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Forecasting water supply shortages in space missions using scenario - based simulation within erp systems

Victor R. Huaman Simeon[a*], Frank R. Quintana Quispe[b], Avid Roman-Gonzalez[c]

[a] *Aerospace Sciences & Health Research Laboratory (INCAS-Lab), Universidad Nacional Tecnológica de Lima Sur, Lima, Peru*, 20a3080277@untels.edu.pe
[b] *Aerospace Sciences & Health Research Laboratory (INCAS-Lab), Universidad Nacional Tecnológica de Lima Sur, Lima, Peru*,1923110543@untels.edu.pe
[c] *Universidad Nacional de Moquegua, Moquegua, Peru*, avid.roman-gonzalez@ieee.org
* Corresponding Author

Abstract

Autonomous resource management is a critical challenge for long-duration space missions, where delayed communication with Earth prevents real-time support. This paper validates a predictive simulation module integrated into an enterprise resource planning (ERP) platform, designed as a decision-support tool for astronauts. The system was tested through multiple operational scenarios in a lunar habitat case study ("Copernicus Mission"), enabling automatic classification of optimal, moderate, and critical water-supply conditions. An embedded intelligence component (ASTRO-AI) generated preventive alerts, risk-specific recommendations, and spoken warnings without human intervention, translating raw consumption data into actionable diagnostics. Results showed that under nominal conditions the system projected safe autonomy beyond 190 days, while degraded efficiency reduced reserves to 50 days, and critical consumption scenarios shortened supply to 16.6 days. These findings confirm that the ERP-based tool enhances situational awareness, reduces crew cognitive load, and supports proactive logistics management. Although validated in a cloud-based configuration, future deployment will require on-edge integration within spacecraft systems to ensure resilience during communication outages. This approach represents a foundational step toward intelligent, autonomous logistics solutions for lunar and Martian exploration.

Keywords: Enterprise Resource Planning (ERP); scenario-based simulation; water supply management; lunar habitat; autonomous prediction; Autonomous Space Technology for Resource Optimization – Artificial Intelligence (ASTRO-AI).

Acronyms/Abbreviations

Application Programming Interface (API); Autonomous Space Technology for Resource Optimization – Artificial Intelligence (ASTRO-AI); Environmental Control and Life Support System (ECLSS); Enterprise Resource Planning (ERP); International Space Station (ISS); Radio-Frequency Identification (RFID).

1. Introduction

Water resource management is a cornerstone of closed-loop life support systems (ECLSS) and a critical factor for survival in long-duration missions [1]. Advancing these technologies is key to ensuring successful operational planning in extraplanetary environments [2]. A main challenge for future lunar or Martian missions is autonomy in this management, as communication delays preclude real-time supervision from Earth [3]. Increasing crew autonomy has therefore become a priority research area for space exploration [4]. Achieving such self-sufficiency requires robust logistics systems [5] and decision-support tools that enable astronauts to operate without continuous intervention from mission control [6].

Current technologies—such as RFID-based inventory monitoring on the International Space Station (ISS)—have improved logistics [7], yet they still focus on stock tracking rather than forecasting risk scenarios. Although ISS recycling systems have reached efficiencies of up to 98% [8], decision-making during anomalies still falls on the crew. The present research seeks to close this gap in predictive and autonomous diagnostic capability [9], a pillar of artificial intelligence applied to space logistics [10].

This work proposes and validates a simulation module integrated into an ERP system, a standard technology in the aerospace industry [11]. Unlike passive systems, our approach uses an autonomous intelligence component (ASTRO-AI) to translate consumption data into clear risk diagnostics. As demonstrated, the system generates preventive alerts and contextual recommendations, improving the crew's ability to manage resources proactively.

The remainder of this paper is organized as follows: Section 2 describes the materials and methods, including the ERP platform, the Copernicus Mission case study, and the ASTRO-AI module. Section 3 presents the simulation results obtained under nominal, degraded, projected, and critical conditions. Section 4 discusses the significance of the findings for autonomous logistics in space missions. Finally, Section 5 summarizes the conclusions and outlines directions for future research.

2. Material and methods

2.1 Platform and Tools

The simulation module was developed on Oracle NetSuite, a cloud-based enterprise resource planning (ERP) system. Development used SuiteScript 2.1, a JavaScript-based API that enables system customization. For dynamic visualization, the Chart.js library was used, while voice alerts were generated through the Web Speech API available in modern browsers.

2.2 Mission Scenario: "Copernicus" Lunar Habitat

To validate the simulation module in a relevant operational context, a 30-day mission in a lunar surface habitat was defined as a case study. This scenario—"Copernicus Mission"—assumes the nominal operational parameters listed in (Table 1), which were derived from the first simulation scenario.

Table 1. Simulation Parameters for the "Copernicus" Mission

Parameter	**Value**	**Source / Rationale**
Mission duration *(Tm)*	30 days	Short-mission simulation parameter
Crew	3 astronauts	Initial simulation parameter
Daily consumption (C_d)	10.5 L/day	Initial simulation parameter
Initial stock *(S)*	500 L	Initial simulation parameter
Recycling efficiency (n_r)	75%	Intermediate life-support system

2.3 System Architecture

The system comprises two main scripts:

a) *Suitelet* – Generates the simulator's visual interface, collects user input parameters (mission days, daily consumption, recycling efficiency, and water stock), and loads graphical elements and interactive buttons.

b) *Client Script* – Performs real-time processing of input data, calculates net consumption, predicts days of supply, classifies risk status, and generates charts as well as visual and audible alerts.

2.4 Variables and Parameters

The system allows configuration of the following inputs:

a) C_d : daily water consumption (L/day)
b) n_r: recycling efficiency (decimal fraction)
c) S : initial water stock (L)
d) T_m: mission duration (days)

With these variables, the evolution of water reserves over time can be simulated.

2.5 Performed Calculations

Given the input parameters, the following calculations are carried out:

Net daily consumption:

$$C_n = C_d \, x \, (1 - n_r)$$

Estimated days until stock depletion:

$$T_a = \frac{S}{C_n}$$

Minimum safe threshold (for three days of mission):

$$U_s = C_n \, x \, 3$$

These calculations are used to determine the risk level according to the conditions shown in (Table 2):

Table 2. Classification of mission risk levels based on projected water autonomy.

Classification	**Condition**
Optimal	$T_a \geq T_m$
Moderate	$T_a \geq 0.6 \, x \, T_m$
Critical	$T_a < 0.6 \, x \, T_m$

2.6 ASTRO-AI Module

The system includes a logic component called ASTRO-AI, which interprets the simulated scenario and generates tailored alerts, including:

a) Predictive visual messages.
b) Risk-specific recommendations.
c) Spoken alerts via speech synthesis.

2.7 Visualization and Usability

The simulator interface includes:

a) An animated water-level gauge (drop representation)
b) A visible minimum-threshold line on the chart
c) Spoken alerts via speech synthesis.
d) Action buttons: "Calculate" and "Predict Days"

e) A summary panel and intelligent alert

To validate module performance, a 30-day orbital mission scenario was simulated with varying consumption and recycling levels. Visual results were manually verified to confirm that generated alerts matched the projected resource status. Screenshots, risk levels, and recommendations generated by ASTRO-AI were documented.

3. Results

To validate the module's behavior under the "Copernicus" Mission scenario, simulations were performed to assess different operating conditions. The system was evaluated across four key scenarios to determine its ability to classify risk and autonomously generate alerts for the lunar habitat crew.

3.1 Nominal Operation Scenario in "Copernicus"

This first scenario assessed system performance under the mission's nominal operational conditions, as defined in Table 1. For a crew of three astronauts and a daily consumption of 10.5 liters, with 75% recycling efficiency and 500 liters of stock, the system computed a net consumption of 2.63 liters per day, projecting an estimated duration of 190.5 days. Visualization showed a linear, stable decline of the resource without reaching the minimum safety threshold (see Fig. 1). ASTRO-AI classified the risk as optimal and issued the message: "Resources are sufficient. Normal operations are ongoing." (see Fig. 2). The orbital gauge remained at 100%, indicating a fully safe situation (see Fig. 3)..

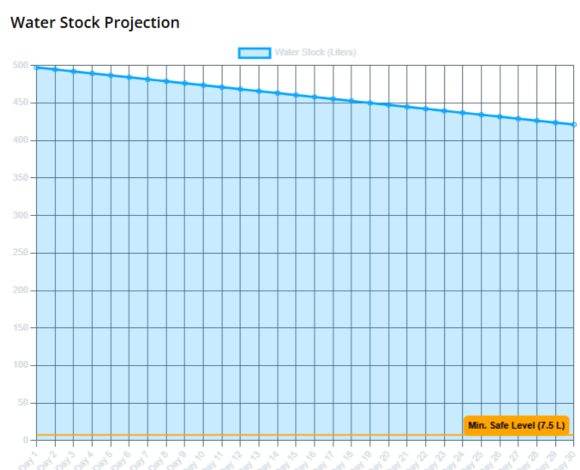

Fig. 1. Daily water-stock projection during the mission. The curve shows the decreasing level as a function of consumption, without crossing the minimum safety threshold.

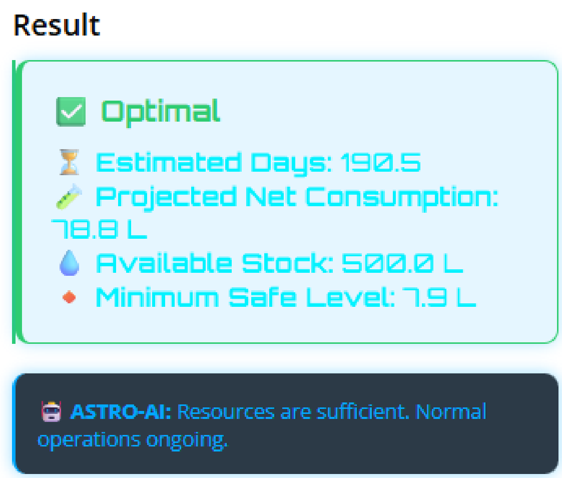

Fig. 2. Simulated analysis results with optimal-risk classification and autonomous message generated by ASTRO-AI.

Fig. 3. Orbital visual gauge at 100%, corresponding to a no-risk scenario.

3.2 Degraded-Efficiency Scenario

This scenario represents a condition in which the recycling system operates with limited efficiency, simulating a partially compromised state. Parameters: daily consumption 10.5 liters, recycling efficiency 40%, and an initial stock of 315 liters for a 30-day mission. The system calculated a net consumption of 6.3 liters per day, yielding an estimated duration of 50.0 days. Although this exceeds the nominal mission duration, it does not reach the threshold considered optimal (≥ 60 days), so the system classified the condition as moderate risk. The visualization revealed a progressive decline near the minimum safety threshold line, set at 33.0 liters (see Fig. 4). ASTRO-AI generated the contextual alert: "Moderate risk. Keep monitoring the situation." along with recommendations to optimize consumption (see Fig. 5). The orbital gauge displayed a relative level of 100%, reflecting the projected autonomy versus the maximum expected value (see Fig. 6). The panel's yellow color and messaging reinforced the moderate-risk classification.

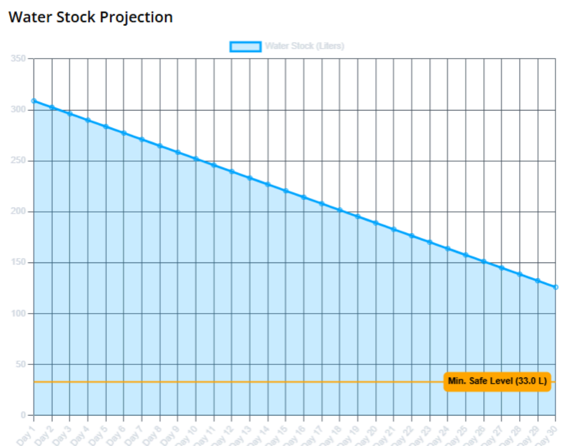

Fig. 4. Projected stock under degraded conditions. The descending curve approaches the minimum safety threshold.

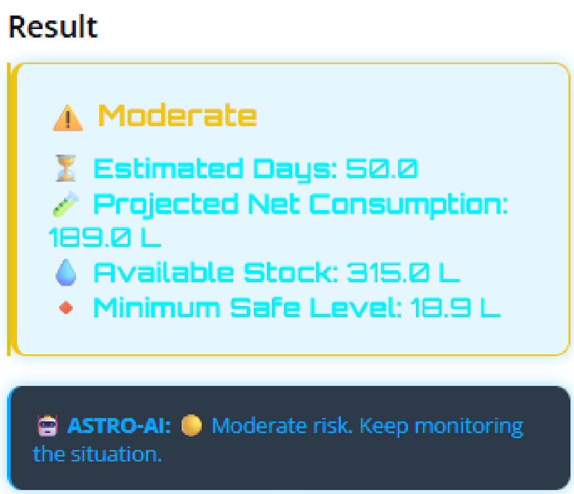

Fig. 5. Analysis result with moderate-risk classification and automatic alert generated by ASTRO-AI.

Fig. 6. Orbital gauge with high visual level (100%) and moderate-risk context.

3.3 Scenario Projected from Current Consumption

This scenario illustrates the system's predictive functionality when no mission horizon is defined, seeking to estimate water autonomy solely from current values of consumption, efficiency, and available stock. The following parameters were entered in the interface: daily consumption 9.0 liters, recycling efficiency 60%, and initial stock 240 liters. The system received these values through the "Predict Days" option, which activates dynamic projection mode (see Fig. 7).

The system computed a net consumption of 3.6 liters per day and estimated a duration of 66.7 days, comfortably exceeding the typical mission duration (30 days) and the optimal-classification threshold (60 days). ASTRO-AI classified the situation as optimal, generating the message "Resources are sufficient. Normal operations are ongoing." and suggesting continued passive monitoring. The stock curve was visually extended using a red dashed line, distinguishing the dynamic projection from the standard calculation (see Fig. 8).

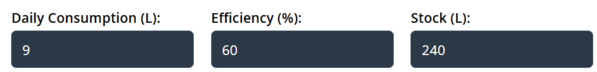

Fig. 7. System interface with input parameters entered.

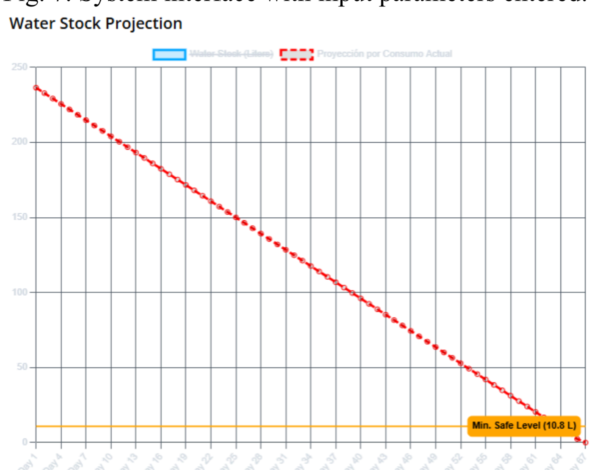

Fig. 8. Automatically generated extended projection curve. The red dashed line represents the duration prediction based on current consumption.

3.4 Critical-Risk Scenario

This scenario represents a severe operating condition in which water consumption exceeds sustainable levels and recycling efficiency is low. Parameters: daily consumption 16.0 liters, recycling efficiency 25%, and available stock 200 liters, for a 30-day mission. The system calculated a net consumption of 12.0 liters per day, projecting an estimated duration of 16.6 days—well below the minimum required. As a result, the system classified the scenario as critical risk, triggering immediate alerts and contingency recommendations.

The stock curve showed a steep depletion slope, evidencing proximity to the safety threshold (see Fig. 9). ASTRO-AI generated the message: “Critical water level! ASTRO-AI recommends immediate intervention.” together with suggestions such as urgent consumption reduction and activation of emergency protocols (see Fig. 10). The orbital gauge appeared in red with a level below 60%, reflecting an unstable situation (see Fig. 11). This type of simulation enables the system to act preventively, warning of conditions that could jeopardize mission continuity even before critical stock levels are reached.

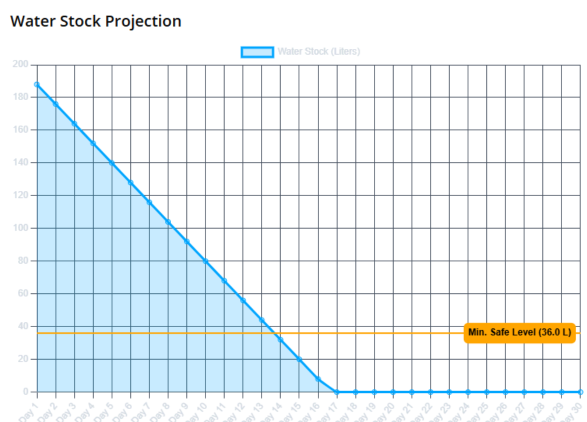

Fig. 9. Stock projection under critical conditions. The curve exhibits an accelerated decline, with an early crossing of the minimum threshold.

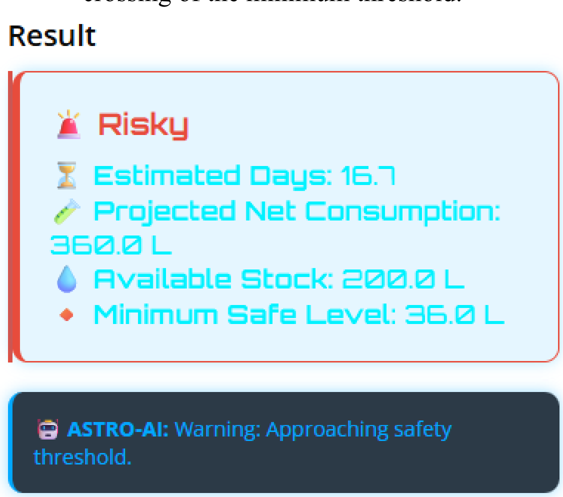

Fig. 10. Critical-level alert generated by ASTRO-AI, with recommendations for immediate action.

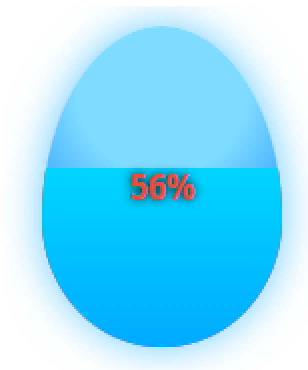

Fig. 11. Orbital visual gauge below 60% in red, corresponding to critical risk.

4. Discussion

The simulation results demonstrate the proposed system’s ability to operate autonomously in evaluating water resources during space missions. Risk classification, projected duration analysis, and real-time alerting allow critical situations to be anticipated without human intervention. This capability aligns with a broader trend in the aerospace industry toward using data-driven predictive modeling to assess mission-critical parameters and enhance overall reliability [12].

These findings are amplified in the context of the “Copernicus” Mission. For example, in the critical-failure scenario (3.4), an early ASTRO-AI alert would give the lunar habitat crew crucial reaction time to diagnose the problem or activate rationing protocols. This shows the system is not merely a monitoring tool but a proactive decision-support system that reduces crew cognitive load in a high-stress environment. This reduction is critical, as the management of cognitive load is a key area of research for improving safety in high-stakes operational environments like aviation [13].

Compared with methods currently used on the ISS, such as RFID-based monitoring, the developed system offers a substantial advantage in autonomy. This level of autonomy addresses long-standing challenges in space exploration related to managing mission-critical risks effectively, especially in an environment of constrained resources and communication [14]. The ASTRO-AI module acts as an intelligence layer that not only interprets data but also communicates specific recommendations. The visual representation of scenarios provides clarity and facilitates decision-making, while differentiation among optimal, moderate, and critical states enables anticipatory actions.

A key limitation of the current proof-of-concept implementation is its dependence on a cloud architecture. While ideal for validation, an operational version for the "Copernicus" Mission would require an on-edge architecture within the spacecraft systems. Future development should focus on a local module that periodically synchronizes with an Earth-based ERP via a lightweight, resilient API, thus ensuring full autonomy even during communication outages.

5. Conclusions

This work demonstrated the feasibility of integrating a predictive simulation module into an ERP platform as a decision-support tool for space missions. Validation via the "Copernicus" Mission case study confirmed the system's ability to autonomously classify optimal, moderate, and critical risk scenarios, translating complex data into actionable visual diagnostics.

Integrating the ASTRO-AI component was key to achieving operation without human intervention—an essential capability for future missions to the Moon or Mars. Although validated as a cloud-based proof of concept, this approach represents a foundational step toward intelligent, autonomous logistics systems. Developing an on-edge version will consolidate this tool as a robust solution for self-sufficiency in extraplanetary platforms. Furthermore, future work could integrate this forecasting module with in-situ resource utilization (ISRU) systems, enabling the dynamic management of both stored and locally-sourced resources on future lunar missions [15].

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