A Value Model for Asset Tracking Technology to Support Naval Sea-based Resupply

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The Version of Record of this manuscript has been published and is available in *Engineering Management Journal.* The article was first published online on June 3, 2016.

Journal Website: https://www.tandfonline.com/doi/abs/10.1080/10429247.2016.1168502

Article DOI: https://doi.org/10.1080/10429247.2016.1168502

A Value Model for Asset Tracking Technology to Support Naval Sea-based Resupply

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Abstract

A value model is developed for military logistics that fulfills emergent requests for tailored resupply packages from the sea. Asset tracking technologies, including Radio Frequency Identification (RFID), barcoding, Internal Positioning Systems (IPS), and camera-aided technology, are considered as alternatives to a multi-objective decision model. Model measures include registration of inventory in the system, stowage factor enablement, storage location precision, retrieval identification accuracy, system compatibility, and security. We present the decision model, using insights from subject matter experts. Given the requirements of selective offloading in dense storage environments, IPS is the preferred asset tracking technology. Sensitivity analysis and recommendations for engineering managers are provided.

Introduction

This article presents a decision model to support logistics associated with military scenarios that require fulfillment of personalized resupply packages from the sea. Naval sea-basing is the process of moving, storing, locating, and redeploying various cargo located on military vessels on open water. This research focuses on the internal cargo flow processes on vessels required to handle requests for tailored resupply packages. These requests are emergent, which means that the requests occur without warning and result in high levels of variability both in when the requests will be made and in what will be requested. To identify asset tracking technology alternatives that may increase efficiency and responsiveness of storage, location, and retrieval of inventory, a Value-Focused Thinking approach is taken. The alternatives considered are barcoding, radio frequency identification devices (RFID), internal positioning systems (IPS), camera-aided technology, or doing nothing. Each alternative is an asset tracking technology that a naval sea-basing system could use to assist in managing inventory. Our model will assess these technologies on their value and identify the preferred technology.

This article begins with a discussion of naval sea-basing logistics, Value-Focused Thinking, and multiple objective decision analysis. Next, the model developed in this work is presented. Finally, results, sensitivity analysis, and implementation recommendations for engineering managers are provided.

Sea-based Logistics

Sea-basing is a military concept where tactical support is provided from the sea, rather than from the shore. From a logistics perspective, sea-basing transforms a set of vessels into floating distribution centers that can provide vital cargo requested for a variety of missions. Sea-based logistics involves determining how best to receive, store, retrieve, and deliver cargo from a vessel at sea.

The cargo flow processes that occur on a vessel involved in fulfilling emergent requests for resupply packages can be divided into the five following functions: (1) the transfer of cargo between ships, (2) the strike-down process, (3) the storage process, (4) the strike-up process, and (5) delivery of the items to their objective location. The strike-down process is the transfer of cargo from the ship onboard point to stowage spaces, and the strike-up process is the transfer of cargo from the stowage space to the offload point for transfer to a delivery vehicle (e.g., high-speed vessel or aerial delivery). Given our focus is on fulfilling personalized resupply packages, we focus on palletized and breakbulk dry cargo, which is typical inventory for a sea-base, during the strike-down, storage, and strike-up processes.

Effective space utilization is an important consideration in logistics systems and is especially important in sea-based military logistics. In such systems, the ability to selectively offload cargo in high space utilization environments is required. The dry cargo storage holds are currently operated manually with workers using forklifts or pallet jacks to store, retrieve, and relocate pallets and containers. Each ship generates a load plan that, ideally, is followed perfectly, giving initial certainty in unit locations. Once in operation, ships receive orders requesting specific units and quantities to be retrieved, which starts the strike-up process. This need to retrieve specific units, perhaps even ones located in inconveniently placed locations, is known as selective offloading and is analogous to the concept of order fulfillment in the warehousing literature (Pazour & Meller, 2011). Currently, assets are not automatically tracked using asset tracking technologies that provide *(x, y, z)* coordinates of asset location. Thus, any shifting in cargo location while retrieving or searching for items results in unit location uncertainty as the system operates.

Knowledge of unit location in dense storage environments has been observed to be lost over time and has resulted in non-value added time spent searching for the requested unit. For example, item location uncertainty when searching for requested crates was 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 (Sullivan, 2012).

A number of peer-reviewed studies have been conducted on sea-based logistics operations. Kang and Gue (1997) built a simulation model to evaluate the performance of in-stream offloading of containers. Gue (2003) developed an optimization model to determine the supply chain network design for distributing cargo to mobile supply units when sea-based distribution is incorporated with land-based distribution. Brown and Carlyle (2008) developed an integer linear program to minimize shortages and maximize utilization of transports and total volume delivered by a specified combat logistics force. Salmerón, Kline, and Densham (2011) produced a global fleet station mission planner tool that enables the user to explore the feasibility of a United States Navy humanitarian engagement plan. During use, the tool allows for the consideration of scenario-specific constraints while seeking to optimize the route and schedule that maximizes the total mission value earned. The focus of each of the aforementioned works has been on macro-level supply chain issues, where cargo is assumed to be on the flight deck (thus, ignoring internal cargo flow operations) and unit location information of cargo stored on the ships is known. More recently, two papers motivated by sea-based logistics have developed models of internal cargo flow processes with item location uncertainty. Reilly, Pazour, and Schneider (2015) provide a mathematical foundation to describe the observed behavior of unit location uncertainty in sea-basing logistics environments, which require both dense storage and selective offloading capabilities. Awwad and Pazour (2015) study the problem of searching for a single item in dense storage systems with uncertainty of item locations using a single searcher.

The United States Joint Deployment and Distribution Enterprise, which is comprised in part by a number of defense agencies and combatant commands, has goals to achieve end-to-end asset visibility and in-transit visibility. Asset visibility provides the "capability to see and redirect strategic and operational flow in support of current and projected priorities" by enabling timely and accurate information on the location, movement, status, and identity of assets, while in-transit visibility is the ability to "track the identity, status, and location of units, nonunit cargo, passengers, patients, and personal property from origin to consignee or destination" (Joint Chiefs of Staff, 2010, p. 15).

There are specific challenges and requirements with achieving asset visibility for tactical-level decision making for distribution processes in a sea-basing environment. These include having limited storage and operational space capacity, requiring the ability to selectively offload cargo, needing increased security measures, and synchronization of sea-based logistics operations with land operations. Exhibit 1 illustrates these challenges and requirements, and how they affect the sea-basing environment, in an influence diagram.

[Insert Exhibit 1 here]

Imperfect visibility associated with sea-basing can consist of a lack of knowledge of item location, item quantity, anticipated storage and retrieval schedules, as well as other factors. These types of imperfect information can impact system performance by decreasing throughput associated with storage and retrieval activities, increasing labor demands, or affecting the feasibility of meeting certain customer requirements. There has been research on the impact of imperfect visibility on logistic performance, but the focus has been on retail and not sea-based logistics (Buyurgan, Rossetti, & Walker, 2010; Kök & Shang, 2007). In this work, we create a decision model based on the challenges and requirements identified in our influence diagram. The model converts needs into measures that evaluate asset tracking technology devices that may increase efficiency and responsiveness for internal cargo flow processes. We also contribute to the understanding of logistics performance in the sea-based environment. We employ Value-Focused Thinking and a multi-objective model.

VFT and MODA

Value-Focused Thinking (VFT) is a decision analysis process that is designed to stimulate meaningful development of a decision model while supporting creative thinking about the problem at hand; its purpose is to enable clear and explicit definition of the decision problem (Keeney, 2008). The creative thinking component of VFT allows the decision maker to brainstorm all possible alternatives and objectives for the problem, from a value perspective. At times, improved alternatives are identified or previously unconsidered aspects of the problem are brought to light. This process leads to definition of a better set of objectives, identification of all alternatives, and a more holistic decision model. The decision maker acts proactively instead of reactively in the decision process, using value to define all that he or she cares about within the context of the problem. Further details on the VFT process can be found in Keeney (1992, 2008).

The United States Department of Defense has used the VFT process with multiple objective decision analysis (MODA) (Dillon-Merrill, Parnell, Buckshaw, Hensley, & Caswell, 2008). MODA is a decision analysis technique for evaluating a decision under multiple objectives or criteria, and the objectives may be conflicting (Parnell, 2007; Keeney & Raiffa, 1976; Kirkwood, 1997). Related methods to MODA include multiple attribute utility theory (MAUT) and multiple criteria decision analysis (MCDA). MODA is a utility approach, where values and preferences are employed to rank alternatives subject to limitations. In the MODA process, objectives are defined in terms of measurable metrics on which the alternatives are evaluated. The measures are organized into a value hierarchy, which has a similar form and function to decision hierarchies created for simple multi-attribute rating technique (SMART) and the Analytic Hierarchy Process (AHP). Then, for each measure on the MODA hierarchy, a value function is defined. These functions can be continuous or discrete and identify both the worst outcome (score of 0) and the best outcome (score of 100). Moderate outcomes in between best and worst are also defined. Alternatives are then scored by creating an additive value function across the value objectives and measures for each alternative (Keeney & Raiffa, 1976). The alternative with the highest score is deemed preferred. The robustness of the decision is examined through sensitivity analysis.

MODA and VFT rely heavily on the inputs of a subject matter expert (SME), who brainstorms measures and alternatives, defines the value functions, and develops weights for every measure. This elicitation process is typically facilitated by a decision analyst. Thus, appropriate and knowledgeable SMEs with significant contextual background in the problem area should be chosen for the model building process.

MODA allows for the addition of alternatives during the model building process. As SMEs think critically, additional value-added activities may be identified. In fact, SMEs are encouraged to initially identify as many alternatives as possible, as part of the VFT process. Additional alternatives can simply be scored and added to the analysis. This approach provides an advantage over other decision modeling techniques, such as AHP. Unlike AHP, alternatives with MODA can be added without redoing pairwise comparisons. For example, the value functions associated with measures may change over time or a new alternative may need to be added for consideration.

Using VFT and MODA allows us to simply update a value function as necessary or create a new value function if needed. With the AHP, pairwise comparisons would have to be redone; as the definition of a measure would change, so would the corresponding assessments of the decision maker. This is tedious and impractical. With VFT, weights for the measures can be updated, alternatives can be rescored on only the revised or additional measures, and the ranking of alternatives would be updated. Rank reversal is not a potential issue. Furthermore, using VFT promotes brainstorming on problem objectives and subsequent creation of alternatives to help satisfy the objectives, whereas methods such as AHP focus on identification of alternatives first and then attributes to evaluate those alternatives (Goodwin & Wright, 2004). As a result, VFT allows for inclusion of alternatives that may not have been originally considered and allows focus on fundamental values of the decision problem.

MODA can handle a complex set of measures to evaluate the objectives. Most decision problems have at least three to five measures, while very complex problems can have up to 100 measures (Scala, Kutzner, Buede, Ciminera, & Bridges, 2012). Further details on the MODA process can be found in Parnell (2007), Keeney & Raiffa (1976), and Kirkwood (1997). A step-by-step outline of the process can be found in Dillon-Merrill et al. (2008).

MODA and VFT have been used in many United States defense-related applications, including base realignment and closure (BRAC) (Ewing, Tarantino, & Parnell, 2006), system components for air and space dominance (Parnell, Conley, Jackson, Lehmkuhl, & Andrew, 1998), psychological operations (Kerchner, Deckro, & Kloeber, 2001), nuclear terrorism protection (Feng & Keller, 2006), workforce planning (Scala et al., 2012), energy transformation (Simon, Regnier, & Whitney, 2014), and Air Force cyber investment (Parnell, Butler, Wichmann, Tedeschi, & Merritt, 2015). The method has also been used in applications not related to defense; an example is transportation disruption response (Tong, Nachtmann, & Pohl, 2015). Value creation models are also used in portfolio analysis; an example is Kirchhoff, Merges, & Morabito (2001). A review of additional military applications using VFT can be found in Keefer, Kirkwood, and Corner (2004). A full survey of VFT applications can be found in Parnell, et al. (2013). Dillon-Merrill, et al. (2008) identify pitfalls and best practices in Department of Defense related models; decision analysts and engineering managers are urged to consider these when utilizing MODA approach.

Model for Asset Tracking Technologies

Our model employs the combined standard, as defined by Parnell, Bresnick, Tani, and Johnson (2013), utilizing a mix of key policy documents and interviews with SMEs. The combined standard of model development is very common in decision-making and incorporates elements of both the platinum (SME driven) and gold (document driven) standards. In this work, we had access to two SMEs provided by the United States Office of Naval Research. The first SME is the president of a consulting firm, has completed several sea-based logistics studies, and is a NATO Civil Expert for sea-basing operations via the Maritime Administration. The second SME has also completed several sea-based logistics studies, including asset tracking projects to locate containers in a depot using asset tracking technologies. The SMEs have similar backgrounds and comparable levels of extensive expertise related to both naval and sea-basing applications. They also have global expertise in asset tracking, outside of the naval and sea-base application areas. Unal, Keating, Chytka, and Conway (2005) recommend such varied expertise in order to reduce bias in SME input. Development of the value hierarchy began with documentation that has either been created or approved by senior decision makers within the U.S. Navy and U.S. Government in order to identify potential measures (e.g., Clark, 2002; Congressional Budget

Office, 2007; Department of the Army, 2008; Gunderson, Canfield, Dann, & McCambridge, 2004; Mallon, 2008; Moore & Hanlon, 2003; National Research Council Committee on Sea Basing, 2005; Naval Research Advisory Committee, 2004). These potential measures were reviewed with our SMEs, who refined the list and created definitions for every measure. The value functions were directly elicited from the SMEs in a series of virtual meetings, which both SMEs attended. The meetings were virtual because the SMEs were geographically dispersed. From this iterative process, a hierarchy was developed from the six final measures discussed in the next section, with each measure on the same level. This hierarchy is both mutually exclusive and collectively exhaustive, a key tenant of a MODA (Parnell, et al., 2013).

A MODA model is comprised of the measures organized in a value hierarchy, definition of value functions for each measure, calculation of weights for every measure, scoring of the alternatives on each measure, and sensitivity analysis of the results. The next section presents the details of the components of the model.

Measures and Value Functions

Through a series of iterative meetings, a set of measures used to evaluate asset tracking alternatives was confirmed by the SMEs. To arrive at this set of measures, taking a process view of the internal cargo flow processes required to fulfill emergent requests in a sea-basing environment assisted in identifying the main concerns in the decision-making situation. For each function, the challenges and requirements associated with sea-basing decision making were identified and grouped. This was done through a gold standard review and discussions with Navy and Marine Corps personnel. Next, the SMEs received a summary document that described the objective and scope of this study and included a gold standard list of measures. The SMEs were asked to evaluate the importance of the measures provided and were encouraged to include any additional relevant measures so that the list of measures was exhaustive. Through this iterative process, some gold standard measures were removed (e.g., maintenance and upkeep), because the SMEs determined them as not important to the sea-basing asset tracking decision, and others were added (e.g., system compatibility). Care was taken to ensure that all measures were important and were defined such that they were quantifiable. As illustrated in the influence diagram in Exhibit 1, each measure is quantifiable and addresses a sea-basing challenge or requirement. Also, each measure addresses significant and measurable areas that provide insight on the preferred asset tracking technology, given the considered alternatives.

The final measures are as follows:

1. *Registration of inventory in the system* is the time needed to setup or register receipt of the items on the ship for each alternative. This is measured per unit or per pallet. Once inventory is registered that it has arrived on the ship, the strike-down process begins.
2. *Stowage factor enablement* is the maximum stowage factor at which the tracking technology enables functional operations of selective offloading capabilities. Specifically, we consider the stowage factor at which the asset tracking technology enables reasonable packing of the holds. This is measured as percent of cube, defined as the cubic feet of stored cargo divided by the cubic feet of available space for storage.
3. *Storage location precision* is the granularity with which the item's storage location can be accurately marked or captured. This is measured by the precision level that is captured by the alternative tracking technologies and is recorded at the strike-down process. One way to measure this is using the granularity of information provided in the physical location codes, such as the deployable unit location number, which consists of nine characters of

granular information (Department of the Navy, 1994). The first character represents the facility location, and the ninth character identifies the subdivision within the segment, such as a drawer or compartment level. Not all items receive a full nine-digit number, depending on the level of detail recorded at the strike-down process.

4. *Retrieval identification accuracy* is the measure of the difference between (1) where the requested item is recorded to be and (2) where it is actually found on the ship. Specifically, confirming that a location is accurate and the item is actually there, given that the item is marked to be in that location. The search process is initiated when a request for retrieval of an item arrives and is the beginning of the strike-up process. This is a mirror operation to *storage location precision* and is defined in terms of navigation to the item in question.
5. *System compatibility* is the ease with which the asset tracking technology can interface with existing Standard Military Information Systems (STAMIS) that are currently or envisioned to be used for In Transit Visibility Tracking and/or property accountability. This is an operational use and is measured by the ease of transferring data between the asset tracking and STAMIS systems.
6. *Security* is the potential for an adversary to intercept and/or hack signals emitted from the technology. Specifically, defining the ease or difficulty of detecting the produced signal. This is measured by the sophistication of the technology alternatives.

Value functions can be loosely defined as the marginality of the decision maker's preferences, and they do not consider risk attitudes (Goodwin & Wright, 2004). Value functions were elicited from the SMEs for each measure. SMEs were asked to identify the best and worst alternative performance for each measure, with the best performance receiving a value of 100 and the worst performance receiving a value of 0. SMEs were then asked to identify moderate levels of performance along with the corresponding value of each option. Exhibit 2 provides the value function definition for each measure; each value function is monotonic. As an illustrative example, Exhibit 3 graphs the value function for *registration of inventory in the system*.

[Insert Exhibit 2 and Exhibit 3 here]

Weights

The rank order centroid method was used to develop weights for every measure. This method is a mathematical technique developed by Barron (1992) where the decision makers rank order the measures under consideration with the ranks converted to weights using the equation $w_k = (\frac{1}{K})\sum_{i=k}^{K}\left(\frac{1}{i}\right)$. The weights sum to unity. The rank order centroid method is useful when multiple decision makers are involved, as achieving agreement on a direct weight can be difficult. The weights are derived systematically, by using implicit information in the ranks, and are not ad hoc, thereby outperforming other weighting methodologies (Barron & Barrett, 1996). The rank order centroid method minimizes the average utility loss, defined by the utility of the optimal strategy minus utility of a random strategy (Edwards & Barron, 1994) and has been used in other MODA applications (e.g. Scala et al., 2012).

The two SMEs provided ranks for the six measures. Both SMEs were present for the elicitation and were in agreement with the order of importance. Exhibit 4 presents the six measures in rank order along with their corresponding rank order centroid weight.

[Insert Exhibit 4 here]

Alternatives

For alternatives, we consider four asset tracking technologies for internal cargo flow processes within the sea-base environment: barcoding, radio-frequency identification devices (RFID), internal positioning services (IPS), and camera-aided technology. For comparison purposes, we also consider doing nothing as an alternative, implying there is no change to the current process.

Barcoding involves utilization of a numeric sticker to identify characteristics of an item. Barcoded scanning and product verification offers a logical and proven means to decrease errors in inventory (Oldland, Golightly, May, Barber, & Stolpman, 2015). A barcoding system requires scanning of the barcode on the item, as well as scanning the barcode associated with the storage location (also called a "license plate"). For an item to be assigned and mapped to a location with barcoding technology, each pallet location requires a license plate location. Thus, barcoding requires a single-deep storage system that could include items stacked on top of each other. Given this environment, an item can then be recorded to be in a specific level within the stack. Items could then be found in a specific stack of a specific aisle or row of a hold. While being stored, items may need to be reshuffled to gain access to other items stacked on top of each other. Given that location updating requires manual intervention, the *retrieval identification accuracy* measure can have a higher granularity than the *storage location precision* measure.

RFID utilizes a transponder with a reader to track items; thus, all items that require tracking are affixed with a transponder. The transponder's microchip passes data to the reader through an antenna, with the reader feeding the data to a computer for computations (Violino, 2005). Active RFID systems have transmitters that broadcast location, and material can be identified proactively by placing an RFID tag on a piece of inventory and locating that inventory in proximity to the reader. Passive RFID systems do not actively broadcast location, and material needs to be passed through a reader in order to be identified. In both RFID systems, data on an item's tag is sent to a reader. However, no positioning information is provided, only that a response has been sent and received. In this work, we consider RFID in a general sense and evaluate the alternative by using the main characteristics of an RFID system. A primary advantage of RFID over barcoding is that items do not have to be physically scanned or touched in order to be read.

An Indoor Positioning System (IPS) is an asset tracking technology that functions similarly to a Global Positioning System (GPS). However, IPS can be used in indoor spaces as it is ground based, whereas GPS is satellite based. An IPS system requires receivers to be attached to the items. In addition, multiple wireless transmitters are required such that item location coordinates can be triangulated. There are many ways to structure an IPS. However, the most common systems use Bluetooth or a wireless local area network (Liu, Darabi, Banerjee, & Liu, 2007; Kim, Seo, Krishna, & Kim, 2008).

A special case of an IPS is a wireless mesh network, where active wireless receiver nodes are capable of communicating with each other and of relaying information among the nodes (U.S. Patent No. 7,852,262, 2010). A wireless mesh network requires more than three nodes to triangulate item information. Wireless mesh networks can consume less power than a traditional IPS, increasing the system lifetime from a single power source. However, to consume less power, the distance between each transmitter must be small, which may require more transmitters. System cost and complexity increases as more transmitters are installed (Mao & Fidan, 2009). We consider IPS in a general sense and evaluate this alternative using the primary characteristics of an IPS system.

Camera-aided asset tracking technology is another potential alternative for sea-based logistics operations. Camera-aided technology can be implemented by affixing multiple digital cameras near the ceiling of each storage hold. Such a system requires that each cargo container has a label attached to it that is visible by the camera (e.g., a unique, large printed marking). Due to the dense storage requirement, items that are on the bottom of the stack are not able to be identified as those items are not in the camera's line of sight. Therefore, such a system provides partial asset location information. This setup also requires that the images from the cameras be sent to a computer, where either human or computer-aided machine vision is used to identify and map the location of each visible cargo container to locations in the storage hold.

In order to realistically bound the decision space, we make the following assumptions and observations.

1. The sea-base storage environment is dense and does not include racking.
2. RFID readers can be fixed to the doors of each hold, allowing inventory to be identified as it enters or exits the hold. As a result, RFID is not able to identify *(x, y, z)* coordinates of storage but is able to identify that an item has entered or exited the hold.
3. The maximum stowage factor in a single-deep storage system is 2/3 (Gue, 2006).
4. RFID tags and barcodes, which are mature technologies, have been placed on items by an upstream supply chain stage; items would be received on the ship affixed with these technologies.
5. Given that IPS is an emerging technology, the receivers required for IPS are assumed to be used only for internal cargo flow. These receivers, which can be a few inches thick, are required to be placed inside cargo when it arrives on the ship, such that stacking of cargo can still occur.

6. The camera-aided technology requires specialized markers that are visible by the camera. These markers, which can be fixed to the outside of the cargo, will be placed on the cargo when it arrives on the ship.

Results

Each alternative was scored on each of the six measures. To do so, a corresponding value was identified and assigned to an alternative for every measure, using policy documentation and technical specifications to support the gold standard of Parnell, et al. (2013). For example, based on the capabilities of the technology and model assumptions, IPS scored 25 for *registration of inventory in the system,* 100 for *stowage factor enablement,* 95 for *storage location precision,* 95 for *retrieval identification accuracy,* 100 for *system compatibility,* and 70 for *security.* The SMEs reviewed the gold standard scoring, providing feedback and validation; they were in agreement with the final scoring of all alternatives. Following standard MODA procedure, a weighted average score s_a for each alternative a was calculated using the following equation: $s_a = \sum_{i=1}^{m} w_i v_{ia}$ where w_i is the weight of measure i as defined in Exhibit 4, and v_{ia} is the value function scale item for measure i and alternative a as defined in Exhibit 2, with *m* total measures. In descending order, scores for every alternative are shown in Exhibit 5.

[Insert Exhibit 5 here]

Our results indicate that IPS are the preferred alternative, with barcoding scoring as the second best alternative. These results are logical, as there are many benefits to an IPS in a sea-based environment that requires selective offloading in dense storage environments. Most importantly, IPS is capable of identifying location coordinates of cargo in densely-packed storage systems and can have an accuracy of 1-5 meters with an 83% probability of finding a specific location within

1.5 meters (Liu et al., 2007). Also, IPS systems have the capability to process anywhere from 11-108 Mbps of data, which allows the entire system to update in seconds (Liu et al., 2007). Such characteristics result in IPS achieving the highest score among the alternatives for *stowage factor enablement, storage location precision*, and *retrieval identification accuracy*. A wireless receiver must be attached to the inside of each cargo container; thus, IPS requires more time to register inventory in the system than other alternatives. Also, given IPS uses a wireless system, it has the possibility of a detectable signal and is slightly less secure than other alternatives. However, the performance in other measures outweighs these factors.

Sensitivity Analysis

We conducted a sensitivity analysis for the results by varying the weight of each measure from 0 to 1, holding the other weights constant and normalizing the sum of all weights to 1. As described earlier, the weights were elicited via the rank order centroid method, which converted an ordinal raking to a ratio weight. Thus, the potential swing or change in a weight must be considered. Specifically, our sensitivity analysis examines if the preferred alternative changes due to a shift in weight. Weights could modify over time due to evolving priorities of the United States Navy as well as further development and use of the sea-based environment. Also, the ordinal ranking of the weights as elicited from the SMEs do not necessarily address their strength of preference of each measure.

IPS remains the preferred alternative for all weights of *storage location precision*, *retrieval identification accuracy*, and *system compatibility*. IPS remains the preferred alternative as long as the weight for *stowage factor enablement* is greater than about 0.05. For a weight to be that small, *stowage factor enablement* would have to drop to fifth or sixth in importance. This is highly unlikely due to the dense storage requirements of naval sea-basing, which place a premium on stowage factor. For *registration of inventory in the system*, IPS remains the preferred alternative as long as the weight for the measure is less than about 0.2. A great increase in the importance of that measure is unlikely. Also, our assumption is that IPS tags are required to be affixed to the inside of the cargo upon receipt, which results in a conservative estimate of the time required for inventory registration. As IPS technology matures, this time is likely to decrease. Finally, IPS remains the preferred alternative as long as the weight of the *security* measure remains below about 0.4. If such a swing in weight occurred, security would become the most important measure, minimizing the importance of the requirements and challenges of the dense storage environment. Clearly, defense scenarios exist when security is at a premium. However, the frequency of such would be ad-hoc, as sea-based logistics usually handles dry cargo, minimizing the amount of sensitive materials. Exhibits 6, 7, and 8 show the results from the sensitivity analysis for *stowage factor enablement, registration of inventory in the system*, and *security*. The *x*-axis represents the weight of the measure, with all other measure weights constant and normalized, while the *y*-axis represents the final score s_a for every alternative. Barcoding is primarily the alternative that becomes preferred as IPS loses dominance, but the likelihood that weights would swing enough to cause a change in alternative is slim. We conclude that the IPS alternative is the preferred choice for tracking naval sea-based inventory, given the challenges presented in Exhibit 1, and this recommendation is robust to changes in measure weights.

[Insert Exhibit 6, 7, 8 here]

Validation and Implications for Engineering Managers

The SMEs reviewed the alternative scores and sensitivity analysis, concluding that the results were reasonable. Each alternative was initially scored using the gold standard, utilizing supporting United States Government and Navy documentation as well as industry specifications, to support the value assessment on every measure. The SMEs reviewed each value and provided feedback and appropriate modifications. Sensitivity analysis was also reviewed, with the SMEs confirming that drastic weight changes for *stowage factor enablement, registration of inventory in the system*, and *security* are unlikely to occur, supporting the robustness of the IPS alternative.

We reviewed our results with project sponsors at the Office of Naval Research and received positive feedback on both the approach taken and the results. Specifically, the recommendation for IPS resonated with the project sponsors, as the mission of fulfilling emergent requests in a sea-basing environment requires selectively offloading cargo in a dense storage environment. For other mission requirements, such as planned resupply of ships where the requests for cargo can be planned in advance and are typically for bulk requests (e.g. pallets of food or ammunition), less complex asset tracking technology may be preferred.

This study does not consider implementation cost as a tradeoff. The true cost to implement any alternative fleet wide would depend on a variety of factors including size of fleet, sourcing of inventory tags, and personnel training time. Availability of funds would be constrained by the congressional budget, and total cost of implementation would likely be driven by the contractor request for proposal process. Future work plans to estimate these costs and support the Office of Naval Research as needed in implementation of asset tracking technology in naval sea-basing.

A challenge to evaluation and acquisition of technologies is that information on newer technologies is difficult to obtain (Daim & Kocaoglu, 2008). IPS is an emerging technology and requires specialized transmitters and receivers. We have been conservative when evaluating this alternative, assigning values that could be lower than actual during implementation. As the technology matures, items could arrive with the tags pre-affixed, which would continue to shorten registration time and increase overall performance. Even with this guarded approach, IPS is still the preferred alternative.

When performing value-focused decision analyses, engineering managers should be careful to engage SMEs who have detailed knowledge of the application area and can reasonably understand the structure, purpose, and mechanics of a MODA model. The SMEs need not have a decision analysis background, but no knowledge of the MODA process may lead to elicitation of values that are unrealistic or inappropriate for the study.

A strong benefit of the VFT process is that assumptions are challenged and stakeholders arrive at a recommendation that is based on value, free of bias and preconceived notions. For example, at the start of this project, the initial reaction of our stakeholders was that RFID would be the preferred alternative. However, RFID scored rather poorly in the analysis and is clearly not the preferred alternative. RFID has limitations, primarily in that it does not provide coordinate location values; instead, RFID tags only identify the hold in which the item is located. Also, combining RFID with a hand-held reader that has coordinate capabilities is not feasible in a dense storage environment without reducing the storage factor enablement. Finally, in a sea-based environment, cargo is required to be densely stored in essentially a metal box structure, which can lead to issues with signals and battery life. Therefore, an important insight relevant to engineering managers is that RFID-tagged items alone will not identify cargo locations to the granularity required when dense storage and selective offloading are required. These requirements exist when sea-basing is used to fulfill tailored requests. An initial reaction without analysis may have advocated for RFID, but a full consideration of all important measures and associated performance proved otherwise. Thus, engineering managers who undertake VFT analyses should be open to the challenge of preconceived notions and be willing to coach the client into understanding and accepting the preferred alternative, even if it differs from original thought. A preferred alternative maximizes value and provides the client with a recommendation that aims to satisfy all needs.

Using VFT in defense applications is a unique process, as cost tends not to be considered, and defense posture or benefit is maximized. Engineering managers working in defense must be cognizant of the unique environment and focus their efforts on full elicitation of value and consideration of all possible alternatives.

VFT models have strong benefits and allow qualitative values to be quantified, supporting a data-driven recommendation. Such analyses can be extremely beneficial, and we encourage engineering managers to consider using this approach to evaluate alternatives in a multiple objective environment.

Conclusions

This article presents a value-focused multi-objective decision model to evaluate asset tracking devices for fulfilling emergent requests in a sea-basing environment. Model measures and value were elicited using SME input and policy documentation. Alternatives were scored, and IPS was found to be the preferred alternative for asset tracking when selectively offloading cargo in a dense storage environment is required. Engineering managers can employ Value-Focused Thinking models in practice utilizing the input of experienced SMEs, while remaining open to preconceived notions being challenged in the modeling process.

Acknowledgements

The authors would like to thank our two subject matter experts for their invaluable insights and time as well as Logan Minor, Vincent Schiavone, Eric Schiech, and Corinne Skala for their assistance with data collection. We sincerely appreciate their contributions to this project. This research is supported by the Office of Naval Research Young Investigator Program: The Design of Responsive Sea-Based Logistic Delivery Systems, Award Number N00014-13-1-0594.

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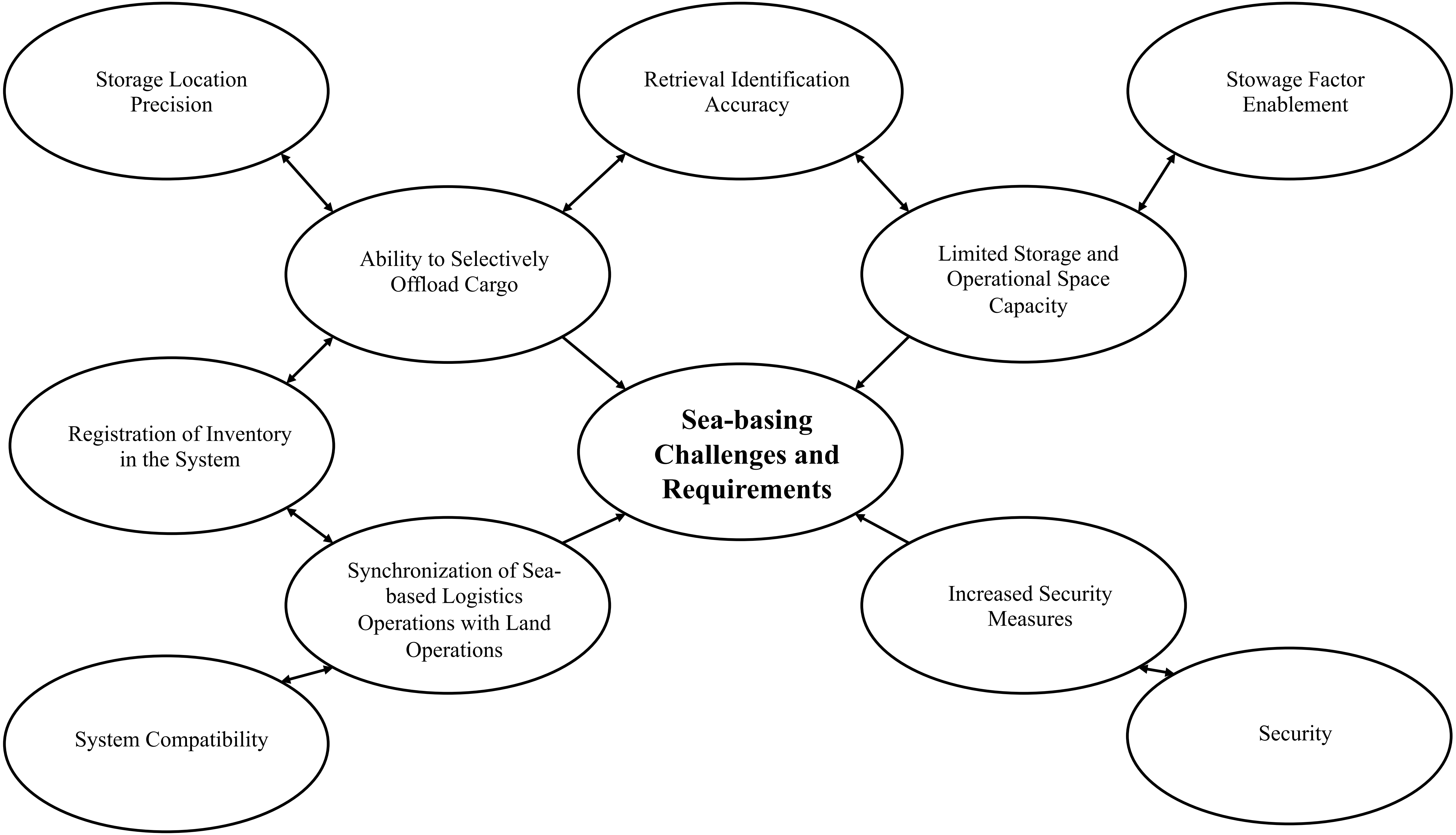
Exhibit 1: Influence diagram of challenges with asset tracking in the sea-base environment


Storage Location Precision
Retrieval Identification Accuracy
Stowage Factor Enablement
Ability to Selectively Offload Cargo
Limited Storage and Operational Space Capacity
Registration of Inventory in the System
Sea-basing Challenges and Requirements
Synchronization of Sea-based Logistics Operations with Land Operations
Increased Security Measures
System Compatibility
Security

Exhibits for
A Value Model for Asset Tracking Technology to Support Naval Sea-based Resupply

Measure	**Performance**	**Value**
Registration of Inventory in the System	Instant	100
	0 to 1 minutes	95
	1 to 2 minutes	85
	2 to 3 minutes	50
	3 to 5 minutes	25
	Greater than 5 minutes	0
Stowage Factor Enablement	70% packed and above (dense)	100
	50% to 70% packed	40
	25% to 50% packed	20
	Up to 25% packed	0
Storage Location Precision	Item recorded to be in a specific subdivision/compartment within the level of the stack (ninth numerical position)	100
	Item recorded to be in a specific level within the stack (eighth numerical position)	95
	Item recorded to be in a specific stack of a specific aisle or row of a hold (sixth and seventh numerical positions)	90
	Item recorded to be in a specific aisle or row in a hold (fourth and fifth numerical positions)	80
	Item recorded to be in a specific hold on the ship (second and third numerical positions)	65
	Item recorded to be on the ship (first numerical position)	50
	Item cannot be recorded to be on the ship	0
Retrieval Identification Accuracy	Item recorded and found to be in a specific subdivision/compartment within the level of the stack (ninth numerical position)	100
	Item recorded and found to be in a specific level within the stack (eighth numerical position)	95
	Item recorded and found to be in a specific stack of a specific aisle or row of a hold (sixth and seventh numerical positions)	90
	Item recorded and found to be in a specific aisle or row in a hold (fourth and fifth numerical positions)	80
	Item recorded and found to be in a specific hold on the ship (second and third numerical positions)	65
	Item recorded and found to be on the ship (first numerical position)	50

	Item cannot be recorded to be on the ship	0
System Compatibility	Seamless between systems, real time updates	100
	Delayed process, but updating throughout the day	90
	Batch transfer that updates once per day	80
	Manual entry	50
	No compatibility	0
Security	Undetectable signal	100
	Detection of signal possible	85
	Detect signal and discern patterns	70
	Detect, read, and understand signal	35
	Actively enter and manipulate system	0

Exhibit 2: Value function definition for each measure

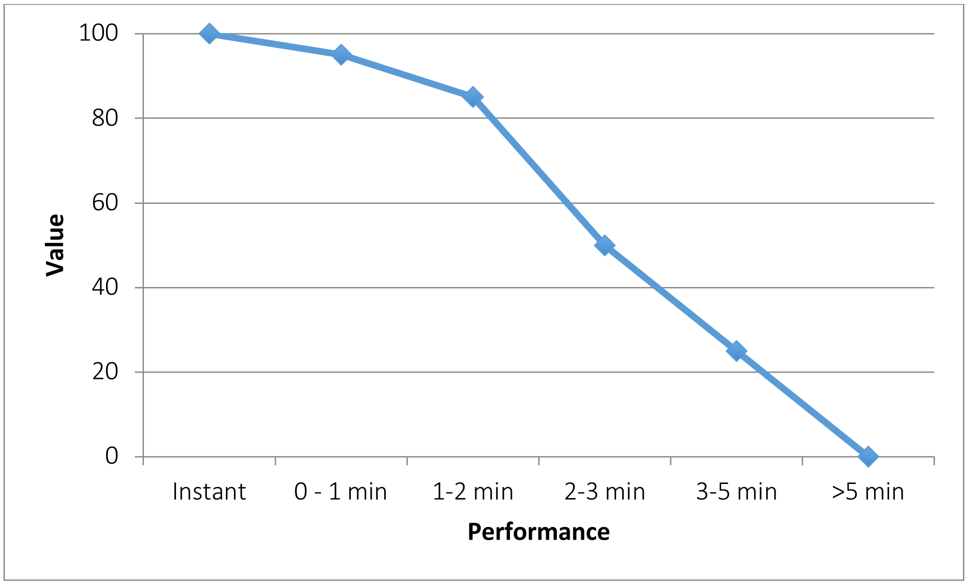


Exhibit 3: Value function for *registration of inventory in the system*

SME Rank	**Measure**	**ROC Weight**
1	Stowage Location Precision	0.4083
2	Stowage Factor Enablement	0.2417
3	Retrieval Identification Accuracy	0.1583
4	System Compatibility	0.1028
5	Registration of Inventory	0.0611
6	Security	0.0278
	Total Weight	1.0000

Exhibit 4: Rank order centroid weights for measures

Alternative	**Score**
IPS	91.75
Barcoding	80.54
RFID	79.75
Camera	78.22
Do Nothing	60.42

Exhibit 5: Final scores s_a for all alternatives in descending order

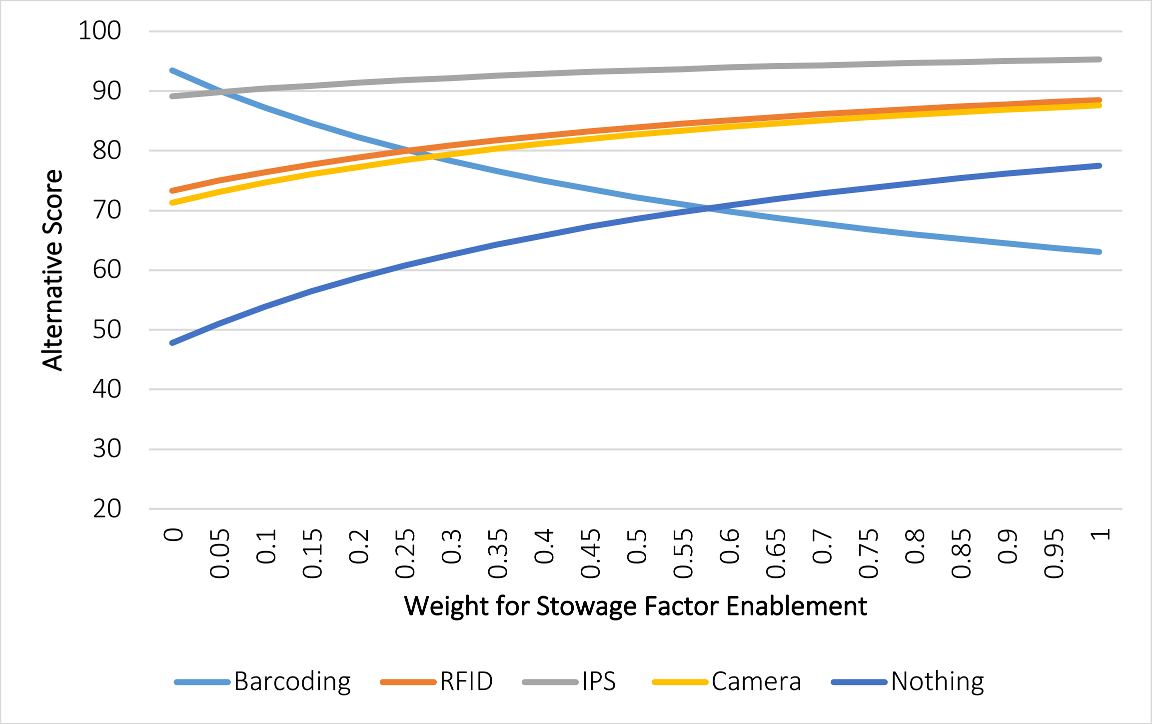


Exhibit 6: Sensitivity analysis for *stowage factor enablement*

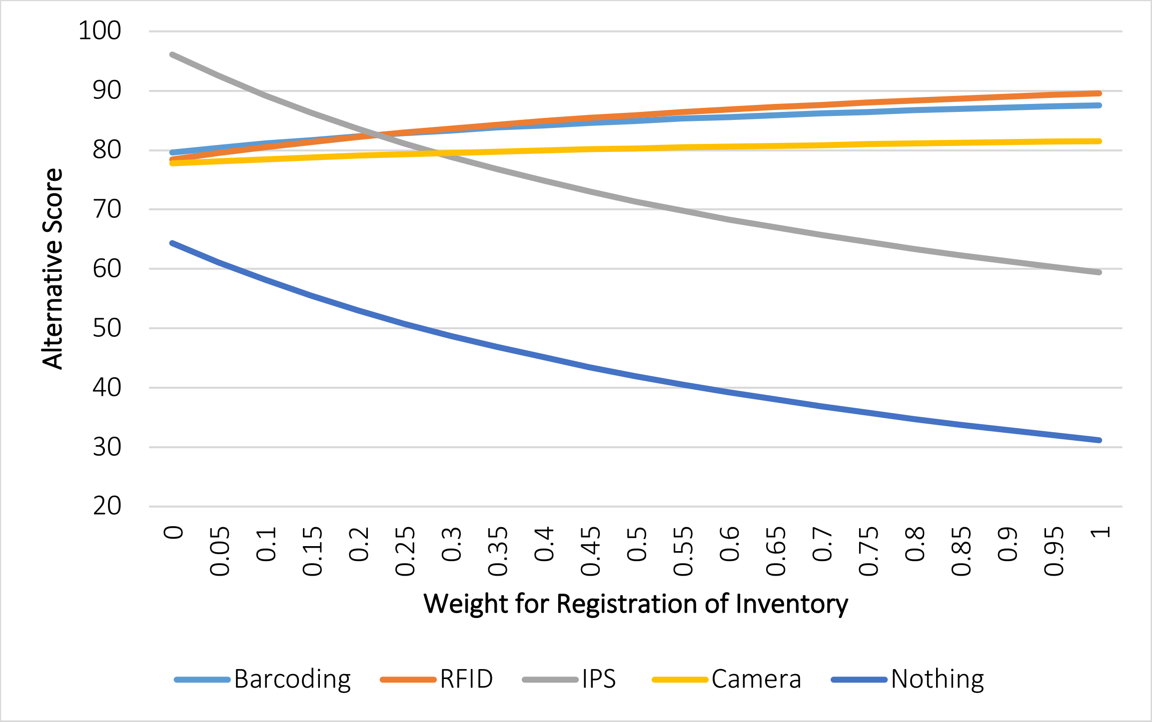


Exhibit 7: Sensitivity analysis for *registration of inventory in the system*

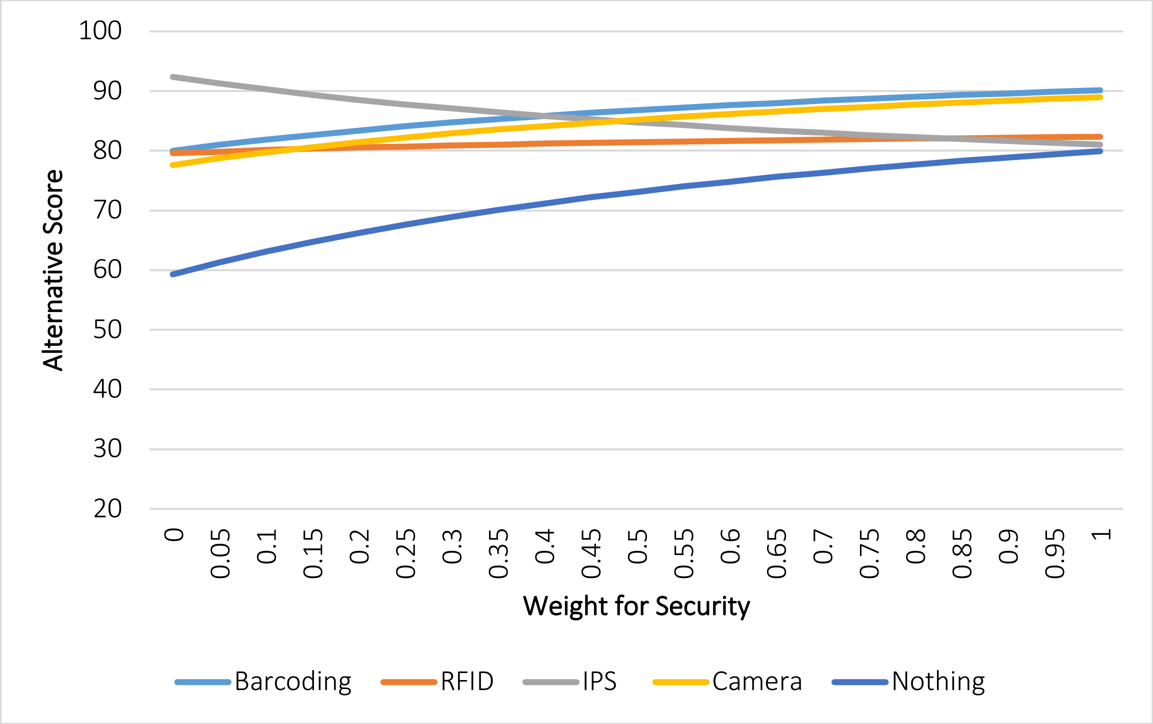


Exhibit 8: Sensitivity analysis for *security*