Optimizing Debris Recycling for in-Space Manufacturing and Logistics: A Conceptual Model

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Abstract

In this paper, we explore the topic of in-space manufacturing, focusing on optimizing the logistic activities revolving around the production mix of Earth-supplied and space-debris recycled input material. We outset a baseline model for the internal and external logistic operations, putting an accent on the specific needs that out-of-atmosphere environment applications require. While the operations happening on the factory-in-space focus on efficient resource utilization, time management, and energy saving, the external ones deal with optimizing debris recovery missions. We discuss the key points of such a formulation, in terms of reliability, accuracy, and computational efficiency, that these recycling systems should strive to achieve for a successful implementation.

Keywords

Factory-in-space, space logistics, space manufacturing, optimization

1. Introduction

Although the idea of being able to see what lies beyond the sky tracks back to the beginning of civilization [1], October 4, 1957, sets the beginning of space exploration when the Russian Sputnik became the first satellite to ever orbit around our planet [2]. In the span of four decades, the International Space Station (ISS) became the current largest orbiting object, now actively used for experimenting in microgravity and space environment conditions.

So far, the manned space missions that have taken place over the years have been planned in such a way that tools, repairing materials, and overall equipment need to be sent together with the astronauts. In order to ensure the safety of the crew and increase the chance of mission success, critical equipment is characterized by redundancy [3]. Direct supply from Earth is, however, sporadic, and astronauts must deal with a best-effort self-reliant system. Hence, establishing independent out-of-atmosphere (OOA) infrastructure is imperative to advance space exploration.

In 2014, a partnership between NASA and Made In Space, Inc. resulted in the Zero-G 3D Printing initiative, where the astronauts boarding the ISS were supplied with a fused filament fabrication 3D printer to study the capabilities of additive manufacturing in microgravity environments [4]. The success of this experiment underscores the potential of in-space manufacturing as a critical milestone for enabling long-term space missions and eventual space habitation.

Enabling manufacturing in space is not solely related to space exploration: asteroids and near-Earth objects contain minerals and metals, which may constitute a supply of raw materials.

While the current unfeasibility of space mining is acknowledged [5], with Earth's population growth straining its resources [6], developing efficient space logistic tools might reveal to be crucial in order to guarantee a sustainable future for the next generations.

Apart from natural resources found in space, anthropical materials such as space debris are abundant.

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Accumulated over decades of space missions, this debris -- particularly in low-orbit areas -- represents a potential resource pool for recycling, supporting both in-space and Earth-based manufacturing activities.

In this work, we focus on the specific problem of conceptualizing an optimization logistic system for the factory-in-space (FIS) manufacturing processes, whose raw materials input can be fed by recycled (mostly) metal debris. We divide the analysis into *internal* and *external* logistics and discuss each individually. For each of them, we provide the baseline for a Decision Support System (DSS) based on modeling a suitable optimization problem. Differently from the usual logistic system, we put an accent on the particular requirement of OOA infrastructure, mostly revolving around the critical management of resources and their remoteness from Earth.

2. Design and Logistic Planning Optimization

The need to differentiate space logistics and planning from their terrestrial counterparts arises due to the distinctly challenging operational conditions posed by OOA environments.

Due to the nature of the goods being moved or the specific environment in which operations occur, logistics has been divided into sub-fields, each characterizing specific aspects of the task to be accomplished. For instance, the practices regarding handling dangerous material (e.g., explosives, corrosive, or toxic substances) have been formalized in the so-called *dangerous good logistics* [7]. We can analogously consider OOA operations as *dangerous environment logistics*, given the complete hostility of OOA environments for human life, which increases the difficulty and risk of the operation. The remoteness of OOA environments from human-inhabited centers adds another layer of complexity to manufacturing, implying that the FIS resupply process is affected by longer delivery times and higher costs from Earth facilities. In general, the key points that a OOA decision support system for the FIS should strive to optimize against are the following:

- **Resources**: given the capability of in-space manufacturing to utilize both recycled and Earth-supplied raw materials in the manufacturing process, one of the objectives is to plan the logistic operations to reduce the resources' consumption by finding the optimal input combination for the production process.
- **Energy**: orbiting anthropical objects harness energy directly from the Sun, thus being a limited resource [8]. When the FIS carries out other vital tasks, e.g., water electrolysis for oxygen production, it is crucial to schedule the related manufacturing activities according to the priorities of each energy load.
- **Time**: Due to its distance from Earth, the supply cycle of the FIS is much reduced and infrequent with respect to the usual restocking cycles companies may experience. Consequently, time plays a much more crucial role in the manufacturing process due to the inherent scarcity and remoteness of OOA environments.

2.1. Internal Logistics

Internal logistics affect all the operations that occur within the boundaries of the factory, i.e., in our case, the FIS facility. An overview of (a part of) the FIS production chain is depicted in Figure 1.

Let $\mathcal{P}$ be the set of products either to be manufactured or serving as input material. Moreover, let $\mathcal{K}$ be the set of time steps constituting the planning temporal window. We assume that consecutive time steps are evenly spaced by $\Delta k \in \mathbb{R}_{\geq 0}$. We consider the step size Δk to be constant. Note that input materials are themselves the resulting product of some manufacturing process, i.e., we consider them as contained in $\mathcal{P}$. This formulation considers both processes that comprise the transformation of input items and assembly steps. Let $\mathbf{T} \in \mathbb{N}^{|\mathcal{P}| \times |\mathcal{P}|}$ be the bill-of-materials matrix, so that T_{ij} indicates the number of instances of material $j \in \mathcal{P}$ needed for producing $i \in \mathcal{P}$. Clearly, $T_{ii} = 0$ for all $i \in \mathcal{P}$. The materials in $\mathcal{P}$ might come from a recycling process or the Earth supply: let $\mathbf{E}[k], \mathbf{P}[k] \in \mathbb{N}^{|\mathcal{P}| \times |\mathcal{P}|}$ be the production mix matrices, such that $E_{ij}[k], P_{ij}[k]$ indicate the amount of items of material $i \in \mathcal{P} -$

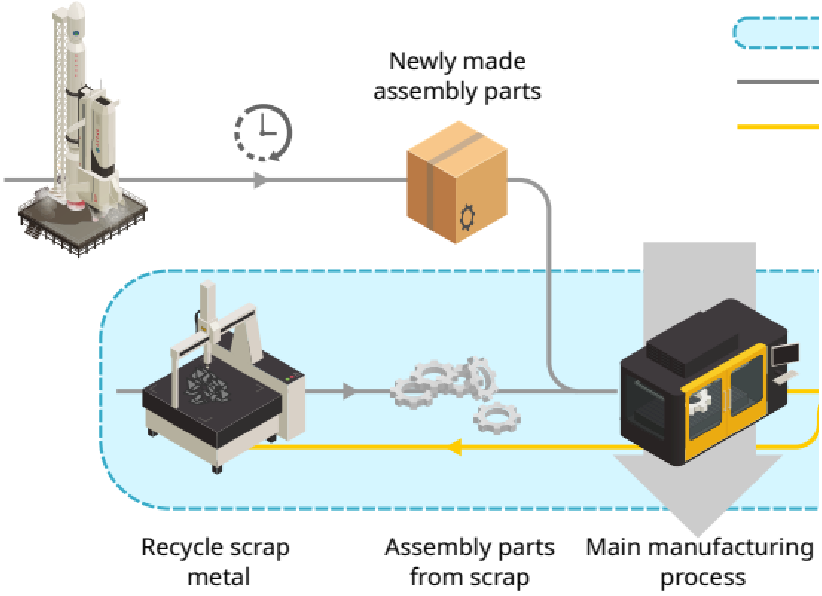

Figure 1: Partial overview of the internal logistic decision chain: the objective item can be produced using recycled scraps, processed directly on board of the FIS (in cyan), or by using the parts supplied by Earth.

ordered to produce $j \in \mathcal{P}$ — being supplied from Earth or produced from scrap recycling, respectively, at time step $k \in \mathcal{K}$. After ordering, each item $i \in \mathcal{P}$ will take $t_i^P \in \mathbb{N}$ time steps to be produced, while when supplied from Earth, it will take $t_i^E \in \mathbb{N}$ time steps to reach the FIS. Let $\mathbf{B}[k] \in \mathbb{N}^{|\mathcal{P}|\times|\mathcal{P}|}$ be the FIS warehouse buffer matrix, so that B_{ij} denotes all stored instances of item i destined to produce j. Moreover, let $\mathbf{p}[k] \in \mathbb{N}^{|\mathcal{P}|}$ be such that $p_i[k]$ indicates the amount of instances of item $i \in \mathcal{P}$ to be ready at time k, i.e., the production targets of i. Therefore, we can express the buffer state as

$$\begin{cases} B_{ii}[k] = B_{ii}[k-1] + P_{ii}[k - t_i^P] + E_{ii}[k - t_i^E] - p_i[k] & \forall i \in \mathcal{P}, \\ B_{ij}[k] = B_{ij}[k-1] + P_{ij}[k - t_i^P] + E_{ij}[k - t_i^E] - T_{ij} \sum_{h \in \mathcal{P}} P_{jh}[k], & \forall i,j \in \mathcal{P}, i \neq j \\ B_{ij}[k] \geq 0, & \forall i,j \in \mathcal{P} \end{cases} \tag{1}$$

Note that E_{ii}, B_{ii} and P_{ii} indicate the items supplied, taken from the warehouse, and produced to meet the production target, respectively. Equation (1) reads as follows: the buffer $B_{ij}[k]$ is composed by the buffering state at the previous time step, the added items whose production and supply were ordered t_i^P and t_i^E steps in the past, respectively, and the withdrawn items. For $i = j$, the latter corresponds to the production target; for $i \neq j$, such a quantity corresponds to the items that are needed for producing j. Ordering the production or supply of an item has its impacts in terms of resources: we denote such costs with $c_i^P \in \mathbb{R}_{\geq 0}$ and $c_i^E \in \mathbb{R}_{\geq 0}$, respectively. For the sake of generality, we will not define them specifically; we reserve further discussion for Section 3. Moreover, each ordering decision leads to a certain amount of energy consumption: we denote with $e_i^P, e_i^E \in \mathbb{R}_{\geq 0}$ the unitary energy amount needed to carry out scrap recycling and from-Earth supply[2] activities. The overall energy load the FIS power system is required to satisfy at time k is denoted with $g[k]$, whose dynamics is described as follows,

[2]Although it might be reasonable to consider $e_i^E = 0$, we remark that external supply operations still require a minimum of power from the FIS side, e.g., items internal transportation and handling.

$$
\begin{cases} g[k] = \sum_{i,j\in\mathcal{P}} e_i^E E_{ij}[k - t_i^E] + \sum_{i,j\in\mathcal{P}} \sum_{\tau\leq t_i} P_{ij}[k-\tau] \\ g[k] \leq \epsilon \overline{g}[k] \end{cases} \tag{2}
$$

where $\epsilon \in (0,1)$ and $\overline{g}[k] \in \mathbb{R}_{\geq 0}$ is the maximum amount of deliverable energy at time k. The equality in (2) indicates that the energy load comprises the amount used for handling just-supplied items and for the ones that are still under processing. Term ϵ represents a safety coefficient that limits the total energy drawn in order to guarantee a critical capacity for vital tasks. Finally, we can state the optimization problem for the internal logistic operations

$$
\text{minimize} \sum_{k\in\mathcal{K}} \sum_{i,j\in\mathcal{P}} \left(c_i^E E_{ij}[k] + c_i^P P_{ij}[k]\right) \text{ subject to (1)-(2)} \tag{3}
$$

where the objective function to minimize in (3) represents the overall cost, in terms of resources, for both the recycling processes and from-Earth supply.

2.2. External Logistics

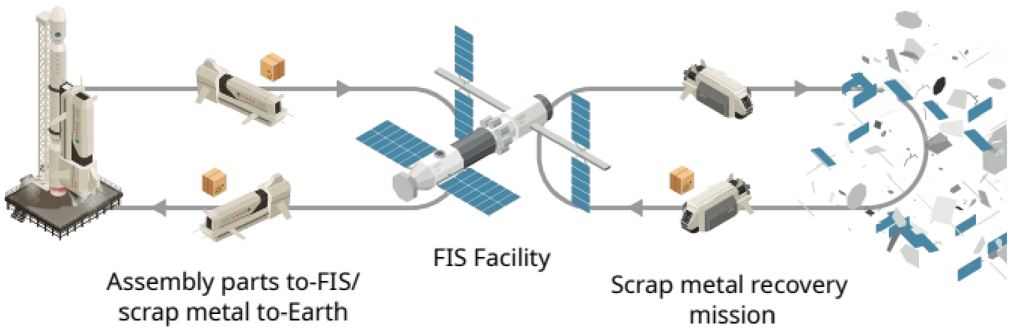

Figure 2: Partial overview of the external logistic decision chain: scrap metal can be collected from nearby pools and brought back to the FIS facility, where it can be used *in-situ* for manufacturing or shipped to Earth for recycling.

Although some works have investigated the logistics of space transportation [9], to the best of the authors' knowledge, very few have proposed frameworks for the planning of a debris-recovery mission in the context of space manufacturing. Figure 2 reports a conceptual scheme of an external logistic FIS operation, where the objective is to collect space debris using a probe able to explore the space near the FIS, with a certain degree of proximity. The recovered debris can be used for recycling, either on the FIS or on Earth by shipping them back.

Let $\mathcal{D}$ be the set of observable debris, i.e., the ones whose trajectory can be predicted. Let $\mathbf{d}_i[k] \in \mathbb{R}^3$ be the position of the i-th debris at time k. Moreover, let $\mathbf{x}[k] \in \mathbb{R}^3$ be the position of the debris probe at time k. Its dynamics can be described by the following set of equations

$$
\begin{cases} \mathbf{x}[k] = \mathbf{x}[k-1] + \mathbf{v}[k]\Delta k & \text{(4a)} \\ \|\mathbf{v}[k]\| \leq \overline{v} & \text{(4b)} \\ \left\| \dfrac{\mathbf{v}[k] - \mathbf{v}[k-1]}{\Delta k} \right\| \leq \overline{a} & \text{(4c)} \end{cases}
$$

where equation (4) describes the position of the probe in space as a function of the velocity vector $\mathbf{v} \in \mathbb{R}^3$. The speed of the probe is constrained by (4b). Moreover, (4c) constraints the acceleration in terms of module and directional shift. The probe can take the i-th debris if $\mathbf{x}[k] = \mathbf{d}_i[k]$ for some

$k \in \mathcal{K}$, i.e., if the probe intercepts it. The occurrence of this condition is indicated by the binary vector $\mathbf{z}[k] \in \{0,1\}^{|\mathcal{D}|}$, defined as

$$z_i[k] = 1 \iff \mathbf{x}[k] = \mathbf{d}_i[k], \quad \forall i \in \mathcal{D} \tag{5}$$

Note that (5) is a logical constraint that can be easily converted into a set of linear inequalities, using well-known transformations [10]. During the mission, we assume that all debris need to be retrieved, so that

$$\sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{D}} z_i[k] = |\mathcal{D}| \tag{6}$$

Given the aforementioned constraints, we can finally state the optimization problem for the external logistic operations

$$\text{minimize} \sum_{k \in \mathcal{K}} \|\mathbf{v}[k] - \mathbf{v}[k-1]\| \text{ subject to (4)-(6)} \tag{7}$$

where the objective function considers the variations in velocity along the probe trajectory. Note that, due to the weaker influence of gravity, motion can be achieved without continuous propulsion. For this reason, the objective in (7) only considers the instantaneous accelerations.

3. Discussion and Future Works

The presented logistic model is characterized by a considerable degree of extensibility. The limiting condition for any extension should be the guarantee of convexity for the derived formulations. In fact, the problems in (3) and (7) are, respectively, linear and (convex) quadratic problems. The model presented in Section 2.1 presents the computationally worst-case scenario, i.e., the non-separability of item quantities. Clearly, many production materials are characterized by real-valued quantities. However, we chose to consider integer values to test the scenario, which would maximally burden the computational infrastructure of the FIS. Several precautions can be taken in order to reduce the computational burden, e.g. imposing that $z_i[\bar{k}] = 1 \implies \sum_{k \in \mathcal{K}, k \geq \bar{k}+1} z_i[k] = 0$, for some $\bar{k} \in \mathcal{K}$. For *convexity*, we refer to problems comprising convex objectives and constraints sets, apart from the (potentially) non-convex variables domain, e.g., integral [11]. We believe that such a condition is paramount for planning critical activities, such as in-space operations. Indeed, convex problems can be solved reasonably fast and are able to provide arbitrarily accurate certified optimal solutions. Although great progress has been made in developing solvers for non-convex problems, they remain bulkier and slower than their convex counterparts. Such theoretical advantages have a direct impact on the design and implementation of the subsequent software, which needs to be easily embeddable on on-board systems, as well as being fast, accurate, and most importantly, reliable.
Future works will focus on developing a more comprehensive framework, stemming from the proposed baseline, with the aim of creating the building blocks of a complete decision support system for in-space manufacturing logistics.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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