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Applying the Systems Design Approach to a Drone-Based Blood Delivery System

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Abstract: Current blood-transport systems provide effective thermal control but were not designed for unmanned aerial delivery on covert, long-range military blood delivery missions. This work applies a structured systems engineering methodology to develop a drone-deployable blood-delivery architecture designed to be released into contested environments 70 km downrange. The Object-Oriented Systems Engineering Method (OOSEM) was used to develop the system's functional and physical architectures, ensuring a direct hierarchy between stakeholder needs, system functions, and subsystem design decisions. Stakeholder-driven customer needs were translated into measurable engineering requirements, and ninety-five concepts were down-selected using weighted Pugh matrix trade studies. Failure Modes and Effects Analysis (FMEA) at the subsystem level informed risk mitigation prior to prototyping. The resulting validated and tested physical architecture integrates thermal regulation, shock absorption, parachute deployment, and modular storage. This effort demonstrates a systems engineering framework for a drone-compatible solution delivering life-saving blood products where existing predicate devices could not.

Keywords: Blood-Delivery, Drone Interface, Austere Environment, Object-Oriented Systems Engineering Method (OOSEM), Failure Modes and Effects Analysis (FMEA)

1. Introduction

This project presents the design and development of a modular, drone-based blood-delivery system capable of transporting 12 units of blood up to 70 km into contested environments. The system integrates two BloodBoxx Basic Nesting Systems (Safeguard Medical, n.d.), a shock-absorption and parachute system, and a reliable attachment and release mechanism compatible with the TRV-150 drone (Survice_Engineering_Company, n.d.). A systems engineering approach guided development, using the Object-Oriented Systems Engineering Method (OOSEM) to establish traceability between stakeholder needs, system functions, and subsystem design decisions. Customer needs analysis identified and prioritized mission, system, and stakeholder requirements, which were translated through functional decomposition into key system functions governing thermal stability, impact attenuation, modularity, and mission reliability. A structured down-selection process, including multi-voting and weighted Pugh matrix evaluations, refined numerous concepts into a feasible system design and defined the resulting physical architecture. Failure Modes and Effects Analysis (FMEA) identified critical risks and informed mitigation strategies. Prototyping and subsystem evaluation focused on maintaining blood viability within the required 2–10 °C range (Wang et al., 2023), protecting the payload from delivery forces up to 1038 m/s (Bates et al., 2021), and ensuring drone compatibility.

2. Background Research and Predicate Devices

One of the primary challenges in drone blood delivery is temperature regulation. Blood products must be stored between 2–10 °C to remain viable for transfusion (Wang et al., 2023). Maintaining stable internal temperatures throughout flight, delivery, and transfer to long-term storage is therefore essential. Existing systems such as the Golden Hour Box, the Autonomous Portable Refrigeration Unit (APRU), and the Collin's Box regulate temperature using phase change materials (PCM) and proportional-integral-derivative (PID) control (Delta_Development_Team, n.d.; Peli_BioThermal, n.d.; Ruby & Reichard, 2022). While effective in conventional applications, these systems were not originally designed for aerial transport integration.

Shock absorption presents an additional design challenge. Blood subjected to excessive shear stress can undergo hemolysis, which compromises its viability (Johnson_and_Johnson_Medtech, 2025). Experimental testing has shown that blood can tolerate impact accelerations between 341–1038 m/s^2 without significant increases in hemolysis, indicating that controlled parachute delivery does not inherently degrade product integrity (Bates et al., 2021; Tong et al., 2021; Fuentes et al., 2022). These findings support the feasibility of aerial delivery when appropriate impact mitigation measures are incorporated.

Several military and commercial organizations have implemented drone-based blood transport systems. The Collin's Box has been integrated with the TRV-150 vertical take-off and landing (VTOL) platform, which can carry payloads up to 150 lb. However, this approach requires the drone to land and personnel to be present for transfer (French, 2025). In contrast, Zipline employs fixed-wing aircraft that navigate via GPS, release blood products by parachute, and autonomously return to base. This model has demonstrated sustained operational success in remote regions (Ackerman & Koziol, 2019).

Despite these advancements, no existing predicate device has been purpose-built specifically for drone-based blood delivery (Delta_Development_Team, n.d.; Peli_BioThermal, n.d.; Ruby & Reichard, 2022). Current systems are often too large, too heavy, insufficiently durable, or not designed for secure aerial attachment. While they remain effective in traditional operational contexts, the unique constraints of unmanned aerial transport necessitate a new, integrated design optimized for thermal control, shock mitigation, and platform compatibility.

3. Methodology

3.1. Object-Oriented Systems Engineering Method (OOSEM)

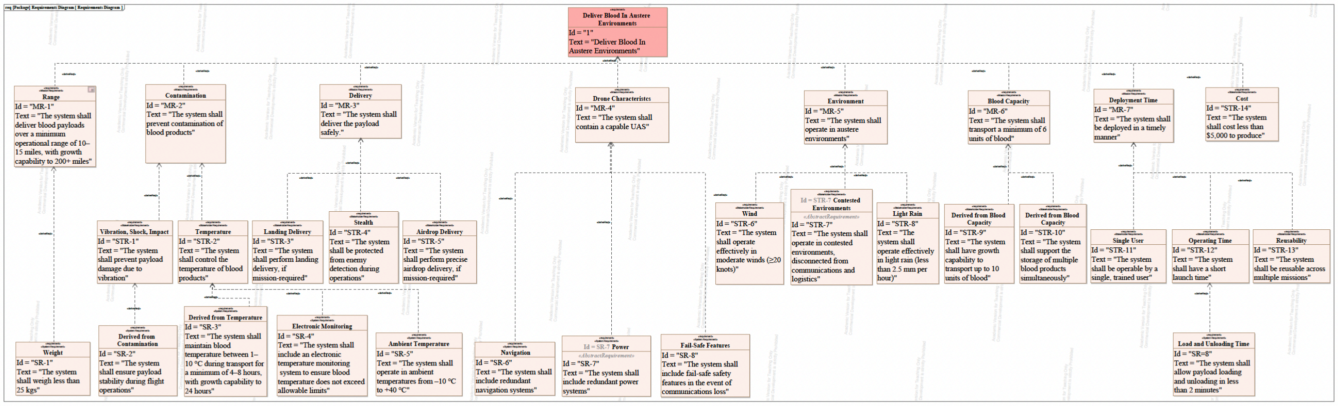
Object-Oriented Systems Engineering Method (OOSEM) is a top-down, scenario-driven methodology that employs SysML to support the analysis, specification, design, and verification of complex systems (Friedenthal, Moore, & Steiner, 2015). Through customer engagement, requirements analysis, architecture development, trade studies, and a Failure Modes and Effects Analysis (FMEA), the OOSEM-based architecture formed the foundation of the system development process. The resulting system hierarchy, encompassing each component of the OOSEM framework, was developed using CATIA Magic, a Dassault Systems Model-Based Systems Engineering (MBSE) software suite (Systèmes, 2024).

3.2. Customer Engagement

Customer needs and requirements were identified through customer engagement with Pacific Air Forces (PACAF), Special Operations Surgical Teams (SOST), and Air Force Blood Program members, as well as a survey distributed to stakeholders across the blood delivery mission. Additionally, a thorough CONOPS and analysis of projected needs was conducted to create the intial list of customer needs. Survey respondents ranked eighteen customer needs from one (least important) to ten (most important), enabling prioritization of key needs. The customer needs, in order of importance, are as follows: Temperature Control of Blood, Prevention of Blood Contamination, Withstand Austere Environments, Reusability of Container, Precision of Airdrop, Storage of Multiple Blood Products, Range > 50 km, Usability/Maneuverability of Container, Easy to Use, Light Weight, Rechargeable Battery, Short Launch Time, Large Blood Unit Capacity, Stealthy Design, Low Cost.

3.3. Requirements Analysis

Through the project life cycle, the customer needs were further defined and compiled into a list of thirty specific, measurable, testable, and feasible requirements. The requirements were then categorized into mission requirements, stakeholder requirements, and system requirements. The requirements diagram can be seen below in Figure 1. The ”deriveReqt” relationship was used in the diagram to show sub-requirements that were composed from other requirements. Requirements analysis was crucial in defining the CONOPS and bounds of the process before beginning subsystem and prototype development.



Deliver Blood In Austere Environments
Id = "1"
Text = "Deliver Blood In Austere Environments"

Range
Id = "MR-1"
Text = "The system shall deliver blood payloads over a minimum operational range of 10–15 miles, with growth capability to 200+ miles"

Contamination
Id = "MR-2"
Text = "The system shall prevent contamination of blood products"

Delivery
Id = "MR-3"
Text = "The system shall deliver the payload safely."

Drone Characteristcs
Id = "MR-4"
Text = "The system shall contain a capable UAS"

Environment
Id = "MR-5"
Text = "The system shall operate in austere environments"

Blood Capacity
Id = "MR-6"
Text = "The system shall transport a minimum of 6 units of blood"

Deployment Time
Id = "MR-7"
Text = "The system shall be deployed in a timely manner"

Cost
Id = "STR-14"
Text = "The system shall cost less than $5,000 to produce"

Vibration, Shock, Impact
Id = "STR-1"
Text = "The system shall prevent payload damage due to vibration"

Temperature
Id = "STR-2"
Text = "The system shall control the temperature of blood products"

Landing Delivery
Id = "STR-3"
Text = "The system shall perform landing delivery, if mission-required"

Stealth
Id = "STR-4"
Text = "The system shall be protected from enemy detection during operations"

Airdrop Delivery
Id = "STR-5"
Text = "The system shall perform precise airdrop delivery, if mission-required"

Wind
Id = "STR-6"
Text = "The system shall operate effectively in moderate winds (≥20 knots)"

Id = STR-7 Contested Environments
«AbstractRequirement»
Id = "STR-7"
Text = "The system shall operate in contested environments, disconnected from communications and logistics"

Light Rain
Id = "STR-8"
Text = "The system shall operate effectively in light rain (less than 2.5 mm per hour)"

Derived from Blood Capacity
Id = "STR-9"
Text = "The system shall have growth capability to transport up to 10 units of blood"

Derived from Blood Capacity
Id = "STR-10"
Text = "The system shall support the storage of multiple blood products simultaneously"

Single User
Id = "STR-11"
Text = "The system shall be operable by a single, trained user"

Operating Time
Id = "STR-12"
Text = "The system shall have a short launch time"

Reusability
Id = "STR-13"
Text = "The system shall be reusable across multiple missions"

Weight
Id = "SR-1"
Text = "The system shall weigh less than 25 kgs"

Derived from Contamination
Id = "SR-2"
Text = "The system shall ensure payload stability during flight operations"

Derived from Temperature
Id = "SR-3"
Text = "The system shall maintain blood temperature between 1–10 °C during transport for a minimum of 4–8 hours, with growth capability to 24 hours"

Electronic Monitoring
Id = "SR-4"
Text = "The system shall include an electronic temperature monitoring system to ensure blood temperature does not exceed allowable limits"

Ambient Temperature
Id = "SR-5"
Text = "The system shall operate in ambient temperatures from –10 °C to +40 °C"

Navigation
Id = "SR-6"
Text = "The system shall include redundant navigation systems"

Id = SR-7 Power
«AbstractRequirement»
Id = "SR-7"
Text = "The system shall include redundant power systems"

Fail-Safe Features
Id = "SR-8"
Text = "The system shall include fail-safe safety features in the event of communications loss"

Load and Unloading Time
Id = "SR=8"
Text = "The system shall allow payload loading and unloading in less than 2 minutes"

Figure 1: Requirements Diagram

3.4. Functional Architecture

The functional decomposition of the blood delivery system decomposed the overarching mission objective into its fundamental sub-functions and internal processes. This MBSE method clarifies what the system must accomplish through a hierarchical breakdown of mission-essential functions and supporting operations. As shown in Figure 2, the top-level functions represent the primary operational objectives of the system and correlate directly to the requirements presented in Figure 1, ensuring traceability between stakeholder needs and system functionality. This traceability extends throughout the design process, linking functional elements to subsystem architectures, component selection, and verification planning. Together, these subsystems introduce potential failure modes that must be systematically evaluated, motivating the use of a Failure Modes and Effects Analysis (FMEA) to assess associated risks and inform mitigation strategies.

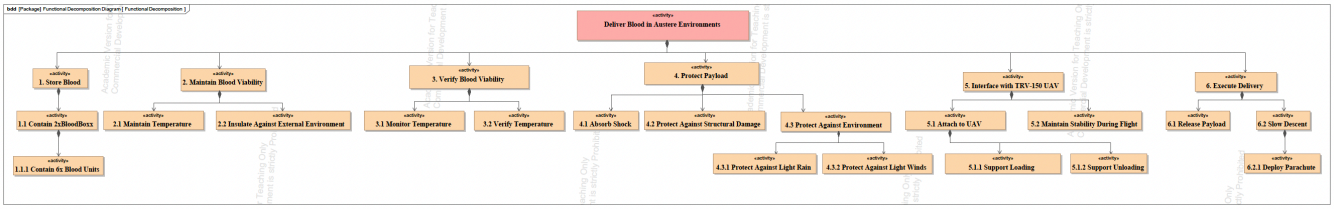


Figure 2: Functional Decomposition Diagram

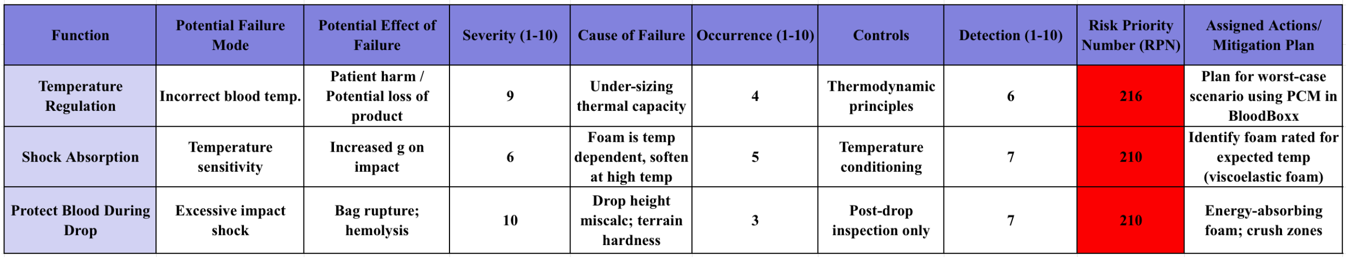
3.5. Failure Modes and Effects and Risk Analysis

A subsystem-level Failure Modes and Effects Analysis (FMEA) analysis was conducted following initial concept down-selection to identify and mitigate mission-critical failure modes before full integration. The FMEA served as a risk-driven design tool and were categorized across thermal regulation, shock absorption, deployment reliability, structural integrity, and authentication subsystems. Key failure modes included PCM degradation causing temperature excursions beyond 2–10 °C, inadequate shock attenuation leading to hemolysis, parachute non-deployment or entanglement, and unauthorized or mistimed payload release. Each failure mode was evaluated using severity, occurrence, and detection metrics to calculate Risk Priority Numbers (RPN) for quantitative prioritization and to calculate subsystem risk rankings.

The 3 high-risk items and potential failure modes that drove targeted design refinements were incorrect blood temperature, temperature sensitivity, and excessive impact shock. Temperature regulation concerns were mitigated through incorporating a combination of insulated containment and phase change materials, while continuous temperature monitoring provides verification that blood remains within the required range. To reduce excessive impact forces during delivery, the system includes shock-absorbing materials and a controlled descent mechanism using a parachute. This FMEA-based assessment ensured subsystem integration decisions were grounded in operational reliability and stakeholder safety requirements.

To mitigate temperature-related risks, a PCM-based thermal regulation system was selected, supplemented with continuous temperature monitoring to ensure compliance with the 2-10°C requirement. To reduce impact- related risks, polyurethane ethofoam shock absorption was implemented in conjunction with a parachute-based deployment system to minimize landing forces. To address deployment reliability risks, a controlled descent mechanism in the parachute system was selected to ensure predictable and safe payload delivery.

The FMEA ensured that the physical architecture decisions were risk-informed, directly linking failure mitigation to architecture development. This process strengthens system reliability and ensures alignment with stakeholder safety and mission success requirements. Building on this foundation, a structured design down-selection process was conducted to evaluate candidate concepts and identify the most effective system configuration.



Function	Potential Failure Mode	Potential Effect of Failure	Severity (1-10)	Cause of Failure	Occurrence (1-10)	Controls	Detection (1-10)	Risk Priority Number (RPN)	Assigned Actions/ Mitigation Plan
Temperature Regulation	**Incorrect blood temp.**	**Patient harm / Potential loss of product**	**9**	**Under-sizing thermal capacity**	**4**	**Thermodynamic principles**	**6**	**216**	**Plan for worst-case scenario using PCM in BloodBoxx**
Shock Absorption	**Temperature sensitivity**	**Increased g on impact**	**6**	**Foam is temp dependent, soften at high temp**	**5**	**Temperature conditioning**	**7**	**210**	**Identify foam rated for expected temp (viscoelastic foam)**
Protect Blood During Drop	**Excessive impact shock**	**Bag rupture; hemolysis**	**10**	**Drop height miscalc; terrain hardness**	**3**	**Post-drop inspection only**	**7**	**210**	**Energy-absorbing foam; crush zones**

Figure 3: Failure Modes and Effects Analysis for the Top 3 RPNs

3.6. Design Down Selection

Following ideation, a structured, multi-stage decision framework was implemented to reduce and evaluate subsystem concepts in a transparent and requirements-driven manner. The first stage employed multi-voting to filter the original 95 concepts into a manageable set of 14 candidates (approximately 3–4 per subsystem). Each of the seven team members received two votes per subsystem and could allocate votes to concepts perceived as most feasible or promising. This process served both as a filtering mechanism and as a functional categorization tool, preserving traceability between ideation outputs and surviving concepts.

For this trade study, the remaining candidates were evaluated using weighted Pugh Matrices, a standard engineering decision tool. Each subsystem was assessed against mission-driven criteria derived from stakeholder priorities, including thermal control (2–10 °C), contamination prevention, survivability in austere environments, delivery range (70 km), usability, weight, capacity, and reliability. Concepts were scored relative to a baseline (Collin's Box), and weighted totals were calculated to reduce evaluator bias. The final selections were Phase Change Materials (PCM) for temperature regulation, polyethylene ethafoam for shock absorption, parachute deployment for attachment, and mission-based modular storage units.

3.7. Physical Architecture

The physical architecture defines the hardware components, subsystems, and interfaces that implement the functions identified during functional decomposition. While the functional architecture describes what the system must do, the physical architecture specifies how those functions are achieved through physical system elements. Figure 3, which shows the block definition diagram of the drone-based blood delivery system, illustrates the hierarchical relationships between the major subsystems.

At the highest level, the system consists of the payload container assembly, shock mitigation structures, deployment subsystem, temperature monitoring system, and the drone interface used to integrate the payload with the TRV-150 aircraft. The payload container houses the BloodBoxx units that maintain the required blood storage temperature, while polyethylene ethafoam inserts provide shock absorption to protect the blood during transport and landing. A parachute-based deployment subsystem reduces descent velocity and landing impact forces, and the temperature monitoring system ensures that blood storage requirements are maintained throughout the mission.

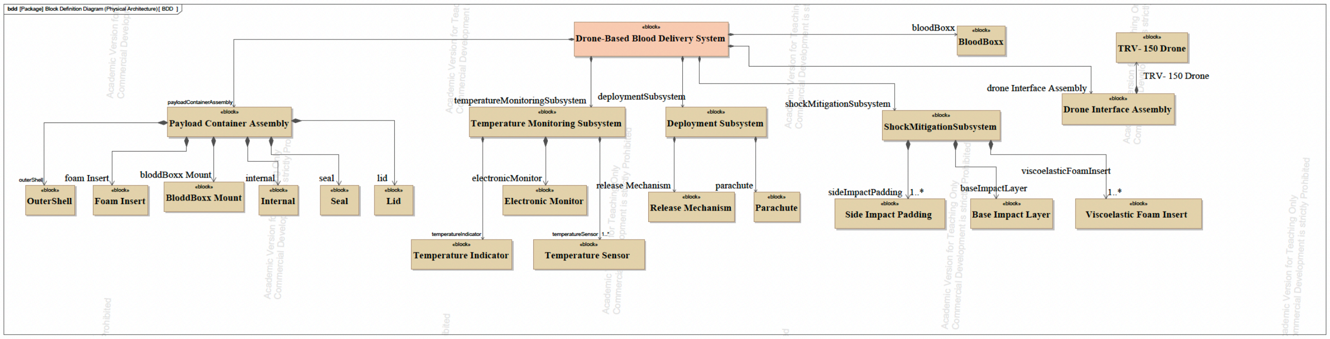


Figure 4: Block Definition Diagram

4. Prototyping and Subsystem Development

The final prototype was developed digitally using CAD modeling (shown in Figure 5), as well as a physical prototype manufactured by Pelican Cases and the USAFA team. Pelican Cases provided a 31.59 in × 22.99 in × 19.48 in custom enclosure with polyethylene ethafoam inserts for each BloodBoxx (Safeguard Medical, n.d.). A 14-ft diameter parachute (Rocketman Parachutes, 2026) is integrated at the top of the box to reduce impact velocity, with sizing determined through velocity and drag analyses to maintain blood viability. The BloodBoxx thermal subsystem ensures viability for up to 72–96 hours. An Arduino Mega 2560 (Arduino, 2026) provides integrated data logging, alarm, and display functions, enabling a simple, all-in-one monitoring solution for ground personnel. Temperature-sensitive blood dot indicators provide an immediate visual Go/No-Go status for each unit. The attachment system is designed for integration with the TRV-150 platform, but remains adaptable to other drones in accordance with PACAF requirements. With a 50 lb payload, the TRV-150 range is expected to decrease from 70 km to approximately 40 km. Overall, the system demonstrates a viable and operationally adaptable solution for blood delivery in austere environments.

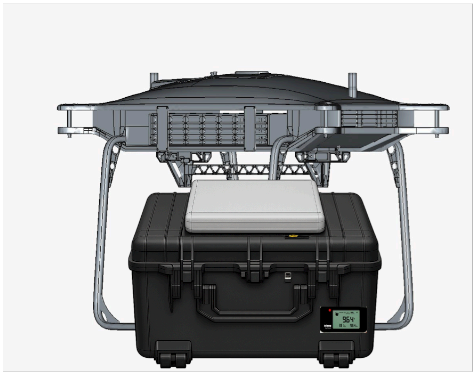


Figure 5: Final Drone-Based Blood Delivery System Digital Prototype

5. Conclusion and Future Development

This effort developed a drone-based blood delivery system designed to operate in austere and contested environments. A comprehensive customer needs analysis produced twenty-eight mission, system, and stakeholder requirements. Functional decomposition was applied to break the complex task of blood delivery into manageable functions that informed the system architecture. Within a Model-Based Systems Engineering (MBSE) framework, these elements were mapped to the physical architecture to maintain traceability between requirements, subsystem design decisions, and verification activities. Structured decision tools—including multi-voting and weighted Pugh matrix evaluations—reduced 95 initial concepts to four primary subsystems: a PCM-based thermal regulation and monitoring module, a polyethylene ethafoam shock-absorption system, a parachute deployment mechanism, and a modular storage container. A physical architecture further defined subsystem components and interfaces, while a Failure Modes and Effects Analysis (FMEA) identified high-risk elements to inform risk assessment. Prototyping efforts refined the design and established a foundation for targeted testing. If successful, this system will enable unmanned aerial platforms to deliver temperature-sensitive blood supplies with high precision over ranges of 70 km, addressing a critical capability gap for military medical operations and humanitarian response. The design advances small payload delivery and supports future integration with autonomous unmanned aerial systems (UAS), expanded payload types, and mission-specific modular configurations, contributing a scalable and operationally relevant solution for austere environments.

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