2 reduction within the system, Solid Polymer Water Electrolysis to produce O_2, Super Critical Water Oxidation for waste recovery and Vapor Compression Distillation for water recovery from urine. For each subsystem, there are numerous technology options that can be used for the same application. Therefore, the question of which technology to deploy for which purpose at which stage of the base's evolution presents a significant challenge for the researchers. This is very similar, if not identical, to the chemical plant design problem considering and planning for the retrofits during the initial design phase. In the ALSS domain, the answer depends on the readiness level of the technology, its efficiency, transportability, safety, reliability and durability, as well as its performance within the integrated system of the overall ALSS. Here, we present a SIMOPT framework to determine the evolution of the ALSS base.

The SIMOPT approach [2] uses the concept of timelines to generate multiple unique realizations of the controlled evolution of the ALSS base. A typical SIMOPT timeline involves several applications of the Deterministic Optimization (DO) algorithm to determine optimized values for system degrees of freedom, such as when to install which technology within any ALSS subsystems. In between each DO optimization on a timeline, the simulation is used to determine the integrated system behavior. The various timelines arise from the randomness introduced through changes in parameter values, and exceptional random events that are imposed on the simulation.

The SIMOPT framework utilizes simulation and optimization together in an iterative fashion. The SIMOPT approach can be implemented using SIMOPT agents, which consist of an inner loop and an outer loop. In the inner loop, discrete event simulation proceeds along a timeline (replication) with decisions determined by DO algorithm. The simulation is used to introduce uncertainty in the model parameters or exceptional discrete events and hence the simulation values will differ from those predicted by the DO optimization algorithm. When the decisions made from the deterministic optimization modules are no longer applicable due to uncertainty, the simulation is paused and the system is re-optimized preserving the state of the system. The new decisions are fed back to the simulation for the remainder of the timeline and the simulation is resumed again preserving the system state. As an example in our application, assume that the DO algorithm determines to install process (technology) *i* at time *t* within the subsystem *j*. Throughout the course of the simulation, suppose, the technology does not behave as predicted by the DO algorithm due to a change in the efficiency of the process or a malfunction. Then, the simulation is paused and DO algorithm is run again to determine the decisions that will be applied for the rest of the simulation. This cycle is repeated as required until the end of the timeline. In the outer loop however information gathered from different timelines is used to update the parameters of deterministic optimization modules used within the inner loop. The success probability of technology *i* is an example of one of the parameters that is used in the DO module. Here, we refer to success probability as the probability of process *i* being able to perform the predefined task within some prescribed upper and lower limits of certainty.

Using the described SIMOPT framework, a case study is carried out to determine the evolution of a Mars base. The transfer opportunity between Mars and Earth occurs once every 26 months. In this study we assume that 3 trips will be done from Earth to Mars which results in a mission of 6.5 years. The technologies that are considered for this study are limited to Physical/Chemical (P/C) or partial P/C technologies, whose behavior can be predicted with better certainty, compared to the biochemical ALSS technologies. The best possible combination of the technologies, the deployment strategy and schedule are determined out of eight different processes for the Air subsystem, ten different technologies for Waste subsystem and 12 different technologies for Water subsystem. We also assume that all the food is shipped from Earth as pre-packaged food, hence Biomass subsystem and Food subsystem involve only storage facilities. The results of this case study will be presented and the similarities with a chemical plant design will be highlighted.

[1] Hanford, A.J., "BVAD: Advanced Life Support Baseline Values and Assumptions Document", NASA JSC 47804, 2004.

[2] Pekny, J. F., "Algorithm architectures to support large-scale process systems engineering applications involving combinatorics, uncertainty, and risk management", *Computers and Chemical Engineering*, Vol. 26, pp. 239-267, 2002.