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Swarming Logistics: The Enabling Concept for Expeditionary Advanced Basing Operations

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## Executive Summary

**Title:** Swarming Logistics: The Enabling Concept for Expeditionary Advanced Basing Operations

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**Thesis:** In order to support swarming tactics in the Expeditionary Advanced Basing Operations (EABO) scheme of maneuver, the USMC and joint partners should adopt a complementary swarming logistics concept, featuring non-linear distribution, forward production, additive manufacturing, and asset prepositioning. When fully realized in a single autonomous forward production concept, swarming logistics provides a unique capability in producing on-demand weapons system sustainment at the time and place of need, without reliance on lines of logistic support, while providing opportunities to evolve capabilities faster than the adversary.

**Discussion:** This paper examines historical cases and war game observations of non-traditional logistics, identifies four concepts of agile logistics required to support swarming tactics in EABO. Taking those four ideas to their logical conclusion and merging them into a singular operating enabled by automation, creates the “hive” concept of autonomous forward production, which represents a significantly different approach to logistical support for swarming operations.

**Conclusion:** An ideal logistics support concept for swarming should reflect the fluid nature of the scheme of maneuver itself. Those qualities include non-linear distribution to prevent critical nodes of vulnerability, forward production to create mass near the point of employment, advanced manufacturing such as 3D printing to enable field manufacturing and rapid prototype development, and prepositioning of assets during contact layer to create flexibility in supporting the scheme of maneuver while reducing transportation requirements during later stages of conflict.

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## *Preface*

When discussing advanced schemes of maneuver such as Swarming and EABO, an inevitable question presents itself: “how are we going to solve the logistics problem?” In my experience, the discussion that follows usually focuses on either applying existing solutions to new problems, using drones to deliver supplies, or leveraging big data and AI as some kind of magical panacea. At the end of the discussion, however, I notice that few are convinced these things will result in a significantly different outcome, and I suspect that’s because they’re essentially updated variations on the same traditional logistics concept that has existed for centuries. That is centralized production of the majority of critical war materials, distributed across the world to the forward maneuver elements.

So when I approached the problem of how to support the swarm in the context of EABO, I tried to imagine a different approach. As an Aircraft Maintenance Officer in the USAF, I’m familiar with, but certainly no expert in USMC operational logistics. I wanted to think about the problem as if I were the maneuver element myself and didn’t particularly care about how logistics was traditionally supposed to support me, as long as I could generate the swarm. What follows is a non-traditional approach to supporting a non-traditional scheme of maneuver, which I believe can be used in concert with traditional approaches with great success in future conflict.

## **INTRODUCTION**

One of the emerging operating concepts in executing Expeditionary Advanced Basing Operations (EABO) is swarming tactics using large volumes of small, autonomous drones. While this concept provides asymmetrical advantages, it creates significant logistical challenges, given the distributed area of operations, the rapid movement of maneuver elements, large volume of platform-specific logistics demand and the non-permissive nature of the operating environment. Accordingly, developing logistic solutions to these challenges is paramount to mission success in the future operating environment.

In order to support swarming tactics in the EABO scheme of maneuver, the USMC and joint partners should adopt a complementary swarming logistics concept, featuring non-linear distribution, forward production, additive manufacturing, and asset prepositioning. When fully realized in a single autonomous forward production concept, swarming logistics provides a unique capability in producing on-demand weapons system sustainment at the time and place of need, without reliance on lines of logistic support, while providing opportunities to evolve capabilities faster than the adversary.

### *Time Horizon, Assumptions, and Risks*

Given the enduring timeline of the contact layer, these recommendations need to be pursued immediately. Fortunately, much of the technology described already exists, albeit the benefits they collectively convey are further enhanced from continued advancement. For the more advanced concepts, the baseline technology largely exists, but would need to be integrated to implement the idea, and further development may be required to optimize effectiveness.

These recommendations assume the US will continue to prioritize investment in peer competition set forth in the 2017 NSS and 2018 NDS. One of the priorities set forth in both

documents is building and leveraging relationships with regional partners. Specific to the concepts contained in this paper, access to key terrain and support from host nation government is critical. As with many forward force projection concepts, if US Government leadership chooses a different approach to military security cooperation, then these concepts may have less value and applicability in a non-global military.

The technology described in this concept largely centers around the use of relatively small airborne drones to as primary agents of the swarm. Using other vehicles for the swarm may or may not create significant changes to the concept, but these considerations have not been explored during the course of concept development.

## **BACKGROUND**

The swarming strategy currently at the center of future military concept development debate provides exciting advantages.<sup>1</sup> However, one of the biggest challenges is sustaining the strategy logistically. In executing swarming, especially in a spatially distributed littoral environment, logistics distribution is challenged to keep up. According to Arquilla and Ronfelt, a swarming force places demands on logistics that differ from the prevailing practices of the past 350 years, which traditionally emphasize the mass provision of munitions, transport, and manpower to and from fixed locations. In swarming, these goods and services will have to be delivered an ever-shifting set of small forces almost all constantly on the move<sup>2</sup> Using a traditional logistics model, the logistics tail does not move as fast as the maneuver elements, so the tip of the spear is consistently waiting for items they need to continue operations. This places limitations on how far and fast maneuver elements can travel before they become ineffective waiting for needed supplies. Furthermore, lines of logistics are inherently soft targets, vulnerable to enemy interdiction. When enemy interdicts, it prevents required items from reaching the point of need at the front. The psychological effect of being cut off from resupply compounds the practical problem of logistics, further degrading friendly force resiliency in a contested environment. However, this is not the first time logistics paradigms have constrained maneuver warfare.

Looking at historical cases, one notable instance of logistics constraining the ideal operational scheme of maneuver is during the second world war. In September of 1944, the Allies were planning the next stage of operations following successes in Normandy and Northern France. To seize the initiative, Field Marshall Montgomery advocated for a deep, knife-like thrust into the lightly guarded Ruhr valley along a single axis in order to disrupt the critical German manufacturing and coal production industry. Montgomery theorized that the German war effort,

already facing shortfalls, would collapse as a result, causing the Germans to surrender given the lack of production.<sup>3</sup> However, General Eisenhower had reservations regarding the supportability of the concept because the port of Antwerp, although liberated was not yet operational. As such, the allies estimated that the logistics throughput would not be sufficient to support the 18 divisions of British and US forces in a 130 mile offensive thrust into Rhur, so this plan was not pursued further.<sup>4</sup> This lack of logistics throughput prevented the allies from capitalizing on a rare opportunity to destroy enemy production which may have brought about an earlier conclusion to the second world war.<sup>5</sup>

Fortunately, logistics considerations haven't always constrained the scene of maneuver. During the U.S. Civil War, General William T. Sherman developed several creative solutions to combat constraints the Union Army encountered during the 1865 Carolina Campaign. Critics will note that the maneuver tactics in this case are not strictly speaking "swarming" and question the relevance. But the operational-level sustainment challenges that resulted from the fast moving maneuver force and lack of following supply tail are similar to the sustainment challenges swarming presents. In reviewing the historical case from this perspective this paper will seek to identify historical trends relating to logistics constraints during maneuver warfare and the solutions to these problems. Ultimately, this section will evaluate whether decentralized logistics provides a more complete and resilient sustainment when conducting non-linear swarming operations beyond the reach of traditional supply lines.

## **Case Background**

The Civil War seems to fall at a crossroads between Napoleonic and modern war. Despite still-primitive weapons technology, many modern concepts were born during this era, such as use of ambulances, telegraphs, and use of railroads. This analysis will focus specifically on logistics concepts developed during Sherman's Carolina Campaign in 1865. For background, prior to this campaign the Union Army seized and razed Atlanta, then marched to Savannah leaving a wake of destruction in its path. Leaving Atlanta, the Union Army marched--largely unopposed--without a rear supply base, instead foraging for sustenance for man and beast. Once gaining control of Savannah, Sherman began planning and refitting for the next campaign. The objective for this campaign would be to join the armies of Sherman and Grant in North Carolina and march to Richmond to decisively defeat Lee's Army of Northern Virginia. To achieve this objective as well as destroy Confederate logistics capability and morale along the way, Sherman planned to march north instead of boarding ships and taking naval transport up the east coast.<sup>6</sup> Based on the previous success in marching from Atlanta without a following supply train, Sherman laid out a plan to do the same in the march north.

While many scholars have written about Sherman's march to the sea, the destruction of total war, and the logistical gamble of cutting rearward supply lines, there seems to be less discussion on the later and arguably more innovative Carolina campaign. However, Civil War historian J. Wade Sokolosky published two books specifically focused on Sherman's Carolina Campaign, writing that Logistics played a critical role in the success of the campaign, pointing to the ability to maneuver a 60,000-man force across two states without a rear line of communication. He argued that the simple explanation that foraging enabled this feat is not sufficient, concluding that operational and strategic transportation, staff logistician planning, and utilization of local resources to supplement military forces played crucial roles in enabling operational success.<sup>7</sup>

## Case Analysis

The next section will examine specific lessons learned from the Carolina campaign. In doing so, we'll consider whether each concept of decentralized logistics provides more complete and resilient sustainment when conducting non-linear swarming operations beyond reach of supply lines, when applied in the modern context of swarming.

### *Forward Resupply Points*

The first concept from Sherman's Carolina campaign is the use of forward positioned logistics nodes based on anticipated campaign routes. Instead of trailing supply lines or hoping to rely solely upon forage for sustaining the Union Army, Sherman's logistics concept featured several resupply points along the route of advance towards the objective. Key ports on the North Carolina coast served as strategic hubs for receiving supplies from the north via naval shipments. From there, supplies were transported via rail or river to points along the way to resupply the maneuver element during the campaign.<sup>8</sup> One key advantage to this concept compared to a traditional logistics tail is faster movement for the maneuver element. Because the force is smaller, it requires less materiel to sustain itself and has less footprint. This makes it easier to traverse difficult terrain change course when required. Another advantage to this concept is that made the force more resilient. Traditionally, a trailing logistics tail is vulnerable to enemy interdiction. Without the tail, Sherman provided the enemy a smaller, more resilient target. Another advantage to this concept, as Sokolosky points out is the flexibility to respond to unforeseen logistics requirements. This is seen in the response to unexpected refugees and freed slaves that Sherman's troops dealt with.<sup>9</sup> If a logistics tail brought supplies and transportation only sufficient to support the march north, then dealing with the unforeseen requirements would have been a tradeoff in capabilities. Instead, the refugees were back shipped to the port for care.

The lesson from this case is that forward resupply points afford more agility for both the maneuver elements and the sustainment posture. In the context of swarming, positioning forward logistic resupply points at various locations in the anticipated area of responsibility creates a similar opportunity. This is especially applicable in the contact layer, with the intent to set favorable conditions for future operations if necessary. In doing so, the maneuver element is free to move more quickly to various terrain, unconstrained by a logistics tail. Furthermore, the maneuver is less vulnerable to being cut off from its logistics umbilical, especially if there are multiple forward re-supply points, because even if the enemy interdicts one line of logistics, there are other forward logistics points from which to resupply. This forward network could be considered a sort of “logistics swarm” instead of a logistics tail.

#### *Criticality of Logistics C2*

Another lesson from Sherman comes the hard way, is seen at the en-route resupply point at Fayetteville. Along the march, the maneuver element encountered water crossings and muddy terrain. This ruined uniforms and boots to the point where this became the top logistics priority. Additionally, union troops were successful in securing forage for the horses and mules along the route of advancement, such that what was originally considered critical was no longer required. However, this word did not make it to the resupply depots shipping supplies to the forward re-supply point at Fayetteville, so instead of uniforms and boots, they shipped corn, coffee, and sugar as originally planned.<sup>10</sup> As a result, Sherman had to remain longer in Fayetteville for minimal quantities of uniforms and boots to be sent on later shipments. This delay could have been prevented had adequate notice been provided to the depot in Wilmington. While in this case, the delay was not catastrophic, it could have been if the enemy was better positioned to attack.

The lesson learned from this case is that robust command and control is critical to ensure the right support reaches the right location at the right time. While this seems self evident, recall that in this concept the maneuver force is travelling with minimum supplies, so the resupply point is critical to continued operations, so the margin for error is smaller than when travelling with a robust supply train. If it you need it and it doesn't come on the supply shipment, you don't have it. Now what? In Sherman's case, he waited for the next shipment and then continued the campaign. In the case of swarming against an aggressive adversary, a breakdown in logistics command and control could be much more dire. Accordingly, the systems and processes utilized to coordinate these requirements must be accessible and reliable during maneuver operations.

#### *Foraging for Resources*

A third major concept from Sherman's Campaigns was relying on the local area for resources required to sustain the maneuver force. This is not a new concept, as Generals from Sun Tzu to Genghis Khan to Napoleon have relied on the areas around their troops for food. Nonetheless, a large part of Sherman's sustainment strategy was foragers gathering what resources they could find from the land as they passed through. This support came in the form of crops, domestic and wild animals, goods secured from locals, and even captured enemy munitions.<sup>11</sup> In this case, the concept was successful, because with few exceptions the land was bountiful with resources.

The lesson learned from this case is that a maneuver force can rely on the local area for resources at a minimum to augment existing supplies. A modern maneuver force may be less likely to eat crops grown in the field as the primary force sustenance strategy, and certainly tanks and HMMWVs don't go far on hay from the field, but the lesson at the most basic level is still applicable. Resources are available on the local economy, which enable the mission and reduce

the logistics burden of transporting recurring requirements from the rear. Examples of this in the modern context could be fuel for vehicles, or even vehicles themselves. Further, to maintain friendly relations with the locals, these resources can be paid for with a contracting officer. Critics will point out that this is not a groundbreaking revelation, as these activities occur frequently today. But the lesson bears repeating for logistics planners in the swarming context where transporting resources are a luxury and increased utilization of forward positioned assets will drive increased reliance on contracted local support, the ethical modern equivalent of foraging, at least from a logistics perspective.

### **Case Conclusion**

From the review of Sherman's Carolina campaign, it is clear that decentralized logistics were critical to enabling maneuver operations beyond reach of traditional supply lines. Sherman's use of forward resupply points, taking advantage of the planned route of travel and multi-modal transportation, allowed the Union Army to dispense with the traditional supply tail. When executed with accurate command and control, forward resupply points had the ability to provide flexibility to respond to changing logistical requirements. Finally, by foraging the local land for resources, Sherman was able to augment the logistics capability and offset the disadvantages of a lean support structure. In the modern context of swarming, each of these concepts provide advantages compared to traditional logistics networks. Accordingly, logistics planners looking for new ideas to age-old problems should start by reading some old books.

### **Insight from War Games**

In addition to traditional historical research, insight may be gleaned from the execution of war games. During the 2018/2019 school year, students from USMC Command and Staff

College participated in a months-long war game called Strategy Lab. While a relatively simple simulation, one of the objectives from the game was to conquer territory around the map using military units generated in factories. Students from Conference Group 10, including the author, were assigned in the game to Team United States, which possessed multiple territories in North America and a large manufacturing base in the Eastern US. From here, Team US set out to take neutral territories in North and South America, which was a largely straightforward affair, given the relative proximity of manufacturing base to the territories where the military action occurred. However, things became more complicated once Team US began to conduct military operations in theatres geographically separated from the Continental US.

One of the challenges in projecting military force in theatres separate from the nation's manufacturing base is the distance across oceans military units must travel. The first solution to this problem was to build transportation assets to transport the military units from the large manufacturing base in the Eastern United States to the front in Western Africa and Europe. However, this was not an ideal solution because resources and time were required to produce the transports, neither of which were available in excess. Once built, the journey itself to cross the ocean took time, and was open to risk of enemy interdiction along the route. Furthermore, transports loaded with military units provided a visual clue to the enemy that US forces were about to commence operations, which could enable the enemy to proactively engage to blunt the attack.

A different approach to the challenge of distance soon appeared. Once an initial foothold was secured in Africa, team US built a small factory to produce military units in the same theatre where they'd be utilized. From here, additional territories throughout the African theatre were secured and factories constructed. This provided a few advantages. First, positioning means of

production near the front meant that as soon as units were produced, they could be utilized for combat operations, reducing the time delay from production to engagement. Second, it reduced the reliance upon the rearward logistics chain, although units continued to ship from CONUS to maximize mass. Third, and most importantly, forward means of production at various points around the theatre provided multiple points of origin for an attack to commence, converging against enemy in an unpredictable manner. The commander could choose to engage a variety of enemy positions, based on objectives and probability of success, instead of following a linear, predictable pattern. This logistical flexibility enabled swarming schemes of maneuver, which were highly successful throughout the war game. In fact, 100% of the attacks where Team US leveraged this CONOP were successful in achieving the objectives. Other teams saw this success and also began to forward build factories to great success, further validating the approach.

The key takeaway from this war game was that the ability to produce military units at various points in theater provides an agile logistics footprint from which commanders can create swarming schemes of maneuver. While the war game itself was simplified, applying the concept to the swarming scheme of maneuver in the real world could potentially provide similar benefits.

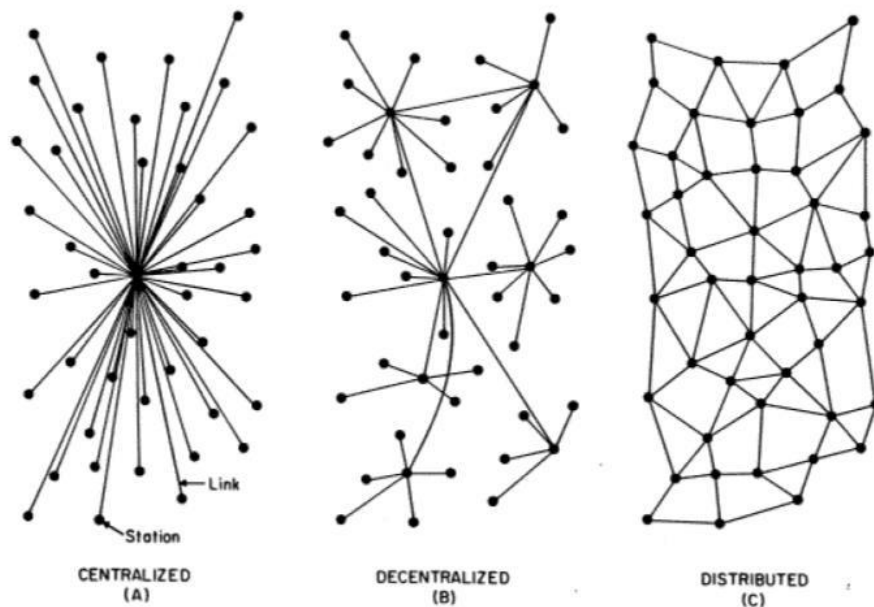
### **SWARMING LOGISTICS CONCEPT**

Based on the research, observations from war games, and technological trends, a swarming logistics concept centers around four main ideas: Non-linear distribution, forward production, additive manufacturing, and asset propositioning. Independently, each have their own merits, but

when leveraged as a singular operating concept, swarming logistics begins to take shape. First, this section will discuss each of the individual concepts.

### *Non-linear Distribution*

As previously discussed, a linear path of distribution is predictable, and susceptible to enemy disruption. It also limits the scheme of maneuver in the sense that operations must logically commence from the end of the linear logistics train. To enable a unpredictable scheme of maneuver, a non-linear path of distribution is required to create support for operations originating from a variety of locations. To create non-linear distribution, establishing a network nodes around the area of engagement, from which varied routes of travel may connect, using a variety of transportation modes. Doing this would mitigate risk of enemy targeting logistics nodes in the contested environment. While this structure does not need to exist purely in a point to point, fully distributed model, shown in figure 1 below, the ability to execute decentralized creates redundancies and increases resiliance to enemy interdiction of nodes.



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Figure 1

Establishing a network of nodes throughout the theatre is not a novel concept. Examining logistics plans from any recent war will uncover planners utilizing multiple nodes. However, the key distinction between non-linear and a more traditional linear, hub and spoke model of distribution is how the nodes themselves are connected, with the intent to avoid becoming reliant on a centralized node. This is because a centralized node is a critical vulnerability in a contested environment. If the enemy targets the hub in the hub and spoke model, it could have severe impacts to the rest of the logistics network. However, if the network features redundant hubs and variable routes of distribution, the impact of enemy targeting against one node is not as significant to the rest of the network.

Utilizing varied routes of travel between the nodes in the network further decreases predictability and complicates enemy targeting. Instead of the route of travel from node to node being defined by the hub and spoke relationship, redundant nodes mean the route of travel for distribution can flex based on environmental factors, to include intelligence. Varying the mode of transportation between nodes adds another layer of redundancy. Air, ground, and sea-based transportation, both manned and unmanned should be employed to disrupt patterns the enemy could otherwise target. Further, as Burdick suggests in Instant Basing, leveraging the “stealthy ubiquity” of commercial shipping is another means of distribution that reduces visibility, especially during the contact layer, when access for commercial shipping is open, and is less likely to escalate tension.<sup>13</sup>

### *Forward Production*

To mass military resources in theatre in the least amount of time, Swarming Logistics should leverage forward production. As seen in the Strategy Lab war game, production in theatre provides required assets at the needed location with less lead-time when compared with a centralized manufacturing and distribution model. A notional equation to illustrate this point can be seen in the following example. A large factory in CONUS may be able to produce 100 parts of a given type in a day. However, it takes one day to ship the parts from CONUS to theatre, and another day to distribute to three forward locations in the AOR, so in effect, it takes 3 days to produce 100 parts using the centralized model. A smaller factory in theatre may be able to produce 33 of the same parts in a day. To create redundancy and positioning to minimize distribution requirements, the commander builds three factories to produce parts, producing a total of 100 parts a day. During the time it takes central production to deliver the first 100 parts, forward production

will have already provided 300 parts. Although a simplification, the example illustrates the advantage forward production provides in the spatial/temporal domains.

Another benefit of forward production is the reduced reliance on intertheater distribution. Because the distribution network is not burdened with shipping 100 completed parts from CONUS to the theatre, less mobility assets are required. This directly reduces costs and risks associated with air mobility, while creating opportunities for strategic airlift to be utilized for other priorities.

Forward production also creates the opportunity to respond more quickly to changing battlefield requirements. Because there is less lag between production in delivery, product updates are fielded more quickly. This is important when facing an intelligent adversary that is able to detect and exploit vulnerabilities. Forward production closes vulnerabilities faster by leveraging faster cycle times.

### *Leveraging Additive Manufacturing*

The growing technology of additive manufacturing (3D printing), optimized for mobile applications represents a potential game changer for flexible logistics and a valuable opportunity the United States Military—regardless of branch of service—should incorporate as an expeditionary logistics concept.

Currently, the DOD is pursuing 3D printing for a variety of purposes. At the depot levels, units are reverse engineering parts that are no longer stocked as solutions to older airframes<sup>14</sup>, and creating F-22 structural components that were never provisioned in the first place<sup>15</sup>. However, even greater opportunity exists to produce Class IX spare and repair parts in the forward location, based on the advantages of forward production discussed above. Some examples of the types of components that could be produced in the field environment using technology available today go

beyond aircraft and weapon system spare parts and structural components. Thanks to powdered metal, even metallic parts can be printed.<sup>16</sup> Munitions are capable of being 3D printed, albeit in a more controlled environment given the explosive risk,<sup>17</sup> and even buildings<sup>18</sup> and bridges<sup>19</sup> have been 3D printed in the field this year. Clearly, this method of manufacturing holds potential for further military concept development

Yet there are still additional development areas that would benefit swarming logistics applications in the near future. With the development of solid state electrolyte batteries,<sup>20</sup> potential exists to develop a 3D printed version for rapid reproduction in the field.<sup>21</sup> Also significant is the development of 3D printed electrical components, with integrated circuit boards. This allows for a 3D printer to print a drone out of a single piece, with electrical tracts and contacts embedded for simplicity and reliability.<sup>22</sup> Electric motors have recently been 3D printed, opening up the possibility of field level printing, with the added benefit of increased thermal conductivity, allowing for greater motor output efficiency.<sup>23</sup> Leveraging surface printing of antennas and sensors onto structural components<sup>24</sup> could also simplify and make more reliable the currently complicated drones. These technologies currently exist in specific manufacturing markets, and must be incorporated into drone designs and field-level print capabilities to realize the benefits of their developments. However, the opportunities they would provide are astounding.

A more strategic opportunity additive manufacturing provides is the ability to design for additive manufacturing. Current weapon system designs have largely been optimized for traditional manufacturing processes. With 3D printing, however, the ability to create lighter, stronger, simpler designs opens the apperture for greater performance and reliability.<sup>25</sup> Less moving parts is more reliable because there are less interfaces that cause wear, misalign, or malfunction. This has great impact on swarming logistics considerations because if the drones in

the swarm are more mechanically simple and reliable, the mean time between failure increases, resulting in significantly reduced maintenance requirements and improved operational reliability.

At the field level, a range of mobile 3D printing applications exist, ranging from man portable to large area machines such as the building printer. In a baseline application, the basic components could consist of: a 3D printer, power supply (Solar is primary, can be connected to grid or gensets as alternates), computer to make inputs, 3D scanner to copy existing items, a recycling unit, and printing materials. Because the technology is rapidly evolving, specifying a specific printer for the future is self-limiting. However, attributes that are desirable for the field environment are compact footprint compared to print area and fast rate of deposition, or print speed. The ability to print using a variety of materials is equally important. Currently, the USMC has developed and fielded a mobile 3D print capability, which indicates the broad appeal. This initiative should be expanded across all services and concepts pursued strategically to capitalize on the opportunity.

Another opportunity that would provide significant benefits to field users is the ability to produce 3D printing filament using recycled materials. The idea is that waste plastic such as ABS or PLA is shredded, melted down, then extruded into a filament spool. Several companies currently execute this process and sell recycled filament spools on the commercial market.<sup>26</sup> At least two COTS filament extrusion machines already exist, such as Filabot, and one fully integrated grinder and extruder unit called Protocycler was developed using an Indigogo crowdsourcing campaign and is currently shipping with high demand.<sup>27</sup> These types of capabilities represent enormous opportunities for forward swarming logistics concerns because of the ability to forage for logistics requirements instead of relying on supply chains. In almost every AOR, waste plastic such as empty water bottles or packaging exists in excess and using it to print drones and weapons

instead of throwing it away and hauling plastic spools halfway across the world to make things is a win-win.

The benefits mobile 3D printing provide to swarming logistics are significant. First, by producing parts and end items on location, the reliance upon supply chain for continuing operations is significantly reduced. A unit can now maneuver further ahead of a main supply node without needing to account for how to get parts and end items from the production factories to their forward operating locations. This is especially beneficial in the contact layer where large distribution efforts could signal escalation. By covertly building supply stocks on location, the unit is self sufficient and not dependent on a supply network, the likes of which could be contested by an adversary with A2AD capability in the event of escalation. This ability to operate free of the supply umbilical is what enables sustained EABO, because a unit is not concerned with reaching back for re-supply, or limited to locations to where logistics can deliver.

Second, by possessing on-demand build capability, a unit no longer requires as many spare parts and end items on hand, because it can make what it needs closer to when it is required. This reduces the logistics footprint of the unit itself, making it easier to maneuver.

Third, with a reliable fielded 3D printing capability, engineers can optimize the design of the next generation of drones and weapons for being produced in the manner described above. This will allow for better performance due to system integration and weight reduction, better reliability due to parts simplicity, and better sustainability because the parts can all be produced at the point of employment. As an added benefit, the systems can be upgraded and adapted in near-real time based on field conditions because the production to employment cycle is near instantaneous with increased user involvement and innovation inputs.

### *Pre-Positioning Assets*

One of the most critical logistics tasks in the contact layer is prepositioning of assets for use later in the campaign. Realistically, this could cover practically all classes of supply, but in the context of swarming and EABO considering the volume of air assets, emphasis should be placed on Class IX spares needed to keep the swarm operational. Currently, not all drone parts are designed for 3D printing, such as batteries, circuit boards and electric motors. Therefore, stocks of these known high-rate of use replacement parts should be forward positioned through out the theater to support the wide range of scheme of maneuver. Munitions are also prime candidates for pre-positioning, not just afloat, but at pre-planned sites as well. As discussed earlier, a historical example of this is seen in Sherman's Carolina campaign, where logistics re-supply points were pre-planned at various points along the anticipated route of maneuver. In this case, maneuver units falling onto pre-planned caches could re-stock on essential items required to support drone ops, launch the swarm, and continue on the scheme of maneuver as required.

Beyond prepositioning specific logistic items required for continued operations, logisticians could pre-position means of forward production at certain sites as well. This could consist of the mobile 3D print lab described earlier, printing supplies and materials, along with the other minimum essential operating support, such as hybrid power generation from Mobile Electric Hybrid Power Source (MEHPS) gen sets. These systems, capable of producing up to 300 kW, feature solar PV panels, battery storage, diesel generators, and a control panel in a deployable package.<sup>28</sup> MEHPS represent a significant opportunity to reduce total theater Operational Energy sustainment requirements, but more critically, reduce the resupply requirements to forward sites, where risk of enemy interdiction is greatest and resupply convoys create visual OPSEC indicators for the enemy to exploit. The idea is that to greatest extent possible, the sites should be self-

sustaining or sufficiently pre-positioned during contact layer to minimize sustainment requirement during blunt and surge layers of conflict. As more items are designed to be 3D printed, the utility of these forward production sites become increasingly useful in reducing sustainment requirements.

### **SWARMING LOGISTICS GREAT LEAP FORWARD: THE AUTONOMOUS HIVE**

Each of the previously discussed concepts enable swarming scheme of maneuver to some degree in their own right. However, applying the ideas into a single cohesive concept provides the most disruptive technological leap forward in sustainment. A forward positioned 3D printing lab is one thing, but a network of autonomous self-sustaining production sites distributed throughout the area of maneuver fundamentally changes the sustainment strategy. Enter the concept of autonomous “hives” to generate the swarm.

At the center of the concept is the hive itself. Notionally designed to fit inside of a standard shipping container, the hive employs 3D printing and robotics to produce and assemble components and end items using a “lights-out” automated manufacturing process, requiring no human interaction. Autonomous drones bring raw material inputs to the hive. In this case, raw materials may be recyclable plastics, which will be converted inside the hive into PLA 3D printing filament. The drones could use AI to seek out recyclables on their own to bring back to the hive or could be programmed to collect the materials from a known recycling center nearby. Once the drones arrive at the hive, they deposit the raw materials into the collector and recharge their 3D printed solid-state batteries at the mass inductive recharging station, located under the solar panels on the roof of the hive.

Powering the hive is the aforementioned solar panel array. Coupled with battery storage, the intent is for the system to be fully self-sufficient for energy, although the system could be optionally powered by existing grid or MEHPS to create redundancies. The solar arrays should be positioned over the hive to minimize horizontal footprint, maximize solar exposure, and provide shade for the operations underneath. Battery storage can be either external or internal to the hive, with modular growth capabilities depending on local solar profile.

Inside, the first step of converting the raw materials into 3D printing filament takes place. As noted in the section above, this recycling technology already exists today. The hive could employ a variety of types of 3D print materials, from plastics such as PLA, to metallics such as titanium and lithium, giving it the capability to manufacture a wide range of components and end items. By leveraging design for 3D printing, items such as batteries, electric motors, circuit boards may be integrated and optimized for hive production, while improving end-item system performance. Another potentiality is to 3D print munitions at these sites, although this adds explosive safety concerns, which may limit hive placement in urban settings. A more ideal weapon to integrate into the types of systems the hive produces is directed energy or rail-gun weapons, because of smaller form factor and decreased explosive risk.

The design files for these items can be a combination of pre-loaded, transferred via secure data link, and even developed and refined by automated machine learning. In the future, AI could analyze intelligence, recognize battlefield trends to include enemy reaction in order to develop and refine friendly system designs. Armed with this timely insight, the hives could update weapon systems designs on the fly and rapid prototype to find the optimal design. This provides the opportunity to out cycle enemy OODA loop in terms of system design, enabled by both AI and automated forward production. In a more mundane setting, the hive can be

deliberately scheduled to produce spare parts or high demand items such as batteries for operating locations elsewhere, reproduce the raw materials collection drones, build repair parts for the hive itself, and even expand the solar panel capacity by constructing additional solar panels for drones to install. The bottom line is that the hive can manufacture a variety of items based on changing requirements.

The ideal final product is a mission-ready end item such as a drone. Once fully assembled, the drone is mated with a fully charged battery and powered on. At this time, any final software programming may occur, to include tasking for the unit's first mission. If applicable, the unit's weapons are loaded and/or readied depending on the type of ordinance employed. Once complete, the drone flies away and joins the swarm.

Despite future advances in designing for 3d printing, some assembly may be required. This is where miniaturized robotics could come into play. Taking the 3D printed components, completing any required finishing, and assembling the end item are common robotics tasks that can be automated for these purposes, removing human interaction requirements from the manufacturing process. Currently, there are a few fully automated factories, such as the FANUC robotics factory in Japan, but machine autonomy in factories is growing.<sup>29</sup> On a small scale such as assisting 3D printers in the hive, robotics appear well suited. By removing human interaction from the production process, constraints on location placement due to environmental concerns, enemy targeting are mitigated, and increased manning requirements are avoided. Further, humans require significant logistics support for daily life. By removing humans from the support requirements, the logistics support for the hive is minimized.

The singular hive described above, while almost entirely self sufficient, does not exist alone. Throughout the theatre, ideally located near the intended maneuver space, numerous

hives can be prepositioned during the contact layer. The more hives concentrated in a given area, the larger the swarm or multiple swarms that may converge against the enemy. This creates redundancies and survivability in the event of enemy attack. The hives can also be mutually supporting, potentially with some sites possessing manufacturing capability for larger items, while others are more specialized. In this case, sub assemblies could be completed in one hive and transported to another hive or even human user for final assembly.

The hives themselves can be either overt or covert as required. For example, the functions of the hive could be discreetly installed in urban spaces such as a vacant building, underground utility tunnels and subways, or in rural settings such as abandoned mines and sheds. They can even be hidden in plain sight by collocating hives with solar farms, which the hive utilizes for power anyway, and where drones are increasingly utilized for performing site maintenance. Further, hives could be mobile, placed on ships, both commercial container, and Naval vessels, or ground mobile on a semi-truck. Finally, because the hives are not reliant on a logistics tail, they provide less visible OPSEC indicators.

## **CONCLUSION**

Given the dynamic nature of swarming tactics employed during EABO, it is clear that a logistics support concept must also be designed to fully support operations. Swarming schemes of maneuver require the fluidity to mass and disperse forces, originating attacks from a variety of locations at once, converging on a target at a location or locations, then maneuver further to avoid retaliatory attacks. Paramount to this concept is agility and the ability to move faster than

the adversary to create physical as well as psychological effects in order to achieve tactical superiority against a potentially numerically greater adversary.

Current logistics support concepts are not ideally suited to support to such an agile scheme of maneuver in a contested environment. Currently, most modern logistics plans feature extended, vulnerable lines of logistic support that follow or detach from the scheme of maneuver, are hub and spoke oriented creating nodes of critical vulnerabilities, and have long lead times associated with centralized production and distribution for most classes of supply. While adequate in previous campaigns, these limitations will constrain the ideal scheme of maneuver when swarming tactics are employed.

An ideal logistics support concept for swarming should reflect the fluid nature of the scheme of maneuver itself. Those qualities include non-linear distribution to prevent critical nodes of vulnerability, forward production to create mass near the point of employment, advanced manufacturing such as 3D printing to enable field manufacturing and rapid prototype development, and prepositioning of assets during contact layer to create flexibility in supporting the scheme of maneuver while reducing transportation requirements during later stages of conflict. Support featuring these characteristics enables the force to maneuver as required because the constraints and vulnerabilities of traditional logistics are mitigated.

A fully realized swarming logistics concept that encompasses each of these tenets is found in a fully autonomous, self-sufficient forward production “hive”. The hive concept has the potential to fundamentally change the character of future conflict by creating overwhelming volumes of autonomous drone swarms from numerous self-sustaining hives all without requiring human interaction. Because trailing lines of logistics are not obvious and the source of production is decentralized, the adversary must seek out each individual hive to interdict

logistics. As a result of prepositioning and forward manufacturing, the hives are capable of producing a significant portion of combat power, on demand and at the place of need. AI and automation create speed in weapon system revisions that out cycle enemy OODA processes. Accordingly, swarming logistics, fully realized in the hive concept enables dynamic support for the swarming scheme of maneuver in a way that no other logistics concept has before.

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<sup>3</sup> Roland Ruppenthal, “Logistics and the Broad-Front Strategy.” In *Command Decisions*, ed. Kent Roberts Greenfield and Center of Military History, 419-427. (Washington, D.C.: Center of Military History, United States Army, 1987), 425

<sup>4</sup> Martin Van Creveld, *Supplying War: Logistics from Wallenstein to Patton*. 2nd ed. (Cambridge: Cambridge University Press, 2004), 225

<sup>5</sup> Van Creveld, *Supplying War*, 223

<sup>6</sup> Johnny Wade Solokosky, “The Role of Union Logistics in the Carolina Campaign of 1865” (master’s thesis, Army War College, 2002), 8-11, <https://apps.dtic.mil/dtic/tr/fulltext/u2/a406865.pdf>.

<sup>7</sup> Sokolosky, “Union Logistics in the Carolina Campaign,” 111-114

<sup>8</sup> Sokolosky, “Union Logistics in the Carolina Campaign,” 73

<sup>9</sup> Sokolosky, “Union Logistics in the Carolina Campaign,” 100

<sup>10</sup> Sokolosky, “Union Logistics in the Carolina Campaign,” 79

<sup>11</sup> Sokolosky, “Union Logistics in the Carolina Campaign,” 66

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