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Design of executable space mission architectures using discrete network flow optimization

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As humans explore Space, the demands for space logistics and infrastructure has increased dramatically since the pioneering suborbital flights: current space program goals such as sending humans to Mars force space mission architecture and planning to become far more sophisticated than simply sending a crewed mission to its destination with everything on board. To this effect, new methods have to be devised in order to address the problems of long duration space flight. One of these is generalized multicommodity network flows. This approach was created by applying network-based logistics methods to space mission planning. Classical network flows optimize the distribution of flows through a network to achieve an optimum, such as the maximum throughput or minimum transportation cost. In the space mission case, commodities such as vehicles, propellant, crew, etc. are abstracted as flows and the problem is formulated to minimize initial mass in low earth orbit. However, this method has shortcomings regarding the fidelity of the models because of its linear network nature: examples of this include the inability of following a vehicle through the network or the generation of unfeasibly small vehicles. In this work, these problems are addressed and solved using mixed integer linear programming and a tracking algorithm. The case study considered is a manned exploration mission to Mars with identical requirements to DRA5.0 using NTR, ISRU, and aerocapture. An architecture of this mission is obtained using this optimization method. It is found that lunar ISRU only reduces the IMLEO by 5% compared to a direct Mars mission. Lunar ISRU is found to be ineffective at reducing IMLEO below the critical value of 3 kilograms of propellant mined per kilogram plant per year. The removal of NTR and aerocapture technologies is found to increase IMLEO by 33.0% and 27.5% respectively with respect to the baseline scenario using both technologies.

Contents

Nomenclature

DFS	Depth-first search
$GMCNF$	Generalized Multicommodity Network Flows
$IMLEO$	Initial Mass in Low Earth Orbit [kg] or [MT]
Isp	Specific Impulse [s]
$ISRU$	*In Situ* resource utilization
$LCH4$	Liquid Methane

LH2	Liquid Hydrogen
LOX	Liquid Oxygen
NTR	Nuclear Thermal Rocket
TPS	Thermal Protection System

Introduction

As space becomes more and more accessible through technology development, space systems design has also become increasingly complex due to the rising performance requirements.

A campaign-level perspective for space systems design is needed in addition to the conventional mission- level perspective. A campaign contains multiple missions that may or may not be for the same destinations or purposes. Campaign-level strategies include uses of technologies and infrastructure considering the whole campaign, such as a combination of pre-deployment, carry-along, and resupply strategies, which will be crucial for interplanetary missions in the long term. In addition, effective use of different technologies and infrastructures such as advanced propulsion system[1–4] , propellant depot,[5–12] and in-situ resource utilization (ISRU)[13–20] have potential to enable or facilitate long term missions.

Given that background, the aim of this work is to find an efficient optimization process considering campaign-level mission planning for future human and robotic space exploration. This paper intends to improve the most advanced work recognized by the authors in space logistics optimization literature, which uses time-expanded generalized multicommodity network flow (GMCNF) approach for space logistics modeling.[21–23] In the previous work, linear programming (LP) based network optimization approaches have been shown to be effective.[21–23]

However, using continuous variables for all flows does usually not provide a realistic solution (i.e. a solution that can not be executed, as will be discussed in section 2).

The new executable formulation is proposed and applied to a case study containing human exploration of Mars. This case study shows that a design from a campaign-level perspective would improve the performance over mission-level based design in terms of initial mass in low earth orbit (IMLEO). However, it mitigates the performance gains advocated in[21,23] using similar methods.
The rest of the paper is organized as follows: Section 2 summarizes past research in space logistics modeling, and Section 3 presents the new method. Section 4 applies the proposed method to the case study. Section 5 provides the results of a case-study and section 6 concludes the discussions.

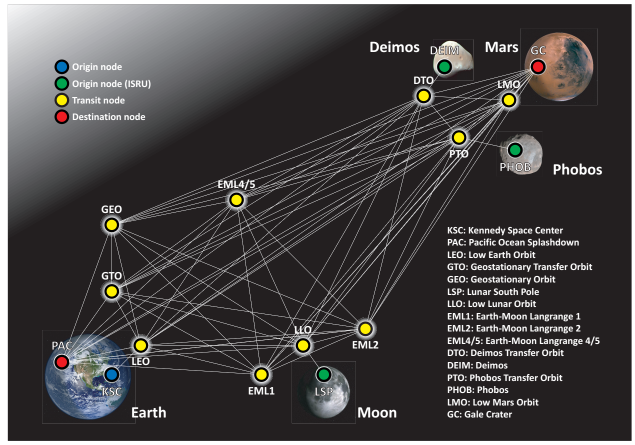


Fig. 1: EarthMoonMars logistics network graph based on the figure by Ishimatsu.[21] Full explanation of this figure may be found in previous work[21]

Literature review

Although the importance of space logistics was recognized as early as the 1960's, only recently has it been studied in the context of the efficient human exploration of Mars. Only network flow based space logistics are discussed here. A detailed literature review of space logistics research can be found in past articles.[22,23]

Network modeling has been found to be an effective technique for efficient optimization of space logistics: by converting the space logistics map into a mathematical graph (as shown in Fig. 1) many mathematical and operational research techniques become applicable to the problem. In this context, the nodes of the network correspond to physical destinations or potential locations for staging or mass transfer in space, whereas the arcs connect pairs of nodes *via* a form of trajectory. The arcs connect each pair of these nodes where transportation is allowed.

Dynamic GMCNF

In order to tackle those problems, Ho extended the GMCNF formulation into a time-expanded network.[23] In this way, the time inconsistencies evident in the static formulation can be removed and the infrastructure deployment phase can be considered dynamically. As a result, the method can be used not

only for architecture trades but also for space mission planning over time:
The essential feature of dynamic GMCNF methods is to expand the spatial network in time. A full time-expanded network duplicates the set of nodes over time so that the dynamic flow can be solved as a notional static network. An assumption that makes this possible is that all necessary time steps (e.g., arc transit time, time windows) are rounded to an integer number of days. Although the dynamic GMCNF methods have solved the problems related to time-paradoxes, they have received criticism in the space logistics community due to a series of problems:

- Solutions exhibits "rubber" hardware: although GMCNF constraints forbid any commodity to spontaneously grow, they do not forbid a commodity to shrink. This phenomenon is useful to model the demise of hardware such as a rocket stage or a no longer useful ISRU plant. However in previous GMCNF formulations hardware commodities were modeled as being continuous,[21, 23, 24] thus hardware elements could "leak" mass (i.e. resize themselves) during a scenario. Because this behavior does not reflect current hardware capabilities, it renders the results infeasible. The continuous nature of the problem also allows unrealistically small flows to exist: previous results[23] show nuclear rocket stages smaller than 10 kg.

- Although the above-mentioned issue was sufficient for not further studying the solutions of dynamic GMCNF, a closer look at them reveals that it is non-trivial to understand how the solution translates to a schedule: because a flow of magnitude μ representing a piece of hardware may split (or merge with another flow) in a way that the exact trace of μ is lost over the network and thus the path that piece of hardware becomes lost. This "mixing" phenomenon is inherent to the continuous nature of the problem. These occurrences render the results logistically infeasible, or *un-executable*: the campaign or mission cannot be executed because the trajectories of the elements in the transportation network are unclear.

The contribution of this work is to address the problems mentioned above and produce a method capable of designing *executable* space missions through numerical optimization. The approach adopted here is the following:
Post-processing of GMCNF results is avoided, because of the high probability of violating constraints such as mass balance, transformation constraints or concurrency constraints. Thus improvements must be made upstream of the optimization process: in order to avoid the "mixing" and loss of information, a transition to integer programming must be made. This first modification leads to the generalized MILP formulation of GMCNF. Although the result produced is executable, there is still no direct information on how different elements travel through the network. This is addressed by post-processing the executable results using a tracking algorithm developed for this purpose.

Executable space logistics modeling

This section presents the mathematical modeling for campaign-level executable space logistics modeling. The goal of the modified GMCNF method described here is to produce results that are executable, i.e. the results can be directly translated into a mission or campaign plan that can be physically executed.
This section presents the two modifications necessary to transition from a dynamic GMCNF to an executable GMCNF:

- the first modification: the discretization of the commodities that model discrete quantities such as crew and spacecraft.

- the second modification: the addition of a tracking algorithm that shows how a given element travels through the network.

generalized MILP formulation of GMCNF

As mentioned above, a continuous range of flows leads to the inability of understanding which part of a flow goes where when flows merge and separate. However, if these flows were multiples of a reference quantity, then it becomes possible to understand how units of this quantity are exchanged at nodes. Going from continuous range flows to discrete flows means transiting from a linear problem to a mixed integer linear problem (MILP). A discrete flow may be modeled by doing a change of variables: the continuous variable x is replaced by $\tilde{x} = \frac{1}{m_{unit}} x$. Because of its linear nature, any variable x_{ije} (flow of commodity e on arc ij) may be normalized in this way by any unit mass m_{ije}. The transformation required to go from the classical to the generalized MILP formulation is presented below. The linear constraints presented in previous work[21, 23] are aggregated into

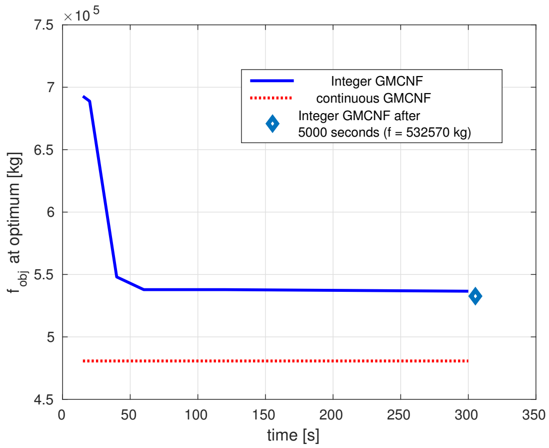


Fig. 2: Convergence of the objective function as function of CPU time for the Mars exploration application shown in Fig.1. The objective function is IMLEO. The processor is a Intel(R) Xeon(R) CPU E5-2620 v3 2.4GHz ×2 (2 processors) that is run using Gurobi®optimization software.

equality constraints $\tilde{\mathbf{A}}^{eq}_{ij}\tilde{\mathbf{x}}_i \leq \tilde{\mathbf{b}}^{eq}_j$: and inequality constraints $\tilde{\mathbf{A}}^{ineq}_{ij}\tilde{\mathbf{x}}_i \leq \tilde{\mathbf{b}}^{ineq}_j$:

$$\begin{array}{ll} \text{Minimize} & \mathcal{J} = \tilde{\mathbf{c}}_i\tilde{\mathbf{x}}_i \\ \text{Subject to} & \tilde{\mathbf{A}}^{ineq}_{ij}\tilde{\mathbf{x}}_i \leq \tilde{\mathbf{b}}^{ineq}_j \\ & \tilde{\mathbf{A}}^{eq}_{ij}\tilde{\mathbf{x}}_i = \tilde{\mathbf{b}}^{eq}_j \\ & \tilde{u}^{lower}_i \leq \tilde{x}_i \leq \tilde{u}^{upper}_i \end{array}$$

Where

$$\begin{array}{rl} \tilde{\mathbf{c}}_i & = \tilde{m}^{unit}_i \mathbf{c}_i \\ \tilde{\mathbf{A}}^{ineq}_{ij} & = \tilde{M}^{unit}_{ij}\mathbf{A}^{ineq}_{ij} \\ \tilde{\mathbf{b}}^{ineq}_j & = \mathbf{b}^{ineq}_j \\ \tilde{\mathbf{A}}_{ij} & = \tilde{M}^{unit}_{ij}\mathbf{A}_{ij} \\ \tilde{M}^{unit}_{ij} & = \mathbf{diag}\left(m^{unit}_i\right) \\ \tilde{\mathbf{b}}^{eq}_j & = \mathbf{b}^{eq}_j \\ \tilde{u}^{lower}_i & = u^{lower}_i \frac{1}{m^{unit}_i} \\ \tilde{u}^{upper}_i & = u^{upper}_i \frac{1}{m^{unit}_i} \end{array}$$

However, as pointed out in previous work,[22–24] MILPs are expensive in computational resources if the global optimum is to be found. However, to achieve an efficient executable mission architecture the global optimum of the function does not have to be found: in the case of space mission design, the optimizer converges rapidly to values close to the global optimum, and increasing the number of iterations beyond yields little improvement, as shown in Fig.2

The combination of using a generalized MILP formulation and using the optimizer to find a locally optimal feasible solution as opposed to a globally optimal solution has the following advantages over previous approaches:

- Unlike heuristic methods such as used in previous work,[25,26] the error with respect to the global optimum may be controlled: current optimization software such as Gurobi will give an optimality gap.
- Unlike non-linear methods such as proposed in previous work,[26] the method can be applied to practical problems such as the Mars exploration problem.

GMCNF Tracking algorithm

The goal of the tracking algorithm is to "untangle" the network and understand how each element moves through the network.

An example of this post-processing can be seen in Fig.3. The outputs of the optimizer and the inputs of the algorithm is a weighted adjacency matrix as shown in Fig.4. Due to the constraints of the GMCNF optimization problem, this initial network has the following properties:

- For all non-starting nodes, we have:

$$\sum \omega^{in}_{ij} \geq \sum \omega^{out}_{ij} \qquad [1]$$

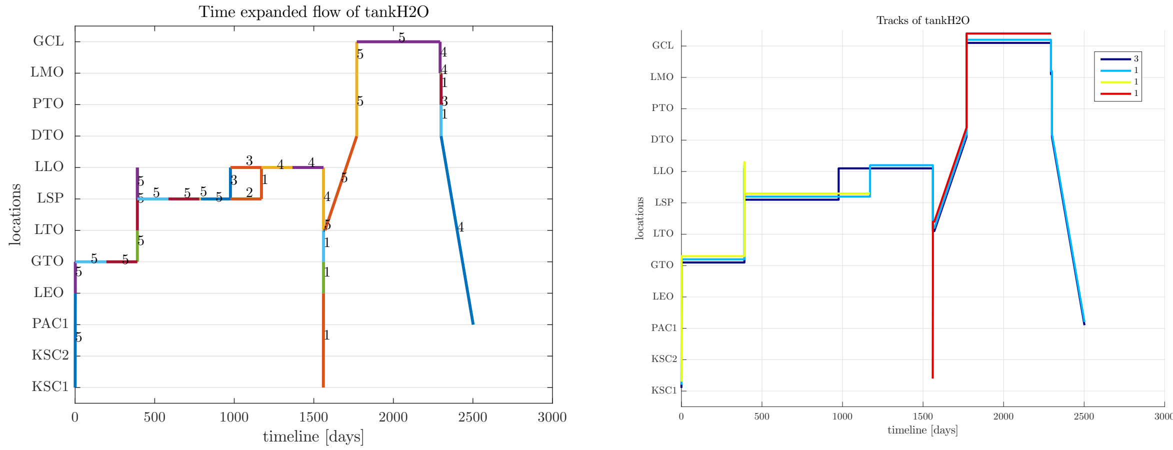
- All starting node have:

$$\sum \omega^{out}_{ij} \geq 0 \qquad [2]$$

- acyclic

Note that any sub-network of the initial network also has these properties.

The tracking algorithm a graph walk that starts at a starting node, systematically skims the list of all connecting edges with non-zero weights, follows that edge, subtracts a unit weight on that edge and repeats the process until it reaches a node with no weights going out. That path is stored, and the process repeated until the entire network has no more weights. In this case, systematically skimming the list means that the list of connecting nodes must not be altered and that it be skimmed consistently throughout the process. For example, the list may be read from top to bottom or bottom to top, but this direction must remain the same throughout the algorithm. Pseudocode is shown below in Algorithm 1.



(a) Raw exeGMCNF output

(b) Post-processed output

Fig. 3: Application of the tracking algorithm: the flows shown in Fig.3a are converted to elements. The color code indicates the element. The numbers in the legend represent how large these elements are. In this case, a single tank weighs 100 kg, thus an element with a 5 is a 500 kg tank.

Departure Node	Arrival node	Weight ω
1	2	4
2	3	1
2	4	2

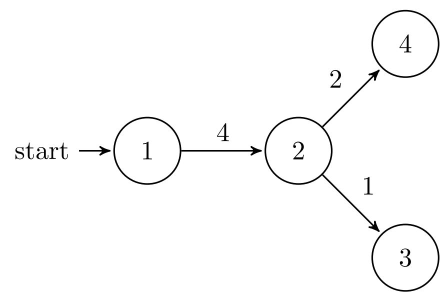


Fig. 4: Output of the optimization process: The adjacency matrix on the left represents the transportation network on the right. Each weight represents the number of units transiting from one node to the next.

Proof:

If the composition of the paths results in the initial network with all the correct weights, then the algorithm has worked. This proof is in two parts:

Conservation of weights within a path Suppose that the weights of the composition of paths has an error in the weights with respect to the initial network. Because the algorithm matches a single ingoing edge to a single outgoing edge, such an error would either propagate back to the starting node, in which case the initial network sought is not the initial network processed.

Full coverage of network The composition of paths might not cover the full network if the algorithm stops before all weights have been removed. This can not happen since the list of connecting nodes is systematically skimmed, leaving no connecting node out.

Case study: manned mission to Mars

This chapter applies the previously described method to a case study. The objective of the case study twofold:

- Give an example of an application of this enhanced method and how it compares to previous ones in terms of objective function (IMLEO)
- Give an example on how to evaluate potential benefits of new technologies such as aerocapture, nuclear thermal rockets and Lunar-based *in situ resource utilization* (ISRU)

Algorithm 1 Tracking algorithm

```
procedure GRAPH G, LIST START)
    Paths := ()
    while !Start.isEmpty() do
        v = Start.head()                          ▷ pick the start node of the path
        if v has a least one neighbor then
            List path = ()
            while v has neighbor u do             ▷ construct the path
                path += (v,u)
                AdjMat[v][u]–                     ▷ indicate in adjacency matrix that we consumed a unit
                v := u
            Paths += path
        else
            remove v from Start                   ▷ nothing to transport from v
    return Paths
```

Introduction

NASA and other institutions have renewed interest or focused their goals on sending humans to Mars.[27,28] Although detailed mission architectures have been proposed[29] many questions remain in terms of which technologies should be developed and to what extent in order to safely and cost-effectively land humans on Mars and bring them back. These technologies can be classified into three categories: (1) propulsion, (2) ISRU, (3) storage:

Propulsion In this study, the effects of 2 propulsion technologies is studies: the first one is the use of a nuclear thermal rocket and the second technology is aerocapture: it is considered here as being a propulsive technology, as it replaces propulsion to slow the spacecraft down during re-entry.

ISRU 2 types of ISRU are considered: one Martian ISRU, and one lunar ISRU. The Martian ISRU is assumed capable of producing methane, oxygen and water (assuming that water exists). Electrolysis is possible for extracted water. The plant mass defined here does not include the tanks. The lunar ISRU is assumed to generate oxygen and extract water (assuming that water exists). Electrolysis is possible for the extracted water. The extraction rate per unit mass of plant on the moon is a parameter that will be subjected to sensitivity analysis.

Storage many studies have been conducted on assessing the advantage of propellant or other commodity storage in space.[5–7] Although they are detailed and thorough, these studies focus on a particular mission or mission leg. By optimizing at campaign level such as it is done in this case, the true advantage (global optimum) of storage and the nature of it can be found, as opposed to an advantage for a given mission configuration (local optimum).

In this paper, only the sensitivity of IMLEO to NTR technology, aerocapture and lunar ISRU are investigated. The other sensitivities are left for future study. The results are compared to previous results.[21,23]

Assumptions

The case study is based on previous work:[23,24] all parameters and assumption are left identical unless mentioned otherwise, only the resolution method is changed. Some of the key parameters are repeated below for sake of clarity.

Mission timeline

The detailed timeline of the time windows can be found in previous work[23,26]

Objective function and variables

The objective function is the initial mass in low-Earth orbit (IMLEO) because it has been used as a typical figure of merit in the past literature.[21]
Unlike previous GMCNF methods, the executable GMCNF needs input concerning the size of the elements that travel within it. The choice of sizes (or discretization) in this paper was obtained using ouput from dynamic GMCNF (such as in[23,24]): in order to have a reasonable range of integers for a given commodity (upper bound < 30) and a reasonable unit size, i.e. a value close to that of existing hardware such as an upper stage.

Commodity	Unit mass [kg]	Variable type	upper bound
vehicle	10000	int	15
payload	-	cont	100'000
crew	100	int	6
crewRe	100	int	6
sample	-	cont	250
hydrogen	-	cont	100'000
oxygen	-	cont	100'000
methane	-	cont	100'000
water	-	cont	100'000
food	-	cont	100'000
waste	-	cont	100'000
inertLOX	1000	int	30
inertNTR	2000	int	30
inertLCH4	1000	int	25
inertLander	1000	int	25
tankLH2	200	int	20
tankLOX	400	int	20
tankLCH4	400	int	25
tankH2O	100	int	20
aeroshell	5000	int	20
plant o2	1000	int	10
plant h2o	2000	int	25
plant methane	850	int	15

Table 1: Summary of the parameters in the executable problem: the table shows the discretization of the different commodities. If the variable is chosen to be continuous, the upper bound is the maximum mass in kg, and if it is chosen to be discrete, the upper bound is the maximum number of instances along one edge. The lower bound is always zero

Demand and supply

Among these commodities, Habitat/Payload and Crew are demanded on Mars, and Returning Crew and Samples are demanded on Earth at a later time. The detailed demand is shown in Table 2. Also, infinite supplies are assumed on Earth for all commodities except for Returning Crew and Samples, which originate from the exploration destination.

Parameters and assumptions

Unless mentioned otherwise, the parameters and assumptions are identical to those in previous work.[24] They are summarized in tab.3. More details can be found in previous work[24]

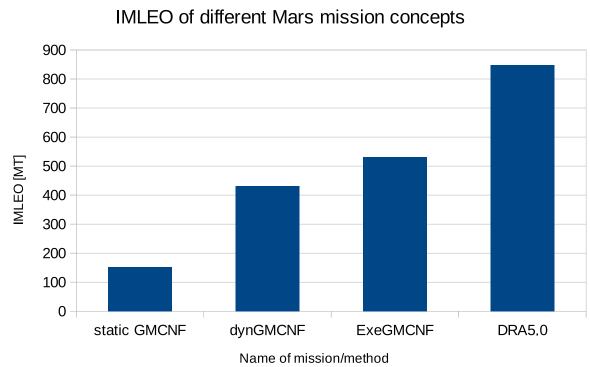


Fig. 5: IMLEO comparison

Results and implications

The IMLEO results are shown in Fig.5: as can be seen the executable GMCNF has a worse mass value than the dynamic GMCNF result from previous work.[23] This can be easily explained: unlike the dynamic GMCNF, the executable GMCNF does not allow vehicles or tank or any other form of hardware to resize itself continuously during the mission. In previous studies,[23] this would be a recurring phenomena: an example of this is the gradual downsizing of a nuclear powered shuttle that would carry ISRU extracted propellant from the Moon to GTO. In the executable GMCNF, this would not happen: either the shuttle would run at reduced capacity, or would not run at all if it were disadvantageous at the campaign level. Another possibility is staging: if a large element is made up of units, then the units may be discarded over time, effectively corresponding to staging.

Fig.5 shows that as the models become more accurate, IMLEO increases: the static GMCNF is overly optimistic because it does not take into account the deployement phase, the dynamic GMCNF is also overly optimistic because it does not discretize the elements in the network and thus allows them to adjust continuously. The executable GMCNF has neither problems, and thus shows a higher IMLEO, but nevertheless significantly lower than DRA5.0.

In terms of qualitative comparison, all missions (except the static GMCNF, which does not describe the timeline) have the same structure, as can be seen by comparing Figs.6,7,8. All missions have 2 distinct parts: the first part is always the propellant and infrastrcture build-up phase, be in on the Moon and Mars, or on Mars alone. The second segment is the actual human flight, represented in the bat-charts as

	Habitat/ Payload [kg]	Crew [ppl]	Crew Return [ppl]	Sample [kg]
Mars	51,700	6	0	0
Earth	0	0	6	250

Table 2: Demand of each commodity at each location for a Mars mission. Habitat mass does not include the consumables, ISRU plant, or crew.

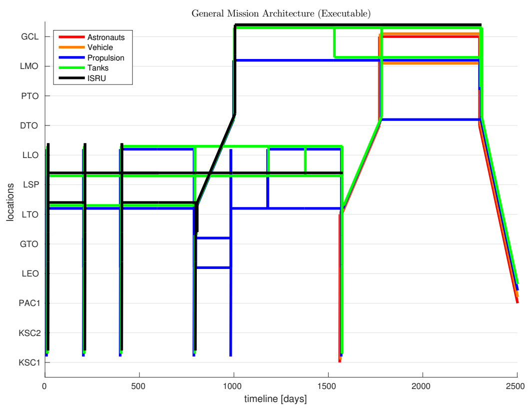


Fig. 6: Executable Mission (reference case, with 5kg/kg/year ISRU extraction rate

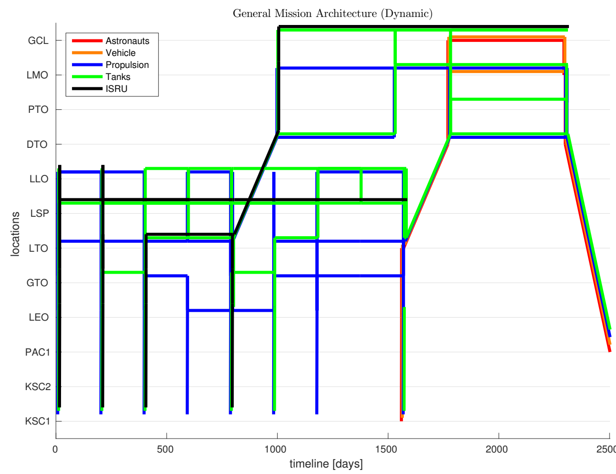


Fig. 7: Dynamic Mission[23] (reference case, with 5kg/kg/year ISRU extraction rate)

the red line. This similarity in architecture resulting from different approaches strongly suggests that this type of high-level mission architecture will be used for Mars mission regardless of how the problem is approached or by whom it is approached.

Although the mission overall mission architectures are similar between all approaches, the executable GMCNF displays different sensitivities than the previous static and dynamic GMCNF methods, as will be discussed next.

Sensitivity Analysis

This section discusses a sensitivity analysis for the results from the executable GMCNF with respect to 3 key technologies: NTR, aerocapture and Lunar ISRU.

Propulsion technology sensitivity

The sensitivity against the propulsion technologies selection is investigated by changing the problem setting in order to remove the technology from the scenario: in the propulsion case, removing the NTR means leaving aerocapture and chemical propulsion, and removing aerocapture means leaving NTR and chemical propulsion. The bat charts of the mission architectures generated by removing NTR or aero-

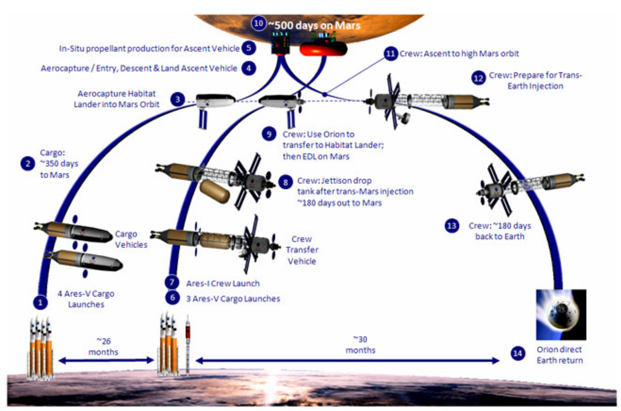


Fig. 8: Design Reference Architecture 5.0 (DRA5.0). This mission architecture uses ISRU to extract only oxygen from the Martian atmosphere at a rate of 12 kg/kg/year.[29]

Table 3: Summary of assumptions used in the analysis

Parameter	**Assumed Value**
Scope of problem	2500 days (7.1 years)
Mission data	
Number of crew	6
Mass per crew member	100 [kg]
Mars Transit Habitat (MTH)	27,540 [kg]
Crew Exploration Vehicle (CEV)	10,000 [kg]
Surface Habitat (SHAB)	51,700 [kg]
Propulsion system	
Chemical rocket (LOX/LH_2)	
Specific impulse I_{sp}	450 [s]
Mixture ratio μ	6.0
Inert mass fraction f_{inert}	0.08 (0.15 for descent/ascent)
Nuclear thermal rocket (NTR)	
Specific impulse I_{sp}	900 [s]
Inert mass fraction f_{inert}	0.35
Boil-off rate r_{bo}	
Hydrogen	0.127% per day ($\simeq$ 3.81% per month)
Oxygen	0.016% per day ($\simeq$ 0.49% per month)
Aeroshell mass fraction θ	40% of total mass being braked
Crew consumables consumption	
Oxygen	0.88 [kg] per crew member per day
Water	2.90 [kg] per crew member per day
Food	1.83 [kg] per crew member per day
Waste generation	5.61 [kg] per crew member per day
Oxygen leakage from vehicle	0.000123 [kg] per vehicle volume per day
ISRU system	
Resource production rate (Lunar soil)	5 [kg] O2 per plant mass per year[13,20]
Resource production rate (Lunar soil)	5 [kg] H2O per plant mass per year[13,20]
Resource production rate (Martian atmosphere)	10 [kg] O2 per plant mass per year[?,24]
Resource production rate (Martian atmosphere)	10 [kg] CH4 per plant mass per year
Maintenance mass required	10% of plant mass per year

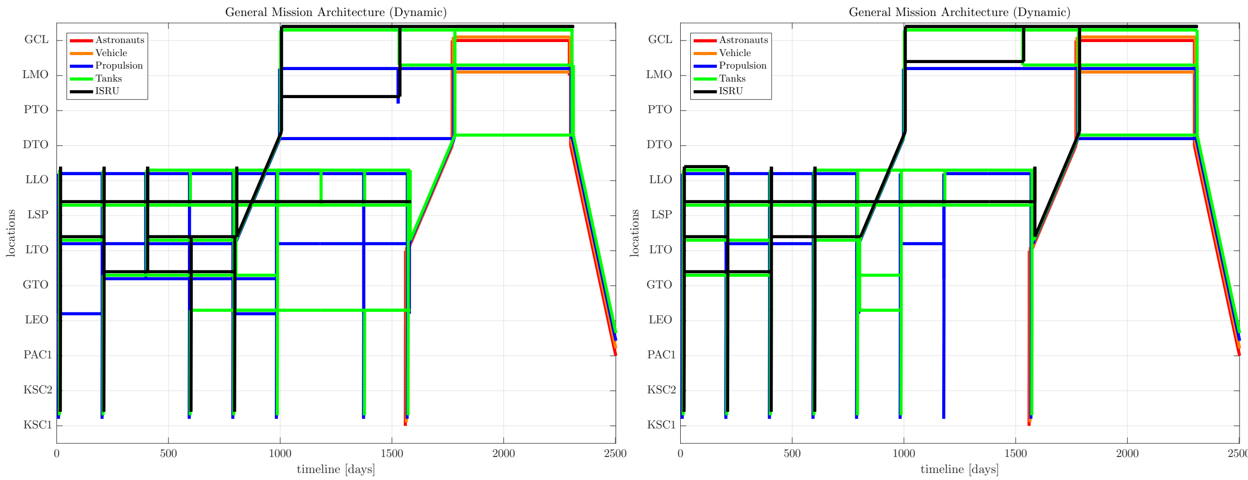
capture are shown in Fig.9a,9b.

Note that although the bat charts do not differ much, IMLEO is strongly affected by both technologies, increasing by 27.5% and 33.0% when NTR or aerocapture are remove, respectively. In the case of NTR, such a gain is in concordance with previous studies such as[4] and justifies the technology choices in.[29] As for aerocapture technologies, it's development this analysis shows it is as important NTR. This conclusion is qualitatively supported by.[30,31]

Lunar ISRU sensitivity

The main difference between the DRA5.0 architecture and the GMCNF methods is the lunar ISRU: it creates the large number of missions and infrastructure that is deployed prior to sending anything to Mars, and lengthens the overall campaign time. Thus the decision of visiting the Moon prior to flying to Mars represents a paradigm change in terms of technological development and space program agenda.

Previous studies, especially[21,23,24] argue that flying via the moon strongly reduces IMLEO, as can be seen in Fig10. When the system is discretized, this benefit is strongly reduced: the flying via the Moon with a 5kg/kg/year extraction rate only sets a 5% penalty on IMLEO compared to 20.2%[23] or a 87.5%[21] penalty at the same extraction rate. Given the investments and the time needed to accumulate the necessary propel-



(a) Mission architecture used when aerocapture is not used. (b) Mission architecture used when NTR is not used.

Fig. 9: When aerocapture is not used (Fig.9a) :Although the general architecture does not change, IMLEO increases by 33.0 % because propellant used to perform Martian capture must be carried along.
When NTR is not used (Fig.9b): Again, the general mission architecture does not change with respect to the base case, but IMLEO increases by 27.5 % with respect to the reference executable GMCNF scenario.

lant using ISRU, it is likely that lunar ISRU be not recommended for the purpose of reaching Mars alone. The inclusion of logistical constraints (forcing the mission to be executable) changes the conclusions regarding lunar based ISRU.
It should also be noted that there exists a minimum ISRU extraction rate value below which the deployment of large lunar infrastructure becomes useless. This point was found to be at a rate of 3 kg/kg/year, as shown in Fig.11. In the case where no ISRU is available on the Moon, the mission architecture become qualitatively very similar to that of DRA5.0: a first series of launches in order to establish ISRU infrastructure on Mars, followed by the human mission segment, as can be seen in Fig.12

Summary of the results

In this paper, the values of IMLEO for different mission architectures were compared. The exectuable GMCNF produces higher IMLEO due to constraining the elements in the network to not vary in size, resulting in underutilized capacity.
In terms of technology choices, it was found that both aerocapture and NTR have the potential to reduce IMLEO by 21.5% and 24.8% respectively. Lunar ISRU was found to have relatively little effect on IMLEO. When no lunar ISRU is considered, the optimal mission architecture closely resembles DRA5.0, but bears a difference in terms of IMLEO primarily because of the better Martian ISRU. These results

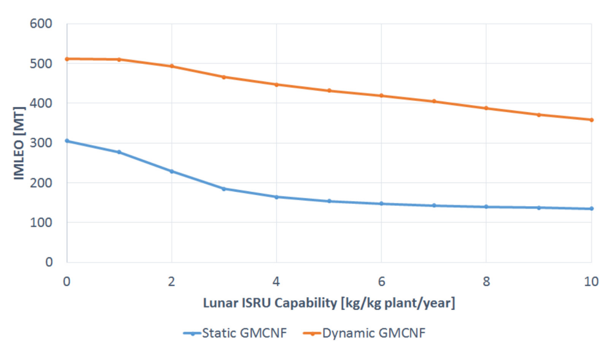


Fig. 10: IMLEO vs lunar ISRU rate. Note the sharper decrease in IMLEO due to ISRU using static GMCNF (result from[21]). The sensitivity of IMLEO to lunar ISRU is far greater than that predicted by executable GMCNF, as can be seen in Fig.11 .Image from.[23]

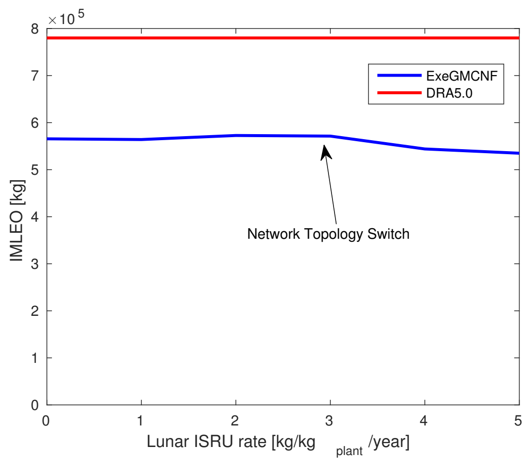


Fig. 11: IMLEO versus Lunar ISRU rate: note that although lunar ISRU is overall beneficial to IMLEO, it only represents a 5% IMLEO reduction at 5 kg/kg/year. An aspect to investigate is the discrepancy between the IMLEO of the dynamic GMCNF at no Lunar ISRU and the DRA5.0 IMLEO: these values should be the same, validating the GMCNF model.[21] uses the same model and falls within 10% of the IMLEO of DRA5.0. The discrepancy presented here is likely due to the Martian ISRU extraction rates that are too optimistic in GMCNF with respect to DRA5.0.

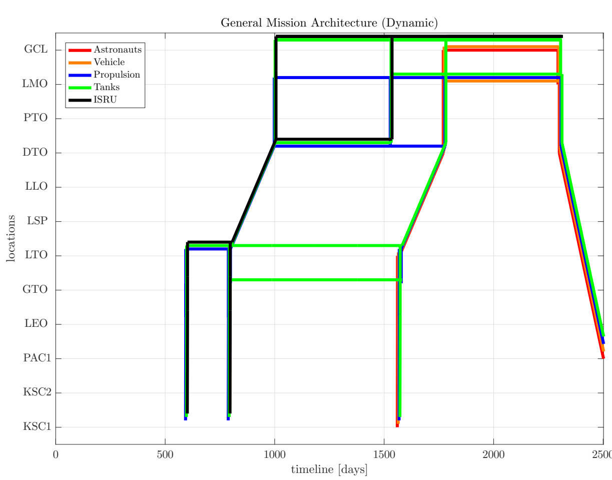


Fig. 12: Executable Mission (reference case, with 0kg/kg/year ISRU extraction rate (similar to DRA5.0)

are summarized in Table 4

Conclusions

In this paper, a campaign-level executable logistics network formulation for life-cycle optimization of human-robotic mission sequences is proposed and applied to the Mars exploration case study.

The proposed method using a time-expanded network and a generalized MILP formulation can find an optimal and executable combination of technologies and operations to be used at each stage of the campaign. The idea is to combine a discretized GMCNF with a time-expanded network to model the dynamic movement of commodities and infrastructure elements over time. A tracking algorithm as shown previously may be applied to the output in order to track each individual element. The resulting formulation provides a executable solution arbitrarily close to the global optimum.

The proposed method can be used to evaluate the campaign- level interdependency between the missions as well as optimize individual elements used in the mission (such as vehicles, reservoirs, engines etc) and trace their trajectory throughout the campaign which was not possible by the earlier space logistics methods.

Although the fact that development of a common space infrastructure is important not only for an initial mission but also for future missions,[24] one of the main findings of this paper is that lunar based ISRU has little overall benefit in terms of IMLEO for a mission to Mars, a conclusion that opposes previous studies.[21,24]

There are a few limitations of this work, such as the unusual mass breakdown displayed in 5. This suggests future work on the following topics:

Modeling non-linearities One large problem is in its linearization and model simplification. In reality, there are nonlinear effects in vehicle design, ISRU plant design, and so on. In addition, allowing nonlinear constraints enables consideration of other new technology options such as solar electric propulsion. This problem has been approached using non-linear formulations,[26] however they become often too computationally intensive to be solved for practical problems.

A way of approaching non-linearities is to approximate the non-linearities by piece-wise linear functions, which can be fed into the problem by adding the different linear segments as dif-

Case name	IMLEO [MT]	Difference to ref. case [%]
DRA5.0	848	+58.8
Exe. GMCNF reference (ref. case)	532	+0
Exe. GMCNF (no Aerocapture)	710	+33.0
Exe. GMCNF (no NTR)	681	+27.5
Exe. GMCNF (no lunar ISRU)	565	+5.8

Table 4: Summary of results concerning technology switches:

General commodity	DRA 5.0 [MT]	exeGMCNF [MT]	Relative differnce [%]
Fuel (LH2, LOX, LCH4)	408.4	194.4	−52.4
Tanks	57.1	10	−82.46
Propulsion (stages)	124.5	39	−68.7
Payload+ Aeroshell+ lander	20.6	262.1	+1172.3
Vehicle (transit habitat+ CEV/SM+ Crew)	43.4	50.5	+16.32
Total (2 unmanned, 1 manned vehicel)	663.8	556	−14.9

Table 5: General commodity breakdown between DRA5.0 et the GMCNF generated solution.Because the categories for mass breakdown between DRA5.0 and the exeGMCNF are not quite the same, relative differences are large. In the GMCNF missions, the Aeroshell commodity is particularly heavy due to the conservative assumption that the heatshield must weigh 40 % of the mass being bracked.

ferent commodities, which remains an interesting research direction because the problem stay mixed-integer linear.

Optimization of the elements in the network Because of the requirement to create an executable scenario the formulation becomes discretized, the discretization becomes an input that can be optimized. By varying parameter values and unit sizes, elements in the network can be optimized in a multi-disciplinary fashion, accounting for the logistics but also for aspects such as performance not of a single mission leg or mission, but throughout the entire campaign. This could provide valuable information such as the sizing and optimization of a baseline element such as an engine for an entire range of missions.

Robust optimization Tolerances to uncertainties are not considered in the optimization in this paper. Consideration of uncertainties using robust optimization or chance-constrained programming is also an important future task.

Integration with other space logistics tools In order to enable detailed analyses of the campaigns produced by executable GMCNF, the results should be post-processed in order to serve as inputs for other space logistics analysis tools. An important such tool is the SpaceNet software,[32–34] jointly developed by MIT and NASA.

Though there is work to perfect the new variation of network based systems design presented in this paper, the potential for applications is wide and very promising.

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References

[1] Borowski, S., "BIMODAL NUCLEAR THERMAL ROCKET (BNTR) PROPULSION FOR FUTURE HUMAN MARS EXPLORATION MISSIONS," BIMODAL NUCLEAR THERMAL ROCKET (BNTR) PROPULSION FOR FUTURE HUMAN MARS EXPLORATION MISSIONS (Technical presentation), Technical presentation at 2003 NASA Seal / Secondary Air System Workshop.

[2] S. Borowski, D. M. T. P., "Conventional and Bimodal Nuclear Thermal Rocket (NTR)Artificial Gravity Mars Transfer Vehicle Concepts," *AIAA 50 th Joint Propulsion Conference and Exhibit, Cleveland, OH, July 28 - 30, 2014*, 2014.

[3] *TRITON: A TRImodal capable, Thrust Optimized, Nuclear Propulsion and Power System for Advanced Space Missions*, 2004.

[4] *NUCLEAR THERMAL ROCKET (NTR) PROPULSION: A PROVEN GAME-CHANGING TECHNOLOGY FOR FUTURE HUMAN EXPLORATION MISSIONS*, 2012.

[5] Goff, J. A., Kutter, B. F., Zegler, F., Bienhoff, D., Chandler, F., and Marchetta, J., "Realistic Near-Term Propellant Depots: Implementation of a Critical Spacefaring Capability," *American Institute of Aeronautics and Astronautics*, 2009, pp. 1–18.

[6] Nasa, "Propellant Depot Requirements Study Status Report," *HAT technical interchange meeting*, Vol. 58, No. 3, 2011.

[7] Tanner, C., Young, J., Thompson, R., and Wilhite, A., "On-Orbit Propellant Resupply Options for Mars Exploration Architectures," *Earth*, pp. 1–15.

[8] Street, D. and Wilhite, A., "1 American Institute of Aeronautics and Astronautics," 2006, pp. 1–13.

[9] Notardonato, W., "Active control of cryogenic propellants in space," *Cryogenics*, , No. 33, 1993, pp. 438–442.

[10] J. Howell, J. Mankins, J. F., "In-Space Cryogenic Propellant Depot Stepping Stone," *International Astronautical Congress, Fukuoka, Japan*, 2005, pp. 1–13.

[11] Liggett, M., "Space-based LH2 propellant storage system: subscale ground testing results," *Cryogenics*, Vol. 4, No. 33, 1993, pp. 236–242.

[12] K. Ho, K. Gerhard, A. N. A. B. J. H., "On-orbit depot architectures using contingency propellant," *Acta Astronautica*, , No. 96, 2014, pp. 217–226.

[13] Inc., E. E., "Conceptual Design of a Lunar Oxygen Pilot Plant: Lunar Base Systems Study," 1988.

[14] *NASA in-situ resource utilization (ISRU) project - development and implementation*, 2008.

[15] *Results from the NASA capability roadmap team for in-situ resource utilization (ISRU)*, 2008.

[16] Zacny, K., Chu, P., Craft, J., Cohen, M. M., Field, M., James, W. W., and Hilscher, B., "Asteroid Mining," *American Institute of Aeronautics and Astronautics*, 2013, pp. 1–16.

[17] Schreiner, S. S., Hoffman, J. A., Sanders, G. B., and Lee, K. A., "Integrated modeling and optimization of lunar In-Situ Resource Utilization systems," *IEEE Aerospace Conference Proceedings*, Vol. 2015-June, 2015, pp. 1–11.

[18] D. Rapp, J. Hoffman, F. M., "The Mars Oxygen ISRU Experiment (MOXIE) on the Mars 2020 Rover," *SPACE Conferences and Exposition 31 Aug-2 Sep 2015, Pasadena, California AIAA SPACE 2015 Conference and Exposition*, 2015.

[19] A. Muscatello, E. S.-M., "Mars In Situ Resource Utilization Technology Evaluation," *50TH AIAA Aerospace Sciences Meeting; 9-12 Jan. 2012; Nashville, TN; United States*, 2012.

[20] Schreiner, S. S., *Molten Regolith Electrolysis Reactor Modeling and Optimization of Insitu Resource Utilization Systems*, Ph.D. thesis, MIT, 2015.

[21] Ishimatsu, T., *Generalized multi-commodity network flows: case studies in space logistics and complex infrastructure systems*, Ph.D. thesis, MIT, 2013.

[22] K. Ho, O. de Weck, J. H. R. S., "Dynamic modeling and optimization for space logistics using time-expanded networks," *Acta Astronautica*, Vol. 105, 2014, pp. 428–443.

[23] Ho, K., *Dynamic Network Modeling for Spaceflight Logistics with Time-Expanded Networks*, Ph.D. thesis, 2015.

[24] Ho, K., De Weck, O. L., Hoffman, J. A., and Shishko, R., "Campaign-level dynamic network modelling for spaceflight logistics for the flexible path concept," *Acta Astronautica*, Vol. 123, 2016, pp. 51–61.

[25] Taylor, C. and Weck, O. L. D., "Integrated Transportation Network Design Optimization," , No. May, 2006, pp. 1–16.

[26] *Integrated Space Logistics Mission Planning and Spacecraft Design with Mixed-Integer Nonlinear Programming*, 2016.

[27] Obama, B., "Remarks by the President on Space Exploration in the 21st Century.John F. Kennedy Space Center, Merritt Island, FL," 2010.

[28] *Making humans a multiplanet species*, 2016.

[29] Group, M. A. S., "Human Exploration of Mars Design Reference Architecture 5.0 ," 2009.

[30] Lyne, J. E., "Physiologically Constrained Aerocapture for Manned Mars Missions," *NASA technical memorandum 103954*, 1992.

[31] D. Vaughan, H. Miller, B. G. B. J. M. M., "Physiologically Constrained Aerocapture for Manned Mars Missions," *AIAA Paper 2005-4110*, July 2005.

[32] Grogan, P., "SpaceNet 2.5r2 Quick Start Tutorial," .

[33] Grogan, P., "SpaceNet 2 . 5r2 User ' s Guide," 2010.

[34] Olivier L. de Weck, David Simchi-Levi, R. S., "SpaceNet 1.3 User ' s Guide," 2007.