The Department of Defense (DoD) operates a world-wide supply chain, which in 2017 contained nearly 5 million items collectively valued at over $90 billion. Since at least 1990, designing and operating this supply chain, and adapting it to ever-changing military requirements are highly complex and tightly coupled problems, which the highest levels of DoD recognize as weaknesses. Military supply chains face a wide range of challenges. Decisions made at the operational and tactical levels of logistics can alter the effectiveness of decisions made at the strategic level. Decisions must be made with incomplete information. As a result, practical solutions must simultaneously incorporate decisions made at all levels as well as take into account the uncertainty faced by the logistician. The design of modern military supply chains, particularly for large networks where many values are not known precisely, is recognized as too complex for many techniques found in the academic literature. Much of
the literature in supply chain network design makes simplifying assumptions, such as constant per-unit transportation costs regardless of the size of the shipment, the shipping mode selected, the time available for the delivery, or the route taken. This article avoids these assumptions to provide an approach the practitioner can use when designing and adapting supply chain networks. This research proposes a simulation-based optimization approach to find a near-optimal solution to a large supply chain network design problem of the scale faced by a theater commander, while recognizing the complexity and uncertainty that the practicing military logistician must confront.

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**Keywords:** DoD Supply Chains, Simulation-Based Optimization, Discrete Event Simulation, Uncertainty, Multimode Transportation
In 1990, as the nation struggled to determine the root cause of a major scandal resulting from a lack of oversight within the Department of Housing and Urban Development, the Comptroller General of the United States sent a letter to Congress identifying the top 14 areas across the federal government where tax dollars might be wasted through mismanagement (Bowsher, 1990). This letter grew into a standard practice, wherein the Government Accountability Office (GAO) sends a letter to each new Congress updating the status of these high-risk government operations. The Department of Defense (DoD) supply chain was on the original list, and remained on the list through 2017 (Dodaro, 2017). In the 2017 letter, the Comptroller General wrote that the DoD should, “integrate distribution metrics data, including cost data, from the combatant commands and other DoD components, as appropriate, on the performance of all legs of the distribution system, including the tactical leg.”

While the GAO removed DoD supply chains from the high-risk list in 2019, the Comptroller cautioned that the DoD supply chain still required significant monitoring and improvement, and committed to continued GAO oversight of DoD supply chains (Dodaro, 2019).

Supply Chain Configuration

Supply Chain

The Council of Supply Chain Management Professionals (CSCMP, 2013) defines a supply chain as:

1. starting with unprocessed raw materials and ending with the final customer using the finished goods, the supply chain links many companies together.

2. the material and informational interchanges in the logistical process stretching from acquisition of raw materials to delivery of finished products to the end user. All vendors, service providers, and customers are links in the supply chain.
A typical supply chain may consist of one or more production facilities producing one or more products, one or more warehouses or distribution facilities, one or more retail outlets, the logistics and transportation links that connect them, and the communications and information systems that coordinate the flow of products and materials between them.

**Figure 1. Very Simple Supply Chain Network**

Figure 1 illustrates a representative supply chain network (SCN). This SCN consists of three echelons or layers. The first echelon consists of one or more factories on the left. Each factory produces products and ships them to one or more warehouses in the middle echelon. The warehouses store products and distribute them, when required, to one or more retail locations in the third echelon, where the products are available to consumers. Other common variations include the addition of raw material suppliers as a fourth echelon of the SCN; the return of defective or used products to the manufacturer in a closed loop supply chain; and the use of environmentally friendly materials, manufacturing technologies, and modes of transportation in green supply chains.

Transportation modes have inherent limitations, such as the maximum size or weight a vehicle may carry. A shipment slightly over this maximum would require an additional vehicle at an additional cost. The number of vehicles available for a route may be limited. Locations such as warehouses have limited storage space. In academic studies that acknowledge these limits, the transportation modes and storage locations are referred to as “capacitated.” While many studies avoid this issue and study only incapacitated systems, studies involving capacitated systems are more relevant to the practitioner.

Several parameters characterize the SCN. Some of these parameters, such as the frequency of deliveries and the size of orders, are controlled by the logistician and are referred to in this article as “controlled parameters.”
Others, such as the time it takes to move supplies from one location to the next or the cost of security for a convoy, are not completely within the control of the logisticians and are referred to as “uncontrolled parameters.” The objective of the designer is to manipulate the controlled parameters in such a way as to maximize or minimize an objective function, such as fully burdened supply chain cost, while adhering to constraints, such as the requirement to deliver ammunition, food, and fuel to every unit regardless of their location or the speed with which orders are fulfilled. Figure 2 lists some of the parameters affecting the supply chain.

Supply Chain Management

The Council of Logistics Management (1998) defines supply chain management (SCM) as, “the systemic, strategic coordination of the traditional business functions and tactics across these business functions within a particular organization and across businesses within the supply chain for the purposes of improving the long-term performance of the individual organizations and the supply chain as a whole.” Similarly, within the DoD, “Supply Chain Management is a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores so that merchandise is produced and distributed at the right quantities, to the right location, and at the right time, to minimize system-wide cost while satisfying service level requirements” (Assistant Secretary of Defense for Logistics and Materiel Readiness, 2003).

Supply Chain Network Design

For purposes of this article, supply chain network design (SCND) is the process of selecting the location and capacity of each facility within the supply chain as well as the transportation modes and routes connecting the facilities, including modifying existing supply chains.

SCM and SCND are recognized as critical to the survival of commercial firms, but are also critical to the success of a military operation where the costs of shipping, storing, protecting, and delivering a gallon of fuel can rise
to $600 (Corley, 2009). The U.S. military includes the cost of purchasing consumable items along with the cost of shipping them to the end user who may be deployed anywhere in the world and engaged in combat operations. Such operations may require armed escorts for delivery, which is called the “fully burdened cost.” One study found that 90.5% of the budget of one Navy major defense acquisition program was directly associated with logistics costs, predominately the fully burdened cost of fuel (Corley, 2009). Forces employed in protecting these storage locations and convoys are diverted from conducting offensive military operations, adversely affecting the “tooth-to-tail ratio.”

Decisions made in the context of SCM and SCND may be divided into three categories based on the duration of their implementation. The academic literature on supply chains defines the three levels as operational, tactical, and strategic (Vidal & Goetschalckx, 1997). While these terms are familiar to most military readers, it is important to recognize that the SCM and SCND literature uses them in a different order. Operational decisions are typically in effect for periods of 3 months or less and are often made at low levels in the organization. Operational decisions include route planning, selecting orders to be expedited, delivery sequence and scheduling, and allocation of cargo to specific vehicles. Tactical decisions occur at a higher level than operational decisions. Tactical decisions are often in effect for anywhere from 3 months to 3 years. Tactical decisions include establishing a selling price, selection of transportation mode (TM) for each route, and selection of inventory management policies such as safety stock and order size for each facility (Islam et al., 2019). According to authorities (Govindan et al., 2017), strategic decisions

- are long-lasting, intended to be in effect for multiple years
- include when to build or acquire new factory or warehouse capacity, how much capacity to acquire, and where it should be located
- often involve the commitment of significant financial resources and require long lead times.
While operational, tactical, and strategic decisions are often considered separately in the literature, these decisions are tightly linked in practice (Daniel & Rajendran, 2005; Perera et al., 2017). The classic approach to making facility selection and location decisions relies on the assumption of a constant price per unit distance to transport products and focuses on minimizing the total demand-weighted distance along all flow paths in the supply chain. Because TMs include varying price structures, including minimum costs, maximum capacities, different per-mile rates, and rates based on differing metrics, the use of a single per unit of distance for transportation is not appropriate in many practical situations (Wang & Meng, 2017). The varying security requirements, and their impact on the fully burdened cost, make this assumption more impractical for the military supply chain. Introducing multiple TMs or volume discounts requires the focus to shift from minimizing total demand-weighted distance to minimizing total SCN cost or maximizing total SCN profits.

A 2002 literature survey focused on the value of integrating strategic and tactical decisions in the design of global supply chains (Goetschckx et al., 2002). The survey found that integrating the decisions when optimizing supply chains produced savings of 5–10% over first optimizing the strategic design and then optimizing the tactical decisions based on the strategic decisions. Despite this finding, most of the literature to date has followed the sequential, or 2-step, approach. The survey concluded that no adequate methodology existed for designs where strategic and tactical decisions are combined.

More recently, a seminal review examined 98 papers published between 1998 and 2008 to survey the literature on facility location problems (Melo et al., 2009). In a particularly powerful assessment, the authors state, “this research field has somehow evolved without really taking the SCM context into account... Extensions seem to have been mostly guided by solution methods.” Eighty percent of the surveyed literature assumed the supply chain, including customer demand, was deterministic. Sixteen percent of the literature assumed stochastic variables, but only examined a single
echelon of the supply chain. The authors concluded that integrating operational, tactical, and strategic decisions in a realistic way remained a gap in the literature.

The stochastic nature of SCNs has received considerable attention over the last 20 years. An even more recent literature survey reviewed 170 papers, published between 2000 and 2017, which addressed the topic of SCN design in the presence of uncertainty (Govindan et al., 2017). The papers found that the use of simplifying assumptions to allow the use of specific solution methods remains a concern. Quantity discounts and variable shipping rates were rarely considered. Only 10.5% of papers included TM selection. Of particular importance to the military logistician, the authors found no papers combining strategic and tactical considerations in the presence of uncertainty.

This article addresses this gap in the literature by creating a discrete event simulation (DES) of the SCN and using Simulation-Based Optimization (SBO). The DES allows multiple levels of decisions to be represented within the same model and optimized concurrently. The DES also allows the logistician to easily incorporate critical aspects of the SCN, such as the maximum capacity of vehicles. Figure 3 illustrates this approach. The SCN in blue represents the physical SCN under consideration. The red SCN is a DES representation of the blue SCN. To the extent possible, the DES should
reflect the actual system as accurately as feasible, including the statistical distribution of any stochastic variables such as demand. The continuous estimator monitors the existing SCN and estimates the value of each uncontrolled parameter to update the DES as conditions change. The designer may adjust these values to reflect planned operations. For example, the designer could increase demand in certain areas where offensive operations are planned. Finally, the SBO engine modifies the controlled parameters in the DES to optimize, or nearly optimize, the objective function while satisfying each of the constraints. Once a near-optimal solution is identified, the controlled parameters from the SBO engine can be applied to the physical SCN and the process repeated.

The optimization function may be a simple calculation of the total cost of operating the supply chain or a more complex function, which includes incentives for speed of delivery, penalties for out-of-stock situations, or metrics related to combat readiness of the supported forces.

### Research Questions

This research attempts to answer two primary research questions:

1. Can an SBO engine composed of a genetic algorithm (GA) converge to a solution for a large SCN of the scale used to support a theater commander, incorporating operational, tactical, and strategic decisions simultaneously while only making assumptions that are representative of the military logistician? Specific assumptions to be avoided include:

   a. The effectiveness of decisions made at one level are independent of decisions made at other levels within the chain of command.
b. Transportation costs and transportation time are independent of shipment size, mode of transportation, required delivery time, or route selected.

c. Warehouses, depots, and vehicles used for transporting materiel have unlimited capacity and availability.

d. Demand, transportation price, and transportation time are fixed and deterministic.

2. Does the use of the SBO approach to optimize operational, tactical, and strategic decisions simultaneously result in a superior result to optimizing the decisions sequentially?

This SBO approach is shown to converge for large SCNs. This article quantifies the impact of making decisions at all three levels simultaneously by demonstrating a 3.5% cost saving over making the decisions sequentially.

**Literature Review**

Although other factors could be included by modifying the DES, this research already incorporates integrating decisions at multiple levels in the supply chain, deciding among capacitated transportation modes with different pricing structures and capacitated facilities, and the uncertainty that dominates modern military operations. The literature review will examine the state of research for each of these factors individually before reviewing the literature on the use of SBO and GAs in SCND.

**SCND Integrating Multiple Decision Levels**

The integration of decisions at multiple levels is known to provide a significant saving over considering these decisions sequentially (Goetschalckx et al., 2002; Govindan et al., 2017; Vidal & Goetschalckx, 1997). The problem studied in this article is a generalization of the location-inventory problem (Daskin et al., 2002; Shen et al., 2003). These problems are in a class of problems called NP-hard (Saha et al., 2020). Although unproven, it is widely believed that NP-hard problems cannot be solved in polynomial time, meaning the time required to solve them becomes prohibitive for any large scale. As a result, many approaches reduce the size of the network or limit the scope to a single decision level or a single echelon of the supply chain. A recent review of research on integrated production and distribution planning examined 72 papers published between 2010 and 2019 and found no papers integrating decisions made at all three levels (Kumar et al., 2020).
Ahmadi-Javid and Hoseinpour (2015) studied profit maximizing location-inventory problems, simultaneously making the strategic decisions of facility selection and allocation, and the tactical decisions of price and inventory policy. They formulate the SCND problem as a mixed-integer nonlinear programming model and propose a novel Lagrangian relaxation algorithm to solve the model. The algorithm converges to near-optimal solutions for uncapacitated networks but not for the capacitated networks used by practitioners.

Similarly, several approaches integrate decisions at multiple levels, but only on small scales or with uncapacitated networks. Saha et al. (2020) examined a joint location and inventory model quantifying the impact of the customers’ preferences and backorders. Akbari and Karimi (2015) apply robust optimization to solve a mixed-integer programming (MIP) model of a multi-echelon, multi-product, multi-period SCN with uncertainty in the time required to manufacture products. Sun et al. (2019) propose a fuzzy, mixed-integer, nonlinear programming model to decide between two modes of transportation in an SCN under demand uncertainty.

SCND with Transportation Mode Decisions

Transportation mode selection has been shown to be an essential part of SCND. Because different modes have different cost structures, the use of a constant value for the cost per unit of product for transportation between two facilities is only valid for a limited range of potential solutions (Bureau of Infrastructure, Transportation and Regional Economics [BITRE], 2017). This assumption also ignores the military reality requiring additional security for some routes but not others.

Mendoza and Ventura (2014) studied the integration of TM selection and inventory policy in a single stage in the SCN. They considered two modes over a fixed distance for each route. One mode was a dedicated truck with a constant cost per trip, independent of the size of the shipment. The second mode was a shared truck such as an express delivery service, with a constant

While much of the research assumes deterministic quantities, practitioners face decisions in a military environment where demand for their products, the lead time to fill orders, transportation costs, required time to acquire new facilities, the cost of holding inventory, and many other parameters are uncertain.
cost per unit of product shipped. Both modes included the cost of holding inventory as well as ordering costs and all-unit discounts, and minimized the total cost of the supply chain. The study found that this problem is NP-hard. A proposed algorithm, which took advantage of a special structure of the mixed-integer linear programming (MILP) model, solved the problem by using decomposition, and an exact solution was found for each subproblem. While the technique works for this special structure, it does not converge in the general case.

Sadjady and Davoudpour (2012) studied a two-echelon SCN including the selection from multiple TMs with different unit cost to transport product between facilities based on the mode of transportation and the distance. They showed the approach worked well for large networks with uncapacitated TMs, resulting in near-optimal solutions in reasonable execution times. The authors state that this approach would require major modification to incorporate the capacitated transportation modes found in practice.

Kheirabadi et al. (2019) studied a two-echelon supply chain incorporating quantity discounts and TM selection. However, the assumptions of deterministic demand required by this technique limit applicability by the military logistician.

**SCND with Uncertainty**

While much of the research assumes deterministic quantities, practitioners face decisions in a military environment where demand for their products, the lead time to fill orders, transportation costs, required time to acquire new facilities, the cost of holding inventory, and many other parameters are uncertain. For an SCND technique to be applied with confidence in this environment, the technique must capture the uncertainty and quantify the impact of the uncertainty on the performance of the objective function (Govindan et al., 2017).
Govindan and Fattahi (2017) studied a three-level supply chain under demand uncertainty. Stochastic demand was studied using weighted scenarios. The authors formulated the supply chain as a deterministic MILP model and used a two-stage stochastic programming approach to strategic and then tactical decisions. Strategic decisions include facility location and capacity in the first stage. Tactical decisions involving inventory were considered independently in the second stage. The approach was unable to obtain solutions for large networks in feasible times. The authors showed this can be mitigated in part through the use of scenarios to further decompose the problem. The scenario-based, stochastic programming approach was expanded by including an efficient tree structure to improve the generation and weighting of scenarios (Fattahi et al., 2018). However, the special structure required by this approach required simplifying assumptions such as a single TM.

**SCND with SBO and GA**

SBO has rarely been applied to SCND. A search on Scopus®, a database of peer-reviewed journals at www.scopus.com, was conducted using the keywords (“supply chain management” OR “supply chain network design”) AND (“simulation-based optimization”) in the title, abstract, or keyword list. The search found only 36 published articles, 18 of which included uncertainty or related terms in the title, abstract, or keyword list.

Jung et al. (2004) use a discrete event simulation within a gradient following optimization engine to determine optimal safety stock in a production facility with demand uncertainty. Schwartz et al. (2006) propose an SBO approach using a discrete event simulation involving simultaneous
perturbation stochastic approximation to determine the optimal inventory policy in an SCN in the electronics manufacturing industry. Nikolopoulou and Ierapetritou (2012) combine MILP with an agent-based simulation to overcome some of the complexity inherent in practical SCNs; however, their approach did not include stochastic variables.

GAs have frequently been applied to SCND, with a significant number of papers addressing uncertainty. A search on Scopus® was conducted using the keywords ([“supply chain management” OR “supply chain network design”] AND [“genetic algorithm”]) in the title, abstract, or keyword list. The search found 499 published articles, 174 of which included uncertainty or related terms in the title, abstract, or keyword list. Govindan (2016) published the results of a literature search on the application of evolutionary algorithms applied to SCM and predicted growing interest in their application to advanced problems in SCM such as the one addressed in this article. Nezamoddini et al. (2020) used a GA and an artificial neural network to manage risk by making strategic and tactical decisions for an SCN in the presence of uncertainty in disruption and demand. Sajedinejad and Chaharsooghi (2018) apply a GA to the problem of supplier selection in an SCN through multi-objective optimization. Afrouzy et al. (2016) applied a priority-based GA to maximize profit during the introduction of a new product into an existing SCN, balancing production capacity and inventory between new and existing products. Table 1 summarizes the literature and places this research in context.
# TABLE 1. REVIEW OF SUPPLY CHAIN NETWORK LITERATURE

<table>
<thead>
<tr>
<th>Author</th>
<th>Echelons</th>
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<th>Transportation Modes</th>
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**Note.**

**Operational Decisions**

O: Place an order. R: Routing. V: Vehicle selection and loading

**Tactical Decisions**


**Strategic Decisions**


**Stochastic Variables**

Problem Definition and Modeling

This research on the SBO approach to SCND in the presence of uncertainty was conducted using an illustrative supply chain in Australia responding to a significant change in the cost of transporting goods over maritime routes. Australia was selected as a surrogate area of responsibility (AOR) due to its size being appropriate for a theater-size AOR with a diverse set of transportation modes and readily available information on the distance between locations by each mode as well as current cost information. In this example, supplies arrive in Australia via military or contracted commercial ships at one of a limited number of secure ports and are then transported to warehouses or depots before being delivered to the final units dispersed across the continent.

Problem Introduction

To develop a broad set of scenarios for this research, a major change in the fully burdened cost of maritime shipping was hypothesized, representing various levels of threats to shipping that required escort by warships. A high threat level was defined as a value of 100% and a high cost per mile of ship travel was established. Lower cost threat levels were established at 5% increments down to 70% of the maximum maritime transport cost to create seven unique scenarios. We limited the number of potential ports to three and the number of warehouses to five based on the high cost of defending such facilities. The design and optimization of this SCN for each of these scenarios was the focus of this research.
Figure 4 illustrates a base line SCN. The heat map of Australia, provided by the Australian Bureau of Statistics (ABS, 2016), shows the population density of Australia in 2016. The base line design used in this research consisted of only two ports and five warehouses. One port was at Darwin and the other at East Intercourse Island. Icons indicate the ports and warehouses. Thick blue lines represent shipments from ports to warehouses, and thin green lines represent shipments from warehouses to retail locations.

A recent study by Lee et al. (2017) found that the most efficient way of transporting products from Asia to Australia was via two routes. The first is between Singapore and the Australian port at East Intercourse Island, on the Northwest corner of Australia. The second is between Ningbo, a Chinese port on the East China Sea, and the Australian port of Townsville in the Northeast. While both of these routes deliver cargo to the Northern coast of Australia, the majority of the population is concentrated along the Southeast coast. Both of these routes require overland transport of the majority of the product to the Southeast coast. This study assumed the shipments originated at either Singapore or Ningbo. Lee et al. predicted that a reduction in maritime transportation costs relative to the cost of land transport, in particular rail transport, would shift the optimal maritime hubs south to ports such as Sydney, Canberra, or Melbourne.

For a given set of selected facilities, tactical decisions included selecting a transportation mode for each ground segment and establishing inventory policies such as safety stock (SS), order quantity (OQ), and reorder point (ROP).

**SCN Description**

The SCN under study consisted of three echelons. The first echelon was the port echelon, which replaced the factory echelon from the typical SCN in Figure 1. The 15 largest ports in Australia were selected as candidate ports for products arriving from the ports of either Singapore or Ningbo. The SCN was constrained to select no more than three of these ports. The second echelon was the warehouse, depot, or distribution center. The Australian Bureau of Statistics (2016) defines 96 Greater Capital City Statistical Areas (GCCSAs) in Australia. Each GCCSA was considered as a potential host for a warehouse in this SCN. Based on the budget available for defending these facilities, up to five warehouses could be selected from the 96 potential sites.
The third echelon was the location of a military unit, similar to a retail location in Figure 1. Each GCCSA was represented as a single unit or retail location in the SCN. Each unit experienced stochastic demand with a mean proportional to the surrounding population.

Supplies arrived in Australia by ship at one of the hubs in standard 40-ft ISO shipping containers. The containers were transported to one of the warehouses by rail or truck load (TL) shipment. The products could be shipped from a warehouse to a retail location as a full container, or as a smaller shipment if less than a full container was required. Transportation from a warehouse to a retail location was by rail, TL, or less than truck load (LTL) freight. The mode chosen for each shipment was the least expensive considering all applicable costs, minimizing the combined shipping cost, holding cost, and ordering cost. The rates for rail and TL shipping were based on freight rates provided by BITRE (2017). The ratio between the cost of TL and LTL was used to determine the LTL rate and was varied over a range found in the literature (Kay & Warsing, 2009; Mendoza & Ventura, 2014; Özkaya et al., 2010). A cost multiplier was provided at each leg to account for required security reflected in the fully burdened cost. The time for each transportation segment was stochastic with a mean dependent on the mode selected and proportional to the distance traveled.

Strategic decisions included selecting up to three hubs from the 15 potential ports, selecting up to five depot locations from the 96 GCCSAs, assigning each depot to a servicing port, and assigning each unit to a servicing depot.

For a given set of selected facilities, tactical decisions included selecting a transportation mode for each ground segment and establishing inventory policies such as safety stock (SS), order quantity (OQ), and reorder point (ROP). The common equation for determining OQ, first proposed by Harris (1990), assumes a constant shipping price for each order. The introduction
of the transportation mode decision includes a minimum cost per shipment by each mode as well as different cost per mile, resulting in a nonconvex cost function (Mendoza & Ventura, 2014; Perera et al., 2017; Tersine & Barman, 1991). Chan et al. (2002) studied this problem and proved it to be NP-hard.

Operational decisions were made for each warehouse and unit each day. The operational decisions included servicing demand and replenishing inventory. Servicing demand entails shipping the amount of product demanded up to the amount on hand. Replenishing, which is done at the end of the day, consists of comparing inventory on hand plus inventory on order to the determined ROP, and placing an order if warranted. If the inventory on hand plus inventory on backorder was below the ROP, the facility placed an order for the OQ using the TM determined at the tactical level.

The SCN attempted to meet all demand. However, out-of-stock situations were possible. A penalty was assessed for any orders that could not be filled. Orders placed at the unit level were not placed on backorder. If warehouses did not have enough inventory on hand to fulfill an order, the order was held on backorder until sufficient stock arrived.

Decisions

Quantifying the impact of considering strategic, tactical, and operational levels of decision simultaneously is a key research objective of this study. At the strategic level, the authors include facility selection and allocation. At the tactical level, the authors include two tightly coupled sets of decisions: transportation mode selection and inventory policies. Transportation model selection for each facility considers four modes of transportation, each with different capacities and cost structures. Inventory policy decisions include order quantity and reorder point for each facility.

At the operational level, the authors include ordering based on realized demand, inventory on hand, and inventory on order.

The decisions at the strategic level include selecting a set of up to three port facilities to serve as maritime shipping hubs and a set of up to five GCCSAs to host depots, as well as selecting which port will supply each depot and which depot will serve each retail location. Location selections are indicated
by the 8-tuple, S, where the first three values indicated selected port locations and the final five values indicated selected depot locations from the list of 96 GCCSAs. A value of zero indicates that no facility will be used. For example, SCND = (2, 5, 0, 5, 82, 93, 0, 0) indicates that only two ports will be chosen as the maritime hubs—one in GCCSA No. 2 and the other in GCCSA No. 5; and only three depots will be established—one in GCCSA No. 5, one in GCCSA No. 82, and the last in GCCSA No. 93. The set P is the set of non-zero, unique, elements from the first three elements of S. The set W is the set of non-zero unique, elements from the final five elements of S. In this example, P = {2, 5} and W = {5, 82, 93}.

**Discrete Event Simulation**

A discrete event simulation of this SCN was created and verified in the form of a stochastic function in MATLAB. The function was used within a script file that set the initial condition and called the function to execute the simulation. The scenario variables as well as simulation control variables were established as global variables accessible to the function. The SCND in the form of an 8-tuple of selected locations was passed to the function as an input parameter. The function simulated a warm-up period followed by a number of repetitions, each simulating one calendar year of operation. It also recorded the total operating cost as well as the individual tallies for the cost components of the elements of the fully burdened cost of the supply chain for each repetition. While a year was chosen as the replication length for this study to align with standard accounting periods, a replication length equal to the planned campaign length may be used if it is known. Upon completion of the final repetition, the function returned the sample mean and the 95% confidence interval (CI) for the total cost and each of the cost components.

This research used cost as the metric to optimize, while requiring the SCN to satisfy all demand. Each incident where demand could not be satisfied triggered assessment of a penalty. The authors recognize that cost is not the only, or even the most important, metric of concern to the military logistician. Speed of resupply and the potential loss of life must be considered. These aspects could be incorporated in future studies by increasing the cost penalty for unsatisfied demand to make such cases so expensive that the optimization routine would prevent them.

“Quantifying the impact of considering strategic, tactical, and operational levels of decision simultaneously is a key research objective of this study.”
One aim of the study was to quantify the impact of making the strategic and tactical decisions together. To accomplish this, a second input variable indicated whether the function should calculate tactical decisions including the order size, reorder point, and transportation mode for each retail location, or should use existing values. Therefore, the model included two options for tactical decisions: (1) a 1-pass optimization approach in which the tactical decisions were calculated for each potential design during each simulation run, and (2) a 2-pass optimization approach. In the first pass of the 2-pass approach, the tactical decisions were made for the base line design and held constant while the strategic decisions were varied for the remaining simulation runs to optimize the SCN performance at the strategic level. Once the strategic decisions were optimized, the function was used one last time to make the tactical decisions based on the selected design and determine the final set of cost data.

Simulation-Based Optimization

Jourdan et al. (2009) divides methods for approaching complex and NP-hard optimization problems into four categories. The first category consists of tools that find an exact optimal solution, often using a gradient-following approach. This category does not scale well for complex problems that are nonconvex, such as many practical SCND problems faced by military logisticians. The second category attempts to find near-optimal solutions through approximations and subdividing the problem into smaller problems that may be solved using approaches from the first category. Again, these approaches do not scale to the required size and do not work well with a large number of nonconvex regions. The third category applies heuristics to solve certain classes of problems efficiently. This category takes advantage of specific aspects of certain classes of problems, but does not work for general problems such as the complex SCND problem. Metaheuristics, which include GAs, is the final category. A metaheuristic is a set of guidelines or strategies that predictably find reasonably good
solutions to problems that may be too hard to solve with a closed-form or equation-based approach. Metaheuristics may not find the optimal solution but may find a near-optimal solution for a complex problem. Metaheuristics may be the only available solution for large scale, complex, highly nonconvex problems found in practice in military SCND where a good solution to the practical problem is better than a perfect solution to a simplified problem.

In this research, a GA was combined with the simulation model to search the tradespace of possible designs for this SCN to identify the SCND, which optimizes the objective function of the total supply chain cost. The simulation model was used to determine the total cost of the supply chain for each potential SCND as the GA altered the structure of the SCN.

**Genetic Algorithm**

The GA accepted the function call for the simulation model, including the constraints on the possible values of each element of the SCND, as inputs. The objective function was defined as the value returned by the simulation model for the specific SCND. The GA generated a random set of 200 SCNDs, each conforming to the constraints of the SCND definition. The GA identified the SCND with the lowest total operating cost.

In each generation, each candidate SCND was evaluated by the objective function and ranked in order of its value, with the lowest ranked SCND having the lowest total cost for a year of operation. Candidates for the subsequent generation were determined by three processes: survival, crossover, and mutation. The survival process selected the 10 lowest cost SCNDs for inclusion in the next generation. Crossover selected the 140 lowest cost SCNDs and randomly exchanged values for subsets of parameters between the SCNDs, such as the ports from design No. 8 with the warehouses from design No. 17. Mutation selected the 50 lowest ranked SCNDs and randomly changed three of the eight selected facilities.

For each new generation, the evaluation and ranking process was repeated and, potentially, a new lowest cost SCND was identified. The GA repeated the process until no improvement greater than 0.5% of the total cost occurred over the course of 50 generations, or until 1,000 generations had been evaluated.
Experimental Approach

A scenario was defined as a specific set of conditions for the SCN, including the geographic constraints such as the possible locations of cities and ports, the cost data such as the per-container cost of maritime shipping to Australia and the fixed cost of operating a warehouse, and the stochastic demand at each retail location. The DES was used to estimate the operating cost for each SCND, and the GA was used to search the tradespace of potential designs to minimize the estimated operating cost using two approaches. The 1-pass method made the tactical decisions within the simulation each time it was called, optimizing the tactical decisions along with the strategic decisions. The 2-pass method determined the tactical decisions for each unit-level or retail location: the first time before the GA was used to optimize the strategic decisions and a second time once a final strategic design was selected. The tactical decisions for each retail location were not altered while the GA optimized the strategic design. For both the 1-pass and 2-pass approaches, the final cost data were recorded for further analysis.

Results

The optimization routine was run for values of the maritime shipping rate from the maximum values to 70% of the maximum values in steps of 5% to determine the impact on the SCN. Figure 5 summarizes the results of the optimization. Each data group contains three sets of data: the performance of the base line SCN, the performance of the SCN optimized using the 2-pass approach, and the performance of the SCN optimized using the 1-pass approach. The base line SCN assumes no changes in the SCND and retains the original ground shipping costs, order costs, holding costs, and fixed costs in each set. The only difference between the base line costs in each of the groups is the reduction in the maritime shipping cost. The 2-pass approach and 1-pass approach both result in the realignment of the SCN to take advantage of the reduced shipping rate. For example, with a high maritime shipping rate, a warehouse in Sydney may be serviced by a port in Darwin using rail transport from Darwin to Sydney. At a low maritime shipping rate, the warehouse in Sydney would be serviced by the port in Sydney. Under this scenario, the maritime shipping cost would be higher due to the longer maritime distance, but the ground shipping cost is reduced by eliminating the rail transport. Figures 6 and 7 illustrate these examples.
FIGURE 5. OPTIMIZED SUPPLY CHAIN NETWORK PERFORMANCE

Total Annual Supply Chain as a Function of Optimization Approach and Maritime Shipping Rate

FIGURE 6. OPTIMIZED SUPPLY CHAIN NETWORK WITH HIGH MARITIME SHIPPING COST

a. Base Line Design  
b. 2-Pass Optimized Design  
c. 2-Pass Optimized Design

People per sq km
- 100.0+  
- 10.0 - 100.0  
- 1.0 - 10.0  
- 0.1 - 1.0  
- <0.1

Icons
- Port  
- Warehouse  
- Both
Figure 6 shows the optimal networks based on the original maritime shipping rates. These networks are represented in the far-left set of three bar graphs (Figure 5). The base line design uses the ports of Darwin and Karratha as recommended by Lee et al. (2017). Each port city held a warehouse, and two additional warehouses were included in the design as indicated in case (a), Base Line Design (Figure 6). The annual operating cost of this supply chain was estimated to be $7,519,689, with a 95% CI of $17,163, and is shown graphically in the Base Line bar of the far-left set of data in Figure 5. Employing the 2-pass approach of holding the tactical decisions constant while modifying the strategic decisions before optimizing the tactical decisions resulted in consolidating all port operations at Karratha as indicated in case (b), 2-Pass Optimized Design (Figure 6). The annual operating cost of this SCN was estimated to be $7,408,560, with a 95% CI of $79,814, and is shown in the 2-pass bar of the far-left set of data in Figure 5. The 2-pass method increased the total maritime shipping cost but reduced the land shipping cost, resulting in a net savings. The 1-pass method of simultaneously optimizing both the tactical and strategic decisions resulted in a design that was similar to the design produced by the 2-pass method, with the addition of one warehouse as indicated in case (c), 1-Pass Optimized Design (Figure 6). The annual operating cost of this SCN was estimated to be $7,169,326, with a 95% CI of $36,846, and is shown in the 1-pass bar of the far-left set of data in Figure 5. The additional cost of operating the warehouse was more than offset by savings in transportation costs.
The final network designs incorporating the projected 30% reduction in maritime shipping rates appear in Figure 7, and they are represented in the far-right set of data in Figure 5. Case (a), Base Line Design (Figure 7), shows the unchanged base line. The estimated annual operating cost of this network is $6,320,758, with a 95% CI of $61,229, and is represented by the base line bar of the far-right set of data in Figure 5. Notably, this set of data is the same as the Base Line bar of the far-left set of data in Figure 5, with the exception that the maritime portion of the bar is reduced by 30%. Employing the 2-pass approach of holding the tactical decisions constant while modifying the strategic decisions and then optimizing the tactical decisions resulted in the network shown in case (b), 2-Pass Optimized Design (Figure 7). The transcontinental shipping from northern ports to southern warehouses has been replaced by southern ports. The estimated annual operating cost of this network is $6,021,737, with a 95% CI of $39,946, and is shown graphically in the 2-pass bar of the far-right set of data in Figure 5. Finally, the 1-pass method of simultaneously optimizing both the tactical and strategic decisions produced a result that resembled the design produced by the 2-pass method, with slightly different warehouse and port locations in the heavily populated southeastern section of the country. The difference appears in case (c), 1-Pass Optimized Design (Figure 7). The annual operating cost of this SCN was estimated to be $5,747,141, with a 95% CI of $41,595, and is shown in the 1-pass bar of the far-right set of data in Figure 5.

### TABLE 2. SUMMARY FOR 30% REDUCTION IN MARITIME SHIPPING COST

<table>
<thead>
<tr>
<th></th>
<th>Cost with Initial Maritime Shipping Rate</th>
<th>Cost with 30% Reduction in Maritime Shipping Rates</th>
<th>Total Savings Over Base Case Initial Cost</th>
<th>Incremental Savings for Each Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>USD</td>
<td>%</td>
<td>USD</td>
<td>%</td>
</tr>
<tr>
<td>Base Line Design</td>
<td>$7,519,689</td>
<td>$6,320,758</td>
<td>$1,198,931</td>
<td>15.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$1,198,931</td>
<td>15.9%</td>
</tr>
<tr>
<td>2-Pass Optimization</td>
<td>$7,408,560</td>
<td>$6,021,737</td>
<td>$1,497,952</td>
<td>19.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$299,021</td>
<td>4.0%</td>
</tr>
<tr>
<td>1-Pass Optimization</td>
<td>$7,169,326</td>
<td>$5,747,141</td>
<td>$1,772,548</td>
<td>23.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$274,596</td>
<td>3.7%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source of Savings</th>
<th>USD</th>
<th>% of Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced Shipping Rate</td>
<td>$1,198,931</td>
<td>67.6%</td>
</tr>
<tr>
<td>2-Pass Optimization</td>
<td>$299,021</td>
<td>16.9%</td>
</tr>
<tr>
<td>1-Pass Optimization</td>
<td>$274,596</td>
<td>15.5%</td>
</tr>
<tr>
<td>Total Savings</td>
<td>$1,772,548</td>
<td>100.0%</td>
</tr>
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</table>
The study found that the 30% reduction in the maritime shipping rate for this SCN would result in a decrease in the total SCN operating cost of 15.9%, from USD $7.5 million to USD $6.3 million. Optimizing using the 2-pass method resulted in an SCN operating cost savings of 19.9%, to USD $6.0 million. Optimizing using the 1-pass method resulted in an SCN operating cost savings of 23.6% to USD $5.7 million. Table 2 summarizes the data for the 30% reduction in maritime shipping rates.

SCN alignment and optimization has a magnifying effect on reductions in costs for any one portion of the SCN. The direct savings from reducing maritime shipping costs accounted for a savings of USD $1.2 million. SCN optimization amplified that savings to USD $1.8 million—an increased savings of 48% for the final scenario.

Note. 2-Pass: Strategic, Tactical, and Operations Decisions are made independently. 1-Pass: Strategic, Tactical, and Operations Decisions are integrated.

<table>
<thead>
<tr>
<th>Maritime Shipping</th>
<th>Base Line Mean</th>
<th>95% CI</th>
<th>2-Pass Mean</th>
<th>95% CI</th>
<th>1-Pass Mean</th>
<th>95% CI</th>
<th>Additional Savings from 1-Pass Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>$7,519,689</td>
<td>$17,163</td>
<td>$7,408,560</td>
<td>$79,814</td>
<td>$7,169,326</td>
<td>$36,846</td>
<td>3.2%</td>
</tr>
<tr>
<td>95%</td>
<td>$7,319,867</td>
<td>$72,404</td>
<td>$7,168,658</td>
<td>$40,834</td>
<td>$6,852,341</td>
<td>$62,757</td>
<td>4.4%</td>
</tr>
<tr>
<td>90%</td>
<td>$7,120,045</td>
<td>$62,158</td>
<td>$6,826,267</td>
<td>$50,892</td>
<td>$6,677,605</td>
<td>$40,156</td>
<td>2.2%</td>
</tr>
<tr>
<td>85%</td>
<td>$6,920,223</td>
<td>$14,914</td>
<td>$6,718,078</td>
<td>$35,550</td>
<td>$6,548,704</td>
<td>$82,784</td>
<td>2.5%</td>
</tr>
<tr>
<td>80%</td>
<td>$6,720,401</td>
<td>$41,331</td>
<td>$6,525,380</td>
<td>$67,403</td>
<td>$6,201,325</td>
<td>$60,905</td>
<td>5.1%</td>
</tr>
<tr>
<td>75%</td>
<td>$6,520,580</td>
<td>$34,237</td>
<td>$6,263,597</td>
<td>$57,190</td>
<td>$6,090,412</td>
<td>$52,672</td>
<td>2.8%</td>
</tr>
<tr>
<td>70%</td>
<td>$6,320,758</td>
<td>$61,229</td>
<td>$6,021,737</td>
<td>$39,946</td>
<td>$5,747,141</td>
<td>$41,595</td>
<td>4.6%</td>
</tr>
</tbody>
</table>

Note. 2-Pass: Strategic, Tactical, and Operations Decisions are made independently. 1-Pass: Strategic, Tactical, and Operations Decisions are integrated.
Table 3 highlights the impact of integrating strategic and tactical decisions while optimizing the SCN. Across the seven maritime shipping scenarios displayed, optimizing the strategic and tactical decisions concurrently, in a 1-pass approach, resulted in an additional savings of 3.5% of the SCN cost obtained by optimizing the strategic and tactical decisions sequentially in a 2-pass approach.

**Conclusion**

SCND has been shown to be NP-hard and mathematically complex in the general case. Many of the techniques in the literature find exact solutions to the SCND problem by making simplifying assumptions, which are driven as much by the requirements of the solution technique as the needs of the practitioner. To the authors’ knowledge, no solution in the literature has been shown to solve the problem without assumptions, either exactly or in an approximate sense. No special structure has been identified in the general case, which would allow a known heuristic to be applied. Therefore, a metaheuristic solution was pursued.

Further analysis showed that integrating tactical and strategic solutions in a single pass provided a structurally different solution than optimizing the strategic and tactical decisions sequentially, and that this structural difference resulted in an additional 3.5% savings in total SCN operating costs.

This study answered the primary research questions. An SBO engine composed of a genetic algorithm converged to a solution for a large SCN of the scale used to support a theater commander. The solution incorporated operational, tactical, and strategic decisions simultaneously, in the presence of stochastic input variables, without making assumptions that are inappropriate to the military logistician. While many of the approaches in the literature make simplifying assumptions such as transportation costs, which are independent of order size, or that the effectiveness of decisions made at the strategic level are independent of decisions made at the tactical level, this approach does not require these assumptions. The results showed that optimization of operational, tactical, and strategic decisions simultaneously results in a superior result to optimizing the decisions sequentially.
To demonstrate the authors’ approach, the authors studied an illustrative SCN responding to a change in the threat environment. To minimize simplifying assumptions, the problem included many of the factors affecting fully burdened defense supply chains:

- The operators of the SCN will make decisions at the strategic, tactical, and operational levels and these decisions are tightly linked.
- The SCN operates in the presence of uncertainty in both demand and transportation lag time.
- The operators must make decisions that include nonconvex response functions, such as deciding between TL transportation with a maximum capacity, a minimum charge per TL plus a per-mile charge independent of the size of the shipment, or LTL transportation with a higher per-mile charge but no minimum charge or maximum capacity.
- The SCN must operate on a large scale, providing service to 96 locations distributed over a continent.

A novel SBO approach combining a DES with a GA and modifying the GA to consider port and warehouse selections as holistic entities in the crossover process, was shown to provide a solution to this problem in feasible time. Further analysis showed that integrating tactical and strategic solutions in a single pass provided a structurally different solution than optimizing the strategic and tactical decisions sequentially, and that this structural difference resulted in an additional 3.5% savings in total SCN operating costs. Therefore, optimization cannot be assured by solutions that consider strategic and tactical decisions either sequentially or in isolation.

Further research is required to compare the solutions obtained by the SBO approach to solutions obtained by exact or approximate methods, for those problems that can be solved by these means, to quantify the degree to which the SBO approach compares to the optimal solution. Additionally, the GA procedures should be further evaluated to identify optimal values or heuristics for determining values for this class of problem (Cosma et al., 2020). The effect these values have on both the time to converge on a solution and the optimality of that solution is left for future research.
# Abbreviations & Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>ABS</td>
<td>Australian Bureau of Statistics</td>
</tr>
<tr>
<td>AOR</td>
<td>area of responsibility</td>
</tr>
<tr>
<td>BITRE</td>
<td>Bureau of Infrastructure, Transportation and Regional Economics</td>
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<tr>
<td>CI</td>
<td>Confidence Interval</td>
</tr>
<tr>
<td>CSCMP</td>
<td>Council of Supply Chain Management Professionals</td>
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<tr>
<td>DES</td>
<td>discrete event simulation</td>
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<tr>
<td>DoD</td>
<td>Department of Defense</td>
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<tr>
<td>GA</td>
<td>genetic algorithm</td>
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<tr>
<td>GAO</td>
<td>Government Accountability Office</td>
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<tr>
<td>GCCSA</td>
<td>Greater Capital City Statistical Area</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>LTL</td>
<td>less than truck load</td>
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<tr>
<td>MILP</td>
<td>mixed-integer linear programming</td>
</tr>
<tr>
<td>MIP</td>
<td>mixed-integer programming</td>
</tr>
<tr>
<td>OQ</td>
<td>order quantity</td>
</tr>
<tr>
<td>ROP</td>
<td>reorder point</td>
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<tr>
<td>SBO</td>
<td>simulation based optimization</td>
</tr>
<tr>
<td>SCM</td>
<td>supply chain management</td>
</tr>
<tr>
<td>SCN</td>
<td>supply chain network</td>
</tr>
<tr>
<td>SCND</td>
<td>supply chain network design</td>
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<tr>
<td>SS</td>
<td>safety stock</td>
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<tr>
<td>TL</td>
<td>truck load</td>
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<tr>
<td>TM</td>
<td>transportation mode</td>
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References


Author Biographies

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