

LOGISTICS MODELS TO SUPPORT ORDER-FULFILLMENT FROM THE SEA

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Abstract

Sea based logistics use maritime platforms to transfer cargo stored on vessels and delivers them ashore. This chapter describes the motivations and logistical requirements of seabasing. The sea base's organizational structure, its material handling environment, and the internal cargo flow processes of the T-AKE vessel are described. Three seabasing distribution network scenarios -- *Iron Mountain*, *Skin-to-Skin Replenishment*, and *Tailored Resupply Packages* -- are described and mapped to warehousing and distribution networks, characteristics, and decision problems. Finally, related literature is reviewed and open areas for logistics research to support order fulfillment from the sea are identified.

1. Introduction to Seabasing

An important focus of military maritime logistics is the ability to support the needs of globally distributed and networked expeditionary forces that allows for increased effectiveness of resources, strategic agility, and responsiveness [12]. To meet this requirement, seabasing -- a concept using maritime platforms to transfer cargo stored on vessels and delivers them ashore -- can be used to forward deploy a set of distributed resources. These distributed resources are leveraged to provide on-time delivery of mission, operational and logistical material, equipment and personnel [12]. Strategically,

seabasing provides flexibility in the ability to conduct a wide range of missions, including humanitarian aid distribution, crisis prevention, combat operations, and operational and tactical sustainment of military forces on the ground [4].

The primary motivations for seabasing operations is to increase mission flexibility, and to reduce the lead time of troop deployment and supply delivery. When a military operates without a seabase, cargo requested to combat zones or to areas in need of humanitarian aid, must first be picked from a warehouse on land, transported to the closest port, and finally loaded onto a vessel where the cargo is then delivered to its destination. By having a pre-established and stocked base in the sea, seabasing is a proactive strategy that can reduce lead time, facilitating a more responsive system. In addition, seabasing can provide access to cargo where establishment of a base on land is not possible or very difficult due to lack of infrastructure, the presence of conflict or the lack of diplomacy within the area. Finally, a sea base can serve a role similar to an e-commerce fulfillment center by fulfilling personalized requests for cargo to be delivered to troops on the ground only when requested.

Seabasing requires conducting logistics operations from the sea. Sea-based logistics operate in a challenging environment and have unique mission characteristics. Seabasing requires increased security measures, synchronization of sea-based logistics operations with land operations, the absence of permanent infrastructure, and individual logistic transport needs. Thus, the design of sea-based logistic delivery systems is critical to ensuring rapid transfer of vital cargo stored on vessels.

The remainder of this chapter is as follows. Next, we describe the material handling environment, relating how a sea base is organized in a hierarchical structure, as well as describing the layout and material handling equipment on a specific platform, the T-AKE vessel. In Section 3, three specific seabasing scenarios including an *Iron Mountain*, *Skin-to-Skin Replenishment*, and *Tailored Resupply Packages* are described and mapped to common logistics systems and decision problems. Related literature is reviewed in Section 4. Finally, we conclude with decision-making challenges and open research questions for seabasing distribution and logistics processes.

2. Material Handling Environment

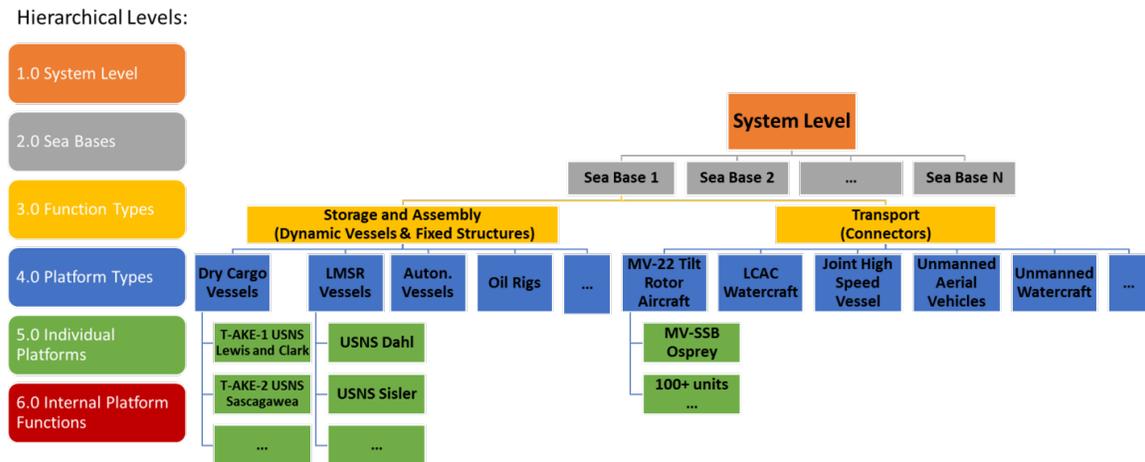


Figure 1: A sea base consists of multiple platforms organized in a hierarchical organization structure

As illustrated in Figure 1, a sea base consists of multiple platforms and hierarchical levels.

Two functional types make up a sea base. The first is *Storage and Assembly*, which is achieved through dynamic vessels and static platforms; the second is *Transport*, which is achieved through connectors, which can be watercraft, aircraft, unmanned systems or other technologies.

For each of the functional types, platforms with varying capabilities and degrees of autonomy are employed. For the *Storage and Assembly* function, different vessel types are used to store and assemble resources. Examples of dynamic storage and assembly platform types include the T-AKE 1 USNS Lewis and Clarke Class Dry Cargo Vessels, the LMSR (large medium roll-on/roll-off) vessels, and autonomous vessels, among others. Static storage and assembly platform types could include abandoned oil rigs or other fixed structures. Each platform type consists of multiple individual instances of the platforms. Examples of internal platform functions include receiving,

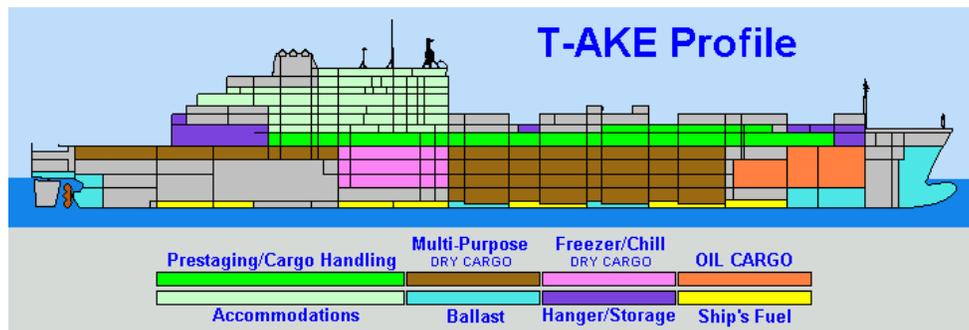
storage, retrieval, assembly, packaging, and shipping.

For the *Transport* function, a wide range of connectors with varying capabilities and degrees of automation are available. Platform types include both aerial delivery platforms (such as the MV-22 tilt rotor aircraft and unmanned aerial vehicles), as well as watercraft (like Landing Craft Air Cushion (LCAC), Joint High Speed Vessels (JHSV), and Unmanned Watercraft). For most of the connector types, there are hundreds of individual platforms in operation.

2.1 T-AKE Ship Background

While many platforms can make up a sea base, T-AKE ships have been targeted for use by the US military to fulfill the *Storage and Assembly* function needs of sea bases [14]. T-AKE ships were ordered in 2001 as a way to provide quick replenishments for the United States Navy at sea without the need of having to go back on land [22, 23]. The construction of these ships was contracted to General Dynamics; the first ship is called the T-AKE 1 USNS Lewis and Clark and was finished in 2005 [7]. Since then, 13 more T-AKE ships were contracted to General Dynamics, with the last ship, T-AKE 14 USNS Cesar Chavez delivered in October 2012 [7].

While some aspects of the ships have changed throughout the 14 iterations, many of the key features have stayed the same. The T-AKEs are built to specification of 689 feet length, 106 ft beam, 29.9 ft draft, dry cargo capacities of 6,675 MT, and a design speed of 20 knots [7, 22, 23]. The ships can hold 23,450 bbl of fuel and 52,800 gal of cargo potable water [7]. A side view of a T-AKE is given in Figure 2.



As described in the *T-AKE 1 Class Ship Cargo Ship and Equipment Operation and Maintenance Familiarization Crew Study Guide* [13], T-AKE ships have 5 levels, with level one being the top level above water and decreasing from level one to five as one descends lower into the ship. The levels are further divided vertically into holds. On top of the ship is a landing pad for helicopters and small airplanes. Connecting the levels are 8 elevators. On the ship are storerooms divided into categories such as parts, metal, lumber, miscellaneous, freezer, pipe, extra-large, and ones for specific chemicals that tend to be smaller in size. There are multi-purpose cargo holds on each vessel that can be reconfigurable and used to store a variety of cargo, from 8-by-20-by-8.5 feet cargo containers, quadcons, and pallets. Both multi-purpose dry stores and freeze stores are available. To increase storage density in these multi-purpose holds, cargo are typically stacked on top of each other and packed tightly with very little room for movement.

Each T-AKE ship has several types of material handling equipment to move cargo internally within the ship and within the holds [13]. There are four cargo cranes that can lift cargo of approximately 11 tons and are used for loading and unloading of cargo. For internal transport, there are 8 diesel fork lifts, as well as 14 electric fork. In addition, electric side loaders and ordnance trailers are available. Thus, each T-AKE ship contains over 30 material handling equipment with varying capabilities to be used for internal cargo transport and storage operations.

3. Sea Based Distribution Network Scenarios

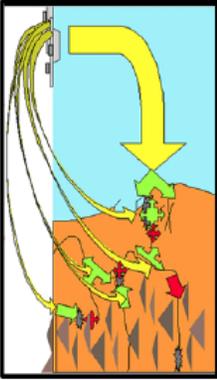
In this section we discuss three different seabasing distribution network scenarios, which exhibit varying levels of complexity [14]. In Table 1, the three scenarios -- *Iron Mountain*, *Skin-to-Skin Replenishment*, and *Tailored Resupply Packages* -- are described and mapped to common logistics system characteristics and decision problems.

3.1 Iron Mountain Scenario

The first and simplest scenario is an *Iron Mountain* scenario. In this scenario, everything loaded on the vessel is offloaded, and the vessel is solely used for transportation, moving cargo loaded at a given origin to its destination, where all cargo is

then offloaded. The key performance indicators are to maximize storage density and to maximize item-

Table 1: The characteristics of three different seabasing distribution network scenarios.

	Iron Mountain 	Skin-to-Skin Replenishment 	Tailored Resupply Packages 
Demand-Level	Mission-Level	Vessel-Level	Individual-Level
Demand Characteristics	Pushed	Plannable	Emergent
Types of Requests	Everything Loaded at its Origin is Offloaded at the Destination.	Bulk Requests for Standard Replenishment Items.	On-Demand, Personalized Requests.
Handling Units	Container, Vehicle, Pallet	Pallet, Case	Case, Piece
Key Performance Indicators	Maximize Storage Density and Item-Type Assortment	Maximize Storage Density and Minimize Transfer Time of Cargo Between Vessels.	Maximize Responsiveness, Item-Type Assortment, and Storage Density
Functional Requirements	Dense Storage	Dense Storage and Item-Type Segmentation	Dense Storage and Selective Offloading
Analogous System	Transportation System	Unit-Load Storage System	Order-Fulfillment System
Decision Problem	Knapsack Problems	Less-than-Truckload Loading and Routing Problems	E-Commerce Order Fulfillment Problems

type assortment. An *Iron Mountain* scenario is the simplest scenario as internal vessel logistics do not play a large role and the handling unit is at the unit load level (e.g., a container, pallet, or even a vehicle). Given all cargo are loaded and unloaded at the same time, the decision problem associated with this scenario is a knapsack problem, which identifies what type of cargo and its quantity to load, given anticipated utility of each cargo type and a limited capacity.

From a holistic supply chain perspective, an *Iron Mountain* scenario is disadvantageous as it is rigid, and does not allow for much flexibility. The items delivered in an *Iron Mountain* scenario are pushed and not pulled. Forecasting demand is required to be done when the sea base ship is loaded. From forecasting theory, as the length of time into the future that demand is being forecasted increases, the accuracy of the forecast decreases. Additionally, mission and thus demand requests can change while the ship is en route, thus making an *Iron Mountain* scenario rigid and not responsive. Given everything loaded is offloaded, this scenario does not allow for much flexibility. A requirement in this scenario is the presence and coordination of a land force that can accept and transport cargo once it is offloaded. Depending on the area where the port is located, there may be need for armed force security to protect the cargo during the offloading and transport process. An *Iron Mountain* scenario, transfers responsibility of storage, transport, and order-fulfillment of cargo to the troops on the ground, which is often in a hostile environment and has limited resources.

3.2 Skin-to-Skin Replenishment Scenario

A more complex scenario is a *Skin-to-Skin Replenishment* scenario, where sea base vessels will transfer cargo to replenish requests by other vessels in open water. This can occur during benign operation, as well as in combat missions. Replenishment using a sea base eliminates the need for all vessels requiring cargo to dock on land to restock. It is especially useful near hostile areas where replenishment is not available. Instead of having to sail back to the nearest friendly port, a vessel can be replenished with cargo for multiple vessels and the sea base can make replenishment deliveries to the other vessels. Therefore, the decision problems in a *Skin-to-Skin Replenishment* scenario are similar to

those for a less-than-truckload company. Specifically, decisions about which vessels to replenish and in what order (i.e., assignment and routing decisions) are required. Such decisions are similar to a traveling salesman problem, however, an added challenge is that the delivery locations are other vessels, which have the ability to move.

The act of transferring cargo from one vessel to another vessel in open water is called skin-to-skin replenishment. There are two different ways to carry out the process. For both processes, the sea base and the vessel requesting cargo must be positioned parallel and traveling at nearly identical velocities. Typically both vessels travel at low speed in order to make coordination easier. Once this formation is achieved, one way to transport cargo is known as connected replenishment (conrep). This requires that a bridge or pulley system is used to connect the two vessels. When a bridge is used, the cargo is manually carried from the sea base to the vessel being replenished. When a pulley system is used, the cargo is shuttled via the pulley between the two vessels. Another way to achieve skin-to-skin replenishment is to use an aircraft to lift cargo from the sea base and drop it onto the flight deck of the vessel requesting cargo. This is known as vertical replenishment (vertrep). While vertrep requires less precise coordination of ship velocity than conrep, it limits the type and amount of cargo that can be transported. Also, aerial delivery vehicles, which are used for a wide range of missions are a limited resources, typically provides slower transport as opposed to a physical bridge connector. In addition, each load needs to be wrapped in special slings or cargo nets, which require additional labor and materials to prepare.

The speed in which the cargo can be transferred is an important criteria in a *Skin-to-Skin Replenishment* scenario because the two vessels are vulnerable to attack when skin-to-skin replenishment is being conducted. Given the loading of cargo impacts the speed at which cargo can be unloaded, considerations of where and how cargo are stored become important. Selectively offloading only the items needed for each vessel may be a challenge in dense storage environments, and the layout and location of cargo stored in the holds needs to be considered. Specifically, cargo needs to be organized in a way to allow for quick access to specific unit-loads.

The demand for a *Skin-to-Skin Replenishment* scenario typically occurs at the vessel-level, and thus demand requests tend to be for full pallet quantities of ordnance, dry stores, and food. Thus, a *Skin-to-Skin Replenishment* scenario requires internal flow operations similar to a unit-load warehouse. Decisions of importance are item-location allocation problems, storage layouts, and storage and retrieval operational design. Given the sea base gets advanced notice of the quantity and type of cargo requested, a *Skin-to-Skin Replenishment* scenario occurs in an environment where demand requests can be planned. Ideally, such information is provided with sufficient time to conduct strike-up processes prior to arrival of the vessel needing the replenishments. If not, questions regarding how much and what types of items should be pre-staged in anticipation of an arriving request to ensure responsiveness are of interest in this scenario.

3.3 Tailored Resupply Packages Scenario

Finally, the most complex scenario is to employ *Tailored Resupply Packages* scenario. Operationally, this requires the ability to deliver emergent requests for tailored resupply packages by selectively offloading cargo stored in the cargo holds of ships [16]. The cargo requested will be for specific items and will be requested in low units of measure (e.g., at the unit or case level). The benefit is that inventory is stored on the sea base until needed, enabling that cargo be located where and when they are most needed [12]. Being at sea also acts as a natural barrier against potential unfriendly disruption, resulting in potential security advantages. The need to support emergent requests requires forward deployed naval forces to pivot and respond in real time because needs, requirements and resource availability will change over time [15]. Therefore, response time is critical.

The internal cargo flow processes on vessels required to handle emergent requests for a *Tailored Resupply Packages* scenario can be broken down into the five functions:

- (1) the transfer of cargo between vessels,
- (2) the strike-down process:
- (3) storage,
- (4) strike-up phase, and

(5) delivery.

Similar to the *Skin-to-Skin Replenishment* scenario, the transfer of cargo between vessels occurs using either conrep or vertrep processes. The strike-down process is the transfer of cargo from the ship's flight deck to stowage spaces. Storage is done to maximize the inventory stored; consequently, pallets and containers are deeply stored, frequently stacked and often without aisles. The strike-up process is the transfer of cargo from the stowage space to the offload point of the vessel for delivery. The strike-up process is analogous to the concept of order fulfillment in the warehousing literature [18]. The strike-up process includes finding and retrieving requested items from cargo holds that are densely packed. Given this may require moving items out of the way to gain access, the process has been found to exhibit high variability [1]. After the items are retrieved and assembled, they are transported to the flight deck, where the personalized package is loaded onto a transport vehicle (e.g., high-speed vessel or aerial vehicle) for delivery to their objective location.

Given the internal cargo processes to fulfill emergent and personalized requests for cargo stored on the T-AKE 1 USNS Lewis and Clark is currently a human-intensive process, emergent and personalized requests are currently a material handling and logistics challenge. Specifically, holds that store dry cargo manually store, retrieve, and relocate pallets and containers using forklifts or pallet jacks. This is a challenging operational environment because of the dense storage environment and the need to conduct selective offloading, which requires the retrieval of specific units, perhaps even ones located in the most inconveniently placed location. This shifting can result in the growth of unit location uncertainty as the system operates. Despite an initial load-plan and initial certainty in unit locations, knowledge of unit location in dense storage environments has been observed to be lost and has resulted in time spent searching for the requested unit. For example, item location uncertainty and searching for requested crates were observed in an exercise conducted in 2012, which had a goal of observing the physical capability of ships to handle emergent requests for tailored resupply packages.

A *tailored resupply packages* scenario is the most complex scenario because

emergent and personalized requests exhibit the following characteristics:

1. Requests occur as a random event in time. This results in requests being highly stochastic and time-varying.
2. Requests are highly personalized; thus, there is variability in what is requested, how it will be requested, and in its delivery location.
3. Requests are expected to be fulfilled quickly. This results in short lead time expectations. Lead time is the time from when a request is made to when the request is fulfilled.
4. Combining 1, 2, and 3 means that a wide variety of requests are made with little warning and are expected to be fulfilled quickly. This results in an environment where operational decision making is crucial.

Emergent and personalized requests result in high levels of variability in when the requests will be made, in what will be requested, in how it will be requested, and where it is needed. Variability degrades performance [5]; systems with more variability also require higher levels of inventory, capacity, and/or lead times to achieve a given service level. Also, systems with high variability exhibit high errors in forecasts, given past requests are not good predictors of future requests. The challenges associated with a *Tailored Resupply Packages* scenario are similar to the challenges faced by an e-commerce order-fulfillment system: the handling units are at the piece or case level, the system needs to be responsive, resulting in the need for quick order-fulfillment times, and last-mile delivery of personalized packages do not have the luxury of economies of scale.

4. Related Literature

In this section we review and map the existing peer-reviewed sea-based logistics research to the previously defined scenarios and logistics functions from Section 3. Focusing on the transfer of cargo from a ship to land, Kang and Gue [11] describe the concept of sea based logistics and develop a simulation model of the offloading process in an in-stream environment. Focusing on macro-level supply chain issues, Gue [8] developed an optimization model to determine the supply chain network design for distributing cargo to dispersed supply units when sea-based distribution is incorporated with land-based

distribution. They find that operational levels of the location of the sea base, the amount of inventory held by combat units, the availability of transportation assets, and the timing of troop movements all play a critical role in deciding whether all deliveries should be made by air, by ground, or by air and ground distribution. Considering the use of seabasing for replenishment operations, Brown and Carlyle [3] build an integer linear program that is used to understand capacity planning needs and the impact of different operating policies. The model uses an objective to minimize shortages and maximize utilization of transport platforms and total volume delivered by a specified combat logistics force. Salmerón, Kline, and Densham [20] produced a global fleet station mission planner tool that enables the user to explore the feasibility of different missions and can be used to understand, for example, how different ship types can be used to accomplish similar missions.

The above mentioned research all takes a macro-view, and assumes cargo to be on the flight deck and does not consider internal cargo flow operations. More recently, both descriptive and prescriptive models have been developed that considers the internal cargo flow processes associated with sea basing.

Motivated by sea basing, Gue [9] studied the layout of storage systems characterized as very high density storage systems. He defined very high density storage systems as ones where not all items are immediately accessible. In such systems, shifting of other stored items to gain access to the desired item may be required. In a k -deep very high density storage system, up to $k - 1$ pallets may have to be moved to gain access to the desired pallet. For instance, in a 2-deep or double-deep system, at most one pallet has to be moved to retrieve the one behind it. Contrastingly, a single-deep storage system is not considered a very high density system, as all pallets are accessible directly from aisles. The highest storage density for a fixed value of the accessibility constant k is achieved in layouts that resemble the inverted T configuration [6].

Reilly, Pazour, and Schneider [19] develop descriptive models that mathematically describe the dense storage environment used in sea-based logistics system, its performance, and the relationships between factors responsible for the

performance. Specifically, a very high density, class-based storage system is modeled as a discrete-time Markov chain in which the state space is the storage unit locations. The units transition from one location (state) to another based upon retrieval requests, and the movement matrix determines the likelihood of each possible location (state) change in the system. An input to this work is a retrieval algorithm, for example, the puzzle-based algorithm developed by Gue and Kim [10]. An analysis is conducted to determine the steady state probability distribution of unit locations. As the first to consider unit location uncertainty in a warehousing environment, they develop metrics that quantify and characterize unit location uncertainty. The developed model and metrics are capable of characterizing how cargo holds evolve from a highly organized state to the observed disorganized state that exhibits imperfect unit location visibility and are used to identify the impact of policies and layouts on uncertainty propagation.

Awwad and Pazour [1] study the problem of single searcher looking for a single item in a very high density storage systems with uncertainty of item locations. An inverted T k-deep storage system is considered and this work incorporates decisions about how to conduct repositioning of items that need to be moved to gain access to other more deeply stored items and their associated put-back operations, in addition to traveling, within a search procedure. An optimization model and heuristic solution approach that minimizes the expected search time for two repositioning policies are studied. A repositioning policy that uses the open aisle locations as temporary storage locations and requires put-back of these items while searching is recommended as it results in lower expected search time and lower variability than a policy that uses available space outside the storage area and handles put-back independently of the search process. The search process in a very high density storage systems is shown to exhibit high variability and the full distribution of search times is recommended for downstream planning.

Scala and Pazour [21] use a value focused thinking approach with subject matter experts to evaluate how to reduce item location uncertainty in a seabasing environment. Functionally, internal cargo flow for sea-based logistics can be supported

through identification technology devices, such as Radio Frequency Identification (RFID), barcoding, internal positioning systems, and camera-aided technology. These asset tracking devices are considered as alternatives to a multi-objective decision model with the goal of selecting the preferred device for seabasing logistics support. Criteria for this model include registration of inventory in the system, stowage factor enablement, storage location precision, retrieval identification accuracy, system compatibility, and security. Given the requirements of selective offloading in dense storage environments, internal positioning systems are the preferred asset tracking technology.

5. Decision-Making Challenges and Open Research Questions for Seabasing Distribution and Logistics Processes

Seabasing presents specific decision-making challenges for distribution and logistics processes. Resources to be requested from the sea base vary, and include different classes of cargo, military tactical vehicles, and personnel. Challenges from the supply-side include having limited resources, limited storage and operational space capacity. For *Skin-to-Skin Replenishment* and *Tailored Resupply Packages* scenarios, the ability to selectively offload cargo in a dense storage environment is required. Challenges on the demand-side focus on the need to fulfill emergent and personalized deliveries, which requires coordination and synchronization of sea-based logistics operations with land operations. Emergent requests can result in having imperfect visibility about when requests will be made. This results in requests being received without warning for a wide variety of resources. Thus, research is needed that (1) develops models to quantify and evaluates strategic resource allocations in a multi-level, dynamic environment, (2) analyzes and designs technologies to aid in material handling in a sea based environment, and (3) designs and evaluates operational strategies to balance the conflicting objectives of responsiveness, storage density, and asset visibility.

One of the major purposes of having a sea base is to allow for quicker response for missions; therefore, one of key characteristics of a sea base is its ability to conduct order-fulfillment processes in a prompt manner. Another is effective space utilization

and the need to maximize the quantity and type of cargo on the sea base. One way to increase the quantity stored is to increase storage density. However, it has been well-established that response time and storage density are inversely related [2]. Increasing storage density can increase the amount of cargo stored. However, increasing storage density limits the amount of maneuvering space and also decreases the likelihood that all items will be directly accessible. Given all items are not directly accessible in dense storage systems, this results in increased time to response to requests, which reduces responsiveness. Given the trade-off between responsiveness and storage density, an open research question is to determine the target storage density for different environments and operational scenarios. Also, for a given storage density, optimization methods to balance the goal of minimizing lead time requirements and maximizing cargo are needed to identify promising layouts in non-depleting systems. To be responsive to changing requirements, operational policies like cycle counting and reshuffling policies [17] should be designed for very high density environments.

Automated storage and retrieval systems are capable of achieving high storage densities and accessibility of cargo. For example, many of the dense automated storage and retrieval systems are well-suited for application in sea basing. Additional research is needed to ensure that automation can function on the open sea and can address changing requirements using an automated system for logistics functions.

Given the distributed and dynamic nature of a sea base, resource allocations to determine which resources are allocated to which platform are challenging. The allocation of inventory to the platforms in the sea base should be done at the systematic level and tied to mission requirements and to product design. For example, if designs use interchangeable parts for multiple purposes and different equipment, inventory pooling effects can be leveraged and the probability of a stock out decreases for a given in-stock quantity. Additional open research questions include considering what cargo should be allocated to which platform, given that a sea base consists of a set of platforms that can be reconfigured for different missions.

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