Massachusetts Institute of Technology
Lincoln Laboratory

ADDER Final Report

Defense Logistics Agency (DLA)
Distribution Modernization Program (DMP)
R&D Strategic Distribution and Disposition (SDD)
Agile, Dynamic Distribution for Effective Readiness (ADDER)

Paula L. Ward
Group 76

Michael P. Shatz
Group 75

Wednesday, 17 July 2023
(Updated)

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

This material is based upon work supported by the Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Under Secretary of Defense for Research and Engineering.

Rams ID# is 1025679

Lexington Massachusetts

1. EXECUTIVE SUMMARY

This Final Report describes the efforts and approach by the Massachusetts Institute of Technology Lincoln Laboratory (MIT LL) starting in Fiscal Year 2019, and ending in Fiscal Year 2023 for Defense Logistics Agency (DLA) Distribution Modernization Program (DMP) to help improve DLA Distribution operational efficiency, inventory management, materiel distribution, asset visibility, and reduce operational cost.

MIT LL utilized a system-of-systems methodology that studied autonomous systems, artificial intelligence, and other technologies for Research and Development (R&D) with DLA to evaluate the current operations and processes and help identify capability gaps, investigate existing and emerging technologies, develop a technology roadmap, and perform research and development on applicable new technologies to address the following:

- **Inventory management** - Improve the effectiveness and efficiency of current inventory management practices and procedures with technology such as big data analytics and forecasting aimed at keeping inventories at appropriate levels.
- **Materiel distribution -** Reduce distribution timelines and overall cost, helping DLA meet delivery standards for supplies and equipment with autonomous systems technologies such as robotics, augmented reality, manipulation, and human-machine interaction applied to materiel handling.
- **Asset visibility -** Improve visibility into, and awareness of identification information and delivery data for cargo and surface shipments with appropriate technology that can also support inventory management.

The ultimate goals for these improvements and roadmap were to make warehouse operations, which includes both physical materiel and data/information, more reliable, repeatable, and cost-effective while striving to improve the safety and security of both physical and cyber environments.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

2. OVERVIEW

The ADDER program began with assessment and study of several major distribution centers across the continental U.S (CONUS). A technology roadmap was evaluated and many capability gaps were identified. Each distribution center is operated with oversight from DLA headquarters and local daily management. Each center has very different operational needs and challenges, and have varying levels of modernization.

Table 1. Table of Site Visits.

Site	Main Technology Evaluated	Additional Technologies Evaluated	Comments
DDCT - Corpus Christi, Texas	Automated Ground Vehicles (AGV)	none	AGVs applied to "tuggers" for indoor and outdoor operation.
DDHU - Hill AFB, Utah	AGV	AutoStore, Exoskeletons	Exoskeletons for sanding & painting Conex boxes with Sarcose Robotics arm technology.
DDOO - Oklahoma City, Oklahoma	AutoStore	LocatorX	Evaluated Boston Engineering's efforts on Augmented Reality (AR) & IoT
DDRT - Red River, Texas	GPS communications, AGV	Drone inventory for outdoor tractor feet	Other pain points identified: trucks getting lost on the base, fire extinguisher refurbishment
DDJC - San Joaquin, California	Automated Arm	AutoStore	Unified Group Rations (UGR) Discrete Event Simulation (DES)

The first distribution center visited and evaluated was DLA Distribution Center - Corpus Christi, Texas (DDCT). They were looking to incorporate a bus route of automated tuggers between various warehouses at the site and within the main warehouse. An Automated Ground Vehicle (AGV) testbed was developed to collect a wide variety of sensor data that informed the requirements definition and could be utilized to evaluate autonomous navigation algorithms for indoor to outdoor autonomous operations. The AGV was later utilized at DLA Distribution Hill, Utah (DDHU) for their underground tugger operations. AGV testbed data was processed for signal connectivity, navigation suitability, and provided to the government. Simultaneous Localization and Mapping (SLAM) techniques were applied for sensor and algorithm feasibility and a report was generated. The Laboratory also participated in source selection for an AGV Small Business Innovation Research (SBIR).

Additional technologies were evaluated or recommended for asset visibility and inventory management such as Automated Storage (AutoStore) for DDHU and augmented reality for Oklahoma City, Oklahoma (DDOO).

The ADDER program later continued assessment and study of additional major distribution centers across the CONUS. These included Red River, Texas (DDRT) and San Joaquin, CA (DDJC) distribution centers. Technology readiness assessments were developed for various new technologies with a focus on the applicability to DLA operations. Beyond AGVs, these included robotic arms with embedded artificial intelligence for DDJC, inventory drones, and wireless location technologies to make the inventory process more accurate and efficient. Additional technologies were evaluated or recommended for asset visibility and inventory management such as automated storage and augmented reality at several other centers.

For DDJC, a Discrete Event Simulator (DES) software tool for warehouse operations simulation was acquired and a detailed model of the Unified Group Rations (UGR) warehouse was created. Multiple site visits identified various bottlenecks in throughput and the DES model identified additional high-impact improvements in overall throughput. This was the busiest warehouse we evaluated during the course of this program. The DES model of warehouse operations for the UGR distribution center was further refined and produced recommendations for improvements to enable the center to meet surge capacity needs. This approach proved to be effective for the UGR warehouse. A suitable level of simulation could inform the insertion impact of various future technologies that are being considered for modernization.

The overall MIT LL Technical Approach is outlined as follows:

A. **Understand Goals and Constraints:** Understand current and planned CONOPS and systems at each distribution center and, to the extent necessary, each warehouse.
    1. What are types of items stored and shipped, volumes stored and frequency shipped or received, types of picking systems and transportation?
    2. What are their sizes and weights? Is there anything else special about the goods such as shelf life, cleanliness, et cetera?
    3. How valuable is compact storage? If more compact storage were achieved what would be done with the space?
    4. What are the desired improvements in the flow of goods, tracking of goods, and data analytics?
    5. How much labor is in the stowing and retrieving of goods, as opposed to labeling, picking and packing?
    6. What are the metrics for improvement?
    7. What are the rollout plans and/or refresh schedules for the pick technology, database technology, changes to the materiel stored and shipped and its location in the warehouses?
    8. Are there any special requirements or improvements desired with the interface Equipment Control System (ECS) to the warehouse management system, Distribution Support Services (DSS) or (SAP)?
    9. What security and safety policies constrain the use of various technologies for moving materiel and data?

B. **Develop requirements:** Based on the needs for improvement in moving and tracking of goods and the data analytics, determine requirements for the systems to support picking, packing, transporting and tracking good and for storing and analyzing data. Analyze those requirements and possible solutions to determine requirements for connectivity. Flow those requirements to requirements for the selected pilot technology in question, the defined metrics for improvement, the required data volumes and tolerable latencies, and the security policy.

C. Provide Recommendations: Recommend actions to be taken by DLA to meet identified requirements.

A System of Systems (SoS) approach for enterprise-wide DLA modernization was developed that includes utilizing tools, such as Model-Based System Engineering (MBSE) and DES with an added focus on process and data flow in addition to technology. A suggested overall DLA modernization roadmap was developed to define this approach, and the results were presented on several occasions to the government. A Smart Warehouse Study was proposed.

The remainder of this report outlines the findings, gap analysis, and suggested courses of action, as a result of each site visit and is organized primarily by the technology being evaluated.

3. AUTOMATED GROUND VEHICLES FOR DDCT AND DDHU

3.1 DDCT SITE VISIT AND AGV REQUIREMENTS DEVELOPMENT

Purpose:

- Assess customer/user needs and objectives; define mission, measures of effectiveness, the environment, and the top-level system
- Develop and baseline top-level requirements and constraints including internal and external interfaces, integrated logistics and maintenance support, and system software functionality
- Identify (additional) key stakeholders
- Identify initial technical and project risks

Condensed from trip report:

- Briefs included Safety and Security by DDCT, Project Overview by M. Casas, Project status, objectives, summary of requirements analysis strategy by G. Gaskin, MIT LL Overview by P. Ward, DDCT vision/technology gap by Deputy Commander J. Beckwith. Tours were led by R. Champion.
- Condensed findings:
  - Site places great value on the capability of integrating a tugger/forklift capability in one vehicle (both autonomous and manual). Their manual tuggers are from Omega Industries (Canadian mining company, out of business)
  - Types of materiel that is lifted by their forklifts currently: standard pallets, B pallets, engines on skids, transmissions on skids, et cetera. They are mostly propane, few diesels, and few electric. In total, the site has approximately 60 tuggers and forklifts.
  - The site has approximately 100 materiel carts towed by tuggers. Carts cannot move in reverse.
  - Current materiel movement is conducted by warehouse supervisors contacting dispatch (phone or email) to request a pickup of carts, and/or delivery of empty carts.
  - There are approximately nine operators that drive forklifts and/or tuggers.
- Requirements analysis was conducted, informed by tours, R. Champion, G. Stacy, K. Persels, J. Beckwith, other team members and the existing requirements draft. Requirements included:
  - Identify, investigate industry/government safety requirements/standards for AGVs (i.e., Occupational Safety and Health Administration (OSHA) and Nevada laws) in order to validate current safety requirements (i.e., max speed, braking speed/distance, et cetera)
  - Identify, investigate industry/government cybersecurity requirements/standards (digest and review J6 SOW for feasibility and understanding, including feasibility of vendor software patching
  - Calculate/approximate smallest required turn radius
  - Develop, review, and approve an AGV tugger operational model

- Conduct test campaign to measure and analyze communication and navigation capabilities and limitations (See Section 2.2)
- Seek appropriate permission to operate on the Navy base (cameras, operate inertial navigation system et cetera, and identify proper base authorities regarding proposed alterations to Navy roads, signage, et cetera)
- Conduct market research to inform and refine requirements
- Identify proposed infrastructure changes, based on industry and navigation requirements
- Create technology insertion roadmap for assembling, integrating, and testing the final system that meets all requirements and the desired operational model.

3.2 AGV TESTBED AND DATA COLLECTIONS AT DDCT AND DDHU

An Automated Ground Vehicle (AGV) testbed was developed to collect a wide variety of sensor data that informed the requirements definition, and can be utilized to evaluate autonomous navigation algorithms for indoor-outdoor autonomous operations at the DLA DDCT.

AGV testbed data was processed for signal connectivity and navigation suitability. SLAM techniques were applied for sensor and algorithm feasibility and a report was generated. The Laboratory participated in source selection for an AGV SBIR.

Figure 1. Automated Ground Vehicle testbed.

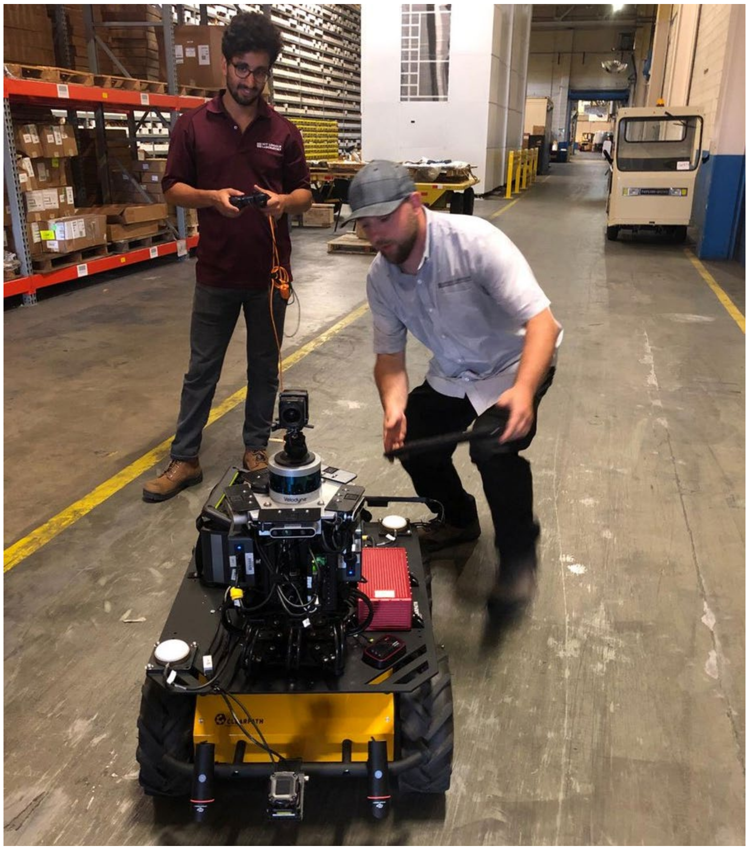


Figure 2. AGV testbed in operation.

3.3 AGV TESTBED DATA ANALYSIS AND CHALLENGES IDENTIFIED

Potential concerns were identified during the requirements definition phase for the procurement of an autonomous tugger or “mule” at various DLA sites. Poor network connectivity at the sites was of concern so the Wi-Fi/LTE landscape for the current delivery routes was mapped to reduce risk. Localization challenges were also identified where the tugger may be responsible for pallet pickup/drop-off inside of a warehouse as well as navigating sidewalks/roads between storage locations. One mitigation is to identify areas where GPS navigation is not feasible (e.g., inside buildings) and develop indoor localization using common robotics techniques.

As can be seen in the figures below, network connectivity was good in some areas and poor to non-existent in others. This was true for indoor and outdoor areas. See filename Corpus Christi-AGV Data Analysis Update 2019-12-17 for additional analysis details.

Areas without any data indicate NO DLA hotspots detected

Figure 3. WiFi Max Signal Strength Map - Indoor.

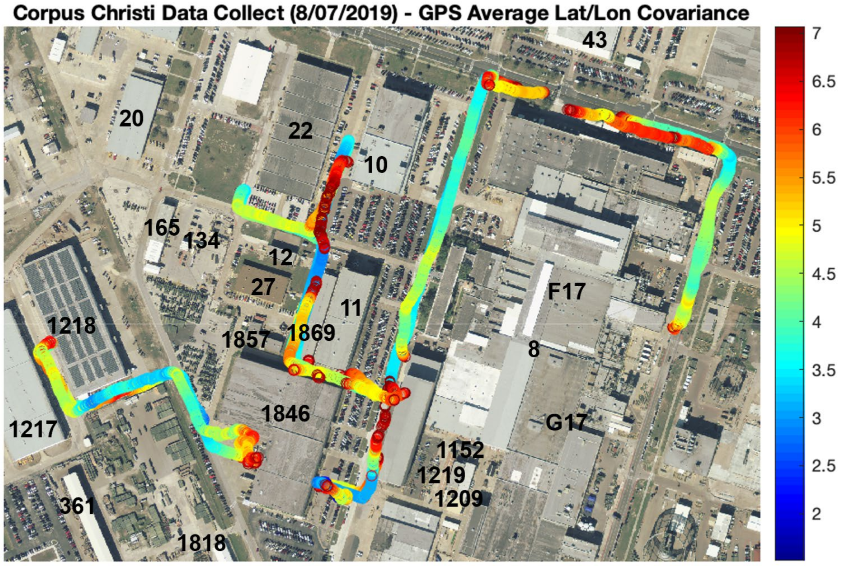
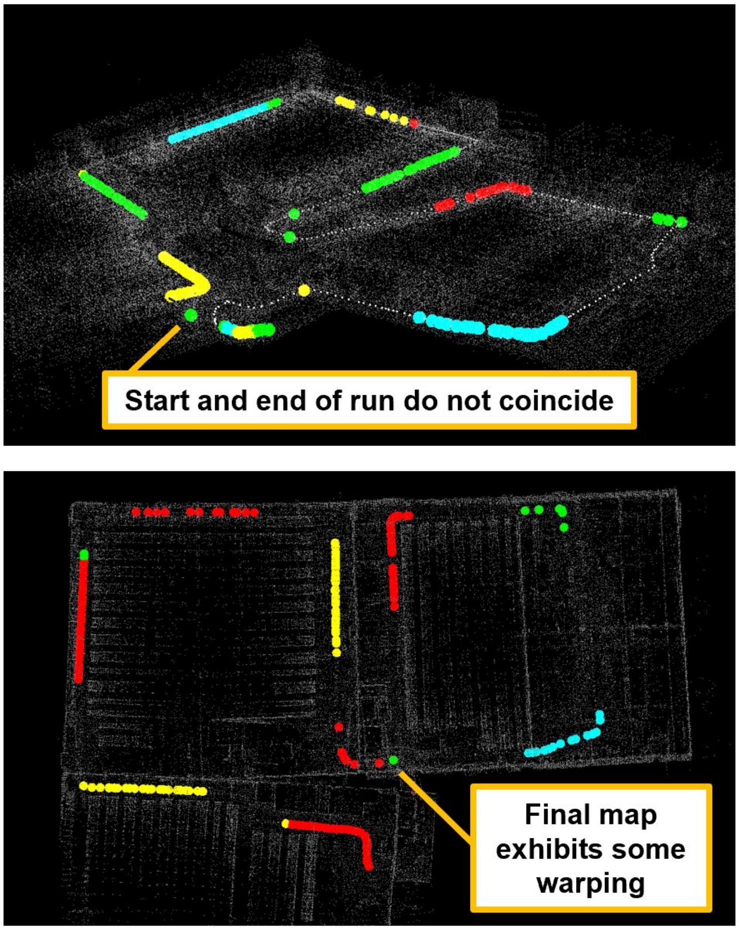


Figure 4. Standard GPS Position Accuracy.


Start and end of run do not coincide

Final map exhibits some warping

Figure 5. Indoor Localization Performance.

3.4 AGV CONCLUSIONS

Large areas of the intended route (indoor and outdoor) do not have sufficient Wi-Fi coverage for reliable communication. Large gaps in connectivity were observed, and it was recommended to have a higher fidelity RF analysis to determine root cause of network issues (e.g. multi-path destructive interference, and access points broadcasting on overlapping channels). LTE signal strength status showed it performed fairly outdoors, although weak in spots, and extremely poorly indoors.

It was recommended to minimize AGV reliance on communication network. As expected, we cannot rely on GPS for localization near to, or inside buildings for any extended period of time. Mixed indoor/outdoor navigation will require fiducials or an AGV equipped with sophisticated perception algorithms and hardware.

4. AUTOSTORE FOR DDOO AND DDHU

Although the AutoStore technology was evaluated for DDOO and DDHU, it became apparent during the modeling of DDJC UGR (See Section 6), that the highest impact to improve throughput for an initial installation for this technology is likely DDJC.

General AutoStore notes:

- AutoStore is the very definition of space efficiency as it delivers the highest storage density of any Automated Storage and Retrieval System (ASRS). AutoStore typically provides twice the storage capacity and in many cases four times. With any shape possible, utilization of the building is at its peak.
    - **The average uptime out of the 300+ systems is 99.6%**
    - AutoStore is distributed, designed, installed, and services by a network of qualified system integrators: Bastian Solutions, Dematic, Swisslog, Pulse Integration, Okamura, and AM Automation.
- **Grid:** Aluminum framework that holds the bins in place while also being the railways for the robots. A flat floor is needed in order to install a grid. Resurfacing a floor can range from 30k – 45k. The size and shape of the grid is restricted only by the warehouse around it, ensuring optimal space usage. AutoStore can potentially reduce the storage footprint in a warehouse by 75%, compared to conventional storage space. The grid includes tracks running in X and Y direction, allowing the robots to access any cell inside the grid.
- **Bins:** Stacked on top of each other, strong construction and durable material. Every bin is identified by a unique number that is stored in the controller database and repeated on a label on the bin. Bins are available in different heights and in different materials, the bins can even be divided into different compartments. Bins cannot be mixed within the system and the max weight is 66 lbs.
- **Controller:** Compatible and can be integrated with SAP/Warehouse Management System (WMS). It provides the network connection to the customer infrastructure, a network switch and the controller PC that provides the physical network interface for the customer network. Wi-Fi network is not required, since data is sent to the robots through a radio frequency (2.4 GHz). Robots continuously self-diagnose and report back to an intelligence notification system, that notifies you as a unit needs care. With the XHandler program, robots will autonomously correct themselves.
- **Robots (R5 and B1):** The controller is continuously calculating the smartest way to work and will sometimes initiate teamwork where the robots dig together. A robots' task is immediately replaced by another robot if they get called to the service. Robots will work 24/7 with control systems always making sure the battery is healthy, an R5 robot can run non-stop for 14 hours before needing a charge. The R5 runs on two lead acid batteries (12 V/105 AH). The B1 includes a Lithium-ion battery, and is able to pick up a fully charged battery whenever needed from the BattPack ejection tray.
- **Ports:**
    - ConveyorPort uses a conveyor belt to move the bins to the operator. While one bin is being

  - presented to the operator, the second bin is held in place above the port by a robot. The smart covering, and sensors, keep the operation safe.
  - CarouselPort operates with three rotating arms, each holding one bin. Two arms are positioned in the back of the port, where robots can place or retrieve two bins simultaneously, the third arm is then in the front where the operator can access the bin.
- Sites should be able to provide the following information:
  - One to two years' worth of order data (products/per shipments)
  - The number of SKUs, number of lines
  - Warehouse size? Current throughput (output/input per hour)?
  - How many movements are done/needed to be done, to complete an order?
  - Product dimensions
  - Products at each site
  - How are orders completed? Phone call? Email?
  - Is deep storage something at each site?

AutoStore System Inc, is able to put together a concept design based on assumptions. An in-person tour of a local AutoStore was informative. This goods-to-person technology can improve both operational and storage efficiency, and many DLA distribution centers. DDOO was selected to pilot this effort.

5. EXOSKELETONS FOR DDHU

As a result of many teleconferences, and after a longer list was considered for exoskeleton application and shortened, two tasks remained: Task 1. Refurbishment of Medical Conex Trailers/Boxes, and Task 4. Medical Kit Assembly & Loading into Tri-Wall Containers. Exoskeletons were considered for both tasks and MIT LL worked with both DLA and Natick Soldier Center on these evaluations.

Task 1 description: Workers at DDHU refurbish the Conex trailers used for field medical facilities. This includes sanding the walls, floor and ceilings and other tool usage. In particular, working with tools overhead can lead to fatigue, strain and injury. A solution that can ease extended-time tool use on the walls, and especially the ceiling, was desired. Exoskeletons were evaluated for this purpose. A list of interview questions was generated. An ergonomics report for the refurbishment was generated by another DLA department.

Task 4 description: Workers at DDHU prepare medical kits for shipment to the field. This involves breaking down incoming supplies, gathering the correct ingredients, wrapping them, and packing them into tri-wall containers. Personnel movement is comprised of lifting, twisting, and bending over while carrying objects weighing up to 40 lbs. for 1 person (up to 100 lbs. for 2 people).

A list of interview questions was generated and a subset is included here:

General questions

- Are there official descriptions or SOPs for the refurbishment and assembly/kitting?
- What are the workload volumes / rates? (x # of trailers per week? Y # of medical kits?
- Does all the Conex trailer refurbishment require a similar amount/duration of work?
- Are there other challenges, shortfalls, issues associated with your operations that, although not explicitly tracked, are a cause for concern? (Think bigger picture, longer term, perhaps interactive/interfacing with other areas or entities, etc.)

Problem-related questions

- What are the injury rates for the Conex refurbishers? (per capita for specific tasks). Are they concentrated in particular types?
- What about physical complaints, that are beneath the threshold for reporting as injuries?
- Are there any standards for how many repetitive-strain-injuries are allowed?
- Are there costs associated with strain injuries, that can be measured to guide how much to spend to reduce them?
- For the refurbishment task, are injuries mapped to task detail e.g., sanding, sidewalls, etc.?
- For assembly/kitting task, are injuries mapped to task detail e.g., wrapping, packing, etc.?

Task-related questions

- Are there Key Performance Metrics (KPMs) associated with these tasks that are tracked?
- Can workers swap off between kitting and refurbishing, to minimize repetitive strain?
- Are workers assigned to / trained for one specific task?
- Do they do any other tasks not listed that are not causing injuries?
- What are the standards for how fast they have to get these jobs done?
- How much do the sanders weigh (with their pneumatic lines)?
- How much pressure has to be applied when sanding?
- If speed requirements are met in assembling the kits and refurbishing the trailers, is there margin that can be used to reduce strain injuries? For example, by adding more break time?

Conclusion: Commercially available exoskeletons that were available at the time of this effort did not have the appropriate capabilities for these tasks. Simpler and more effective solutions were suggested for reducing the loads for repetitive movements such as tripod-like devices on wheels. As of the writing of this final report, commercially available co-bot arms are now available that are capable of performing wall and ceiling sanding and painting, as well as assembly and kitting for repetitive movements.

6. VARIOUS TECHNOLOGIES FOR DDRT

DDRT had a particularly long list of challenges. An opportunity support matrix was generated and an investigation was assigned by DLA and supporting organizations, and segmented into mechanical and IT solutions. This list included battery lifting and handling, fire extinguisher packing, drone inventory of outdoor storage of approximately 400,000 tractor feet in bundles larger than a person, and commercial trucks getting lost on the Army base.

Battery lifting, transporting, packaging, and handling operations and performance requirements were gathered from interviewing workers. A customized ball transfer table capable of allowing workers to tape around the package (y-axis) without flipping/tipping the package (i.e., a hole in the table providing clearance for the tape, and hand or a railing/guide, that prevents the package from falling off the table but allows for package overhang. Therefore, providing clearance for the tape and hand, or the ability to disable the ball/roller movement, etc.,) was suggested.

Fire extinguisher packing can achieve substantial efficiency improvements with commercially available technology. When we visited DDRT, they had a person who was spending substantial time cutting foam blocks by hand (~45 minutes each), to protect fire extinguishers during long-term storage. We considered blown-in foam as a possible solution. However, a commercial vendor was located who can create custom cutouts that would cost approximately $1 each from a 3D scan. This would be far more cost effective than the blown-in foam, not require training to operate the blower, and certainly be less messy. The first, and perhaps with most potential impact with minimal effort, is a vendor that makes custom foam cutouts from a CAD file. The vendor is Merryweather Foam (www.merryweather.com), and the person we spoke with was Manny Myers. MIT LL offered to perform a scan with a hand-held scanner, so a quote could be obtained.

Drone inventory of the tractor feet was deemed impractical unless an estimation of the quantities was acceptable, which it was not.

Commercial trucks getting lost on base was a rather frequent occurrence. After interviewing several people at the facility, it was deemed that a combination of commercially available technology (handing inexpensive, commercially-available GPS tracking fobs to drivers), and process improvements (trading the fob for the driver's license when entering the base, and locking the license in a small tagged box used to store the fob when not in use), could be very effective in tracking, logging, and IDing commercial trailers, in addition to providing a means for ensuring the delivery/pickup paperwork was completed before leaving the base.

7. ROBOTIC ARM FOR DDJC UGR PACKING LINE

We were asked to examine the packing line for the Unified Group Rations (UGR) warehouse at the DLA facility in DDJC; in particular, whether that would be a suitable site for piloting a robotic arm. A full report of this effort, which was previously sent to DLA, is entitled "UGR Simulation Study Report 2021-01-29".

7.1 DDJC SITE VISITS AND UGR PACKING LINE REQUIREMENTS DEVELOPMENT

UGR is responsible for distributing meal rations to soldiers overseas, normally and domestically during periods of national emergencies. The facility is laid out as shown in Figure 6. An important metric UGR tracks and seeks to improve its monthly throughput of meals. At UGR, meals are called 'mods,' where each mod consists of three boxes, each with its own designated ingredients. Mods are then loaded onto pallets, each of which is packaged with eight mods, or 24 boxes. Currently, the goal is a throughput of 20,000 mods per month, which UGR aims to triple to 60,000 mods. During national emergencies such as a natural disaster, UGR surge capacity throughput needs to increase by a factor of 20 to 400,000 mods per month by extending hours of operation and adding more staff. Table 2 outlines UGR's current throughput metrics below. It is important to note that the columns *Current Requirement* and *Goal (X3)* were calculated to show what UGR must execute to meet its monthly goals in a single seven hour shift per day. The facility has had some difficulty meeting their current requirements as shown in Figure 7.

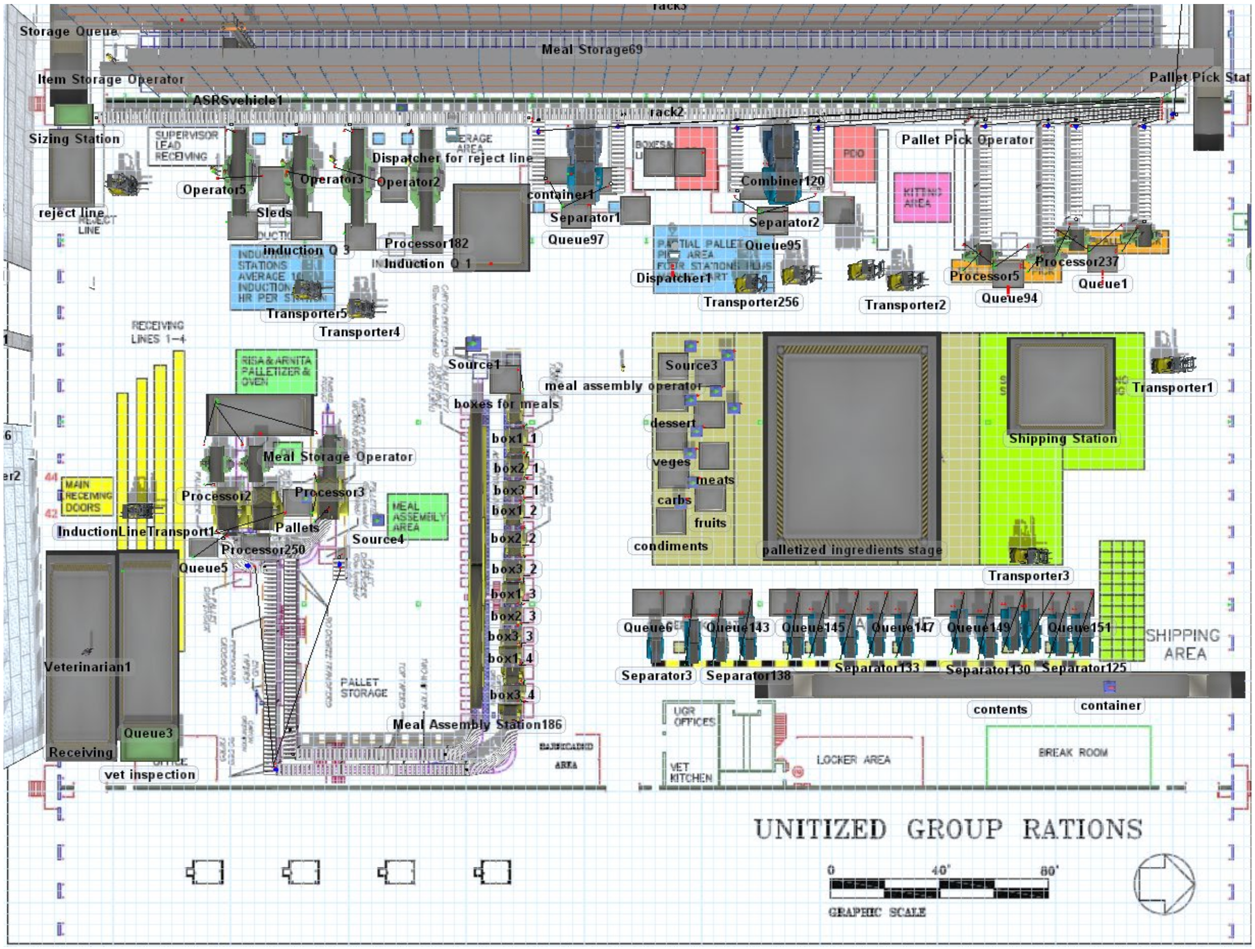


Figure 6. Layout of UGR processing line at San Joaquin.

Table 2. Current requirements and goals for the UGR line at DDJC.

	Current Requirement	**Goal (X3)**	**Surge Capacity* (X20)**
Mods per Month	**20,000**	**60,000**	**400,000**
Mods per Day (20 work days per month)	1,000	3,000	13,333*
Pallets per Day (8 mods per pallet)	125	375	1,667*
Pallets per Hour (7 hours per day)	18	54	70*

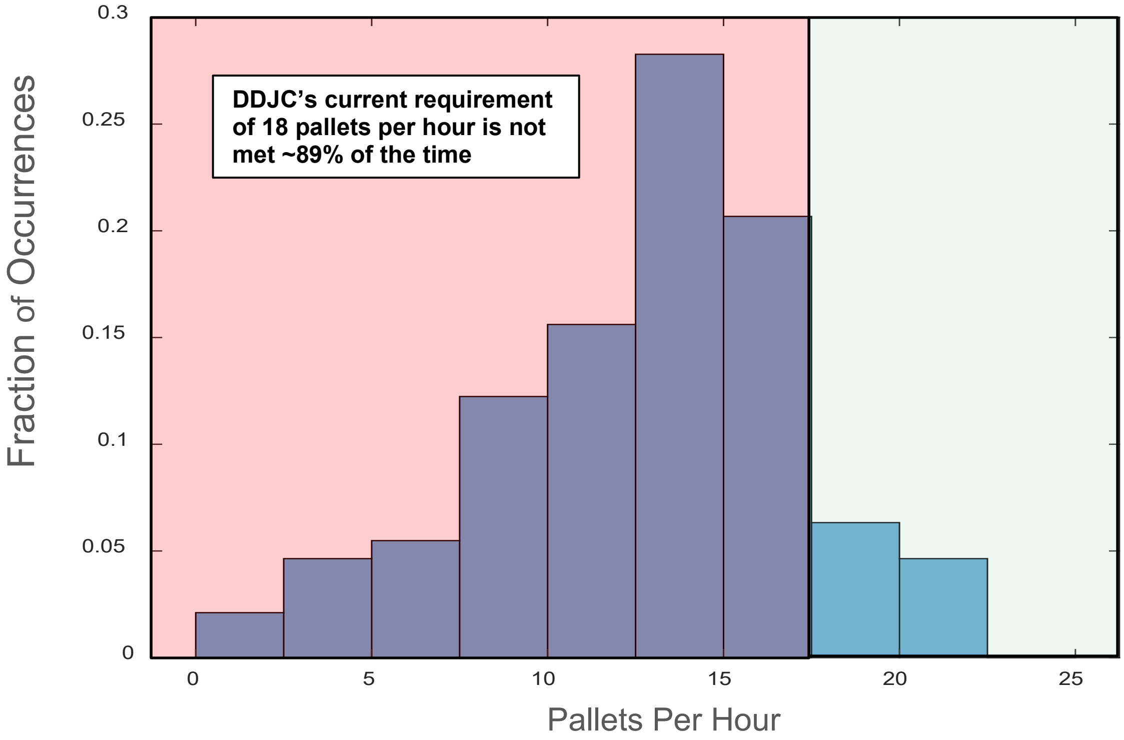


Figure 7. UGR throughput as provided in a 2019 visit.

Figure 8 shows a flow chart of the process at the facility. The basic steps are:

The operations are outlined as follows:

1. Orders of palletized ingredients enter the warehouse.
2. Forklifts transport pallets of ingredients into the warehouse, one at a time to the receiving lines.
3. Veterinarians inspect each pallet to ensure that it is undamaged, and its contents match the order.
4. Pallets are labeled and sent to induction, where they are prepared for storage by being placed on packed sleigh boards. Pallets then must pass through a sizing station to ensure that the pallet has been packed onto the sleigh such that nothing hangs over the sides of the pallet. If the pallet fails the sizing station, it is rejected and waits in a 'rejection line' to be re-inducted.
5. Pallets of ingredients are placed into high-rise storage using an ASRS crane system.
6. Pallets of ingredients are taken out of storage and sent to either partial pallet pick or full pallet pick:
    a. Pallets sent to full pallet pick are sent to staging.

   b. Pallets sent to partial pallet pick require that the pallets of ingredients be broken down before they are sent staging. For example, if a pallet has 100 items, but the order only requires 75, then the pallet must be sent to partial pallet pick where operators can remove the 75 needed items, and re-pack and re-induct the rest of the 25 items back into storage. The 75 palletized items needed for the order are then sent to staging with the rest of the ingredients to be sent eventually to depack.
   c. At staging, Quality Control and Quality Assurance (QC/QA) checks to ensure that the pallets are undamaged and that they match the order appropriately. If approved, the pallets are sent to depack.
7. At depack, every item is removed from the pallet where it can then be brought and staged at the assembly station.
8. Ingredients are packed into meals and palletized.
9. Palletized meals are assigned a new location and inducted.
10. Palletized meals are then sent back into storage.
11. When ordered, palletized meals are only sent to full pallet pick.
12. Meals are then transported to staging where they are prepared to be sent out for shipment.

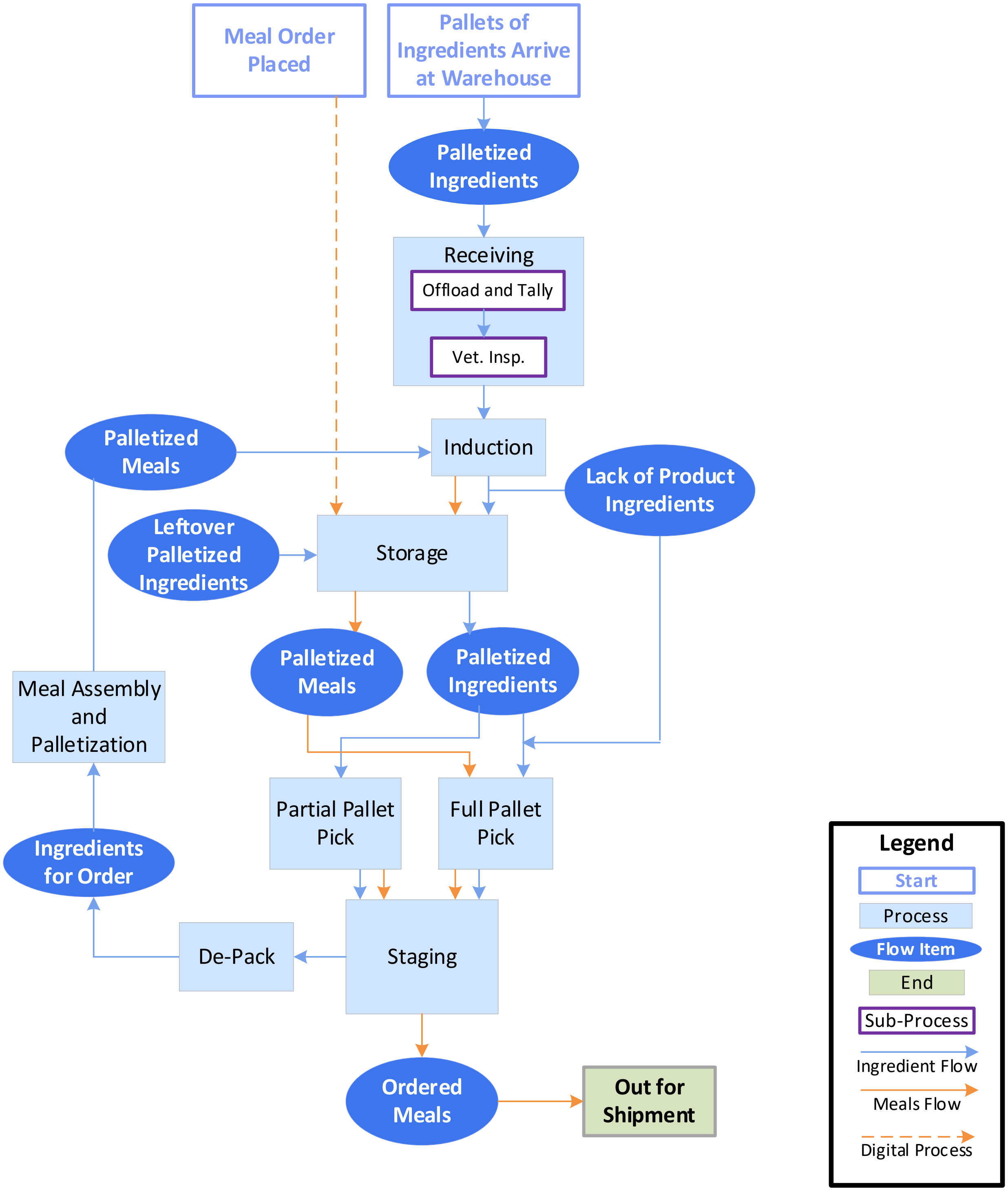


Figure 8. Flow diagram for the UGR line.

7.2 DISCRETE EVENT SIMULATION (DES) DEVELOPMENT AND RESULTS

In order to properly analyze the ability of various interventions to affect the throughput of the line, the line was modeled using a commercial DES tool. These tools are commonly used to assess warehouse performance. DES designates each event to occur for a specified time, at a particular instance in time, with specific related properties and characteristics, and it assumes that no changes in the system occur between events.

For example, a forklifts' movement consists of two events: departure from point A and arrival at point B. At departure, a forklift may pick up an item from point A, and drop it off at point B upon arrival. Both events consist of a system change, separated only by a discrete time delay. Modeling events in this way applies to any action that can occur in a warehouse during day-to-day operations. Whether the resource is a delivery truck, a conveyor system, an operator, or a machine or robot performing a task, each resource consists of a starting point, an ending point, a change to the system, and a time delay.

DES software also automatically calculates time delays when various characteristics of a resource are known. The size of a resource, the speed at which it can operate, the speed at which it can travel, obstacles it must avoid, and the distance it must travel, are just some characteristics that a DES model can take into consideration when calculating how long it takes to perform a task. These model elements can be customized in the model to reflect UGR's resources and facility layout. For example, the software will automatically calculate how long it will take a 10 ft. long forklift to travel 50 ft. at 2 mph. After examining several commercial DES systems, we chose FlexSim for this effort. Details of the time taken by various steps and the details of the steps were modeled based on information provided by DDJC Staff:

Col. Tiffany Harris – Commander DDJC

Jodie Johnson-Micks – Deputy Commander DDJC

Daniel Borba – Chief, Operations Cell DDJC

Nathan Duffy – Chief, Distribution & Specialized Mission Group DDJC

Darren McFall – Chief, Distribution & Specialized Mission Group DDJC.

The initial hypothesis was that a robot arm that could speed up the packing at the meal assembly stations (Step 9 above) could improve the throughput of the line. In fact, what we found was the meal assembly was far from the rate limiting step. Indeed, the rate limiting processes occur elsewhere on the line. Look at the diagram in Figure 9. The first bottleneck is at the 90˚ turn at the lower right-hand corner. To move the boxes across this, a hydraulic push-arm is used. This adds approximately seven seconds of delay, and increases the separation between boxes after they leave the packing station. Thus, Figure 10 shows the throughput as a function of the time between boxes at the packing station. One can see from the figure that the current value of two seconds is already at full performance. Further decreasing this time, even if a robotic arm could do so, would have negligible effect on the throughput. On the other hand, Figure 11 shows that if we could reduce the separation at the palletizer, which could be accomplished either by reconfiguring the line to round the sharp turn eliminating the need for the pusher arm, or getting a quicker pusher arm, would increase the throughput.

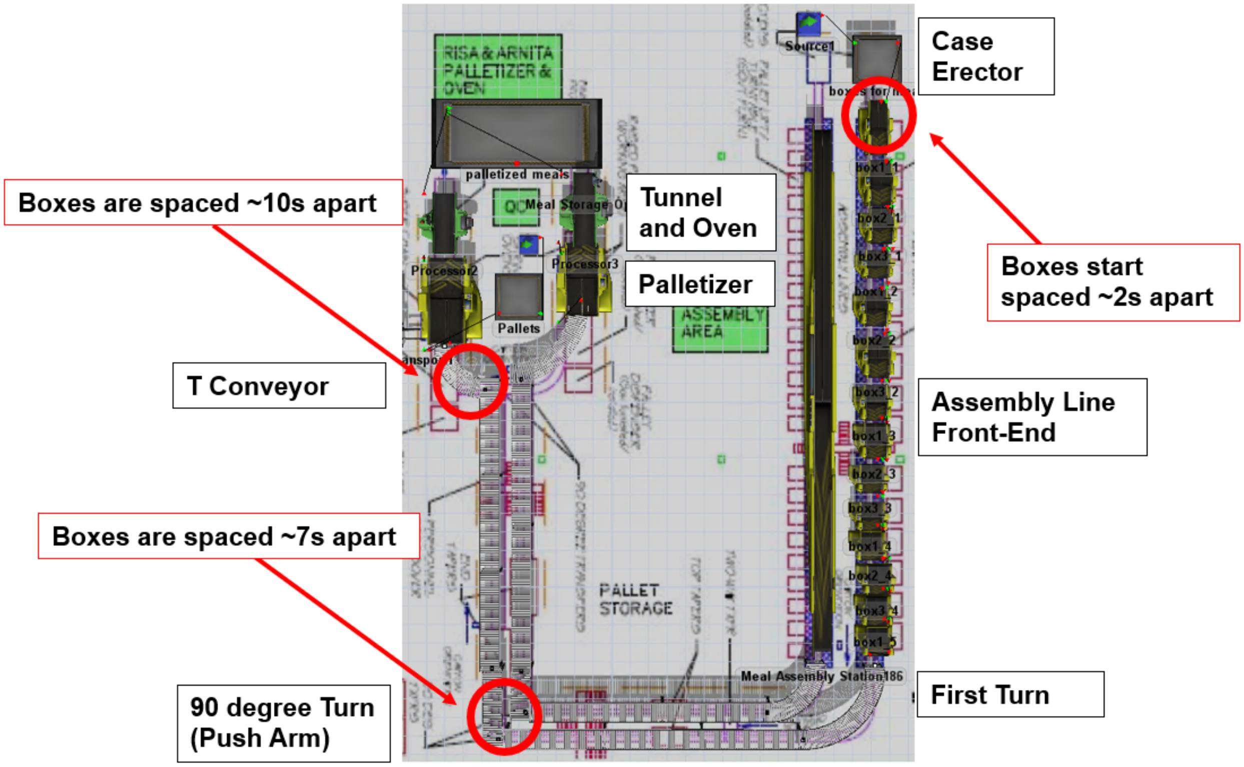


Figure 9. Assembly Line Layout.

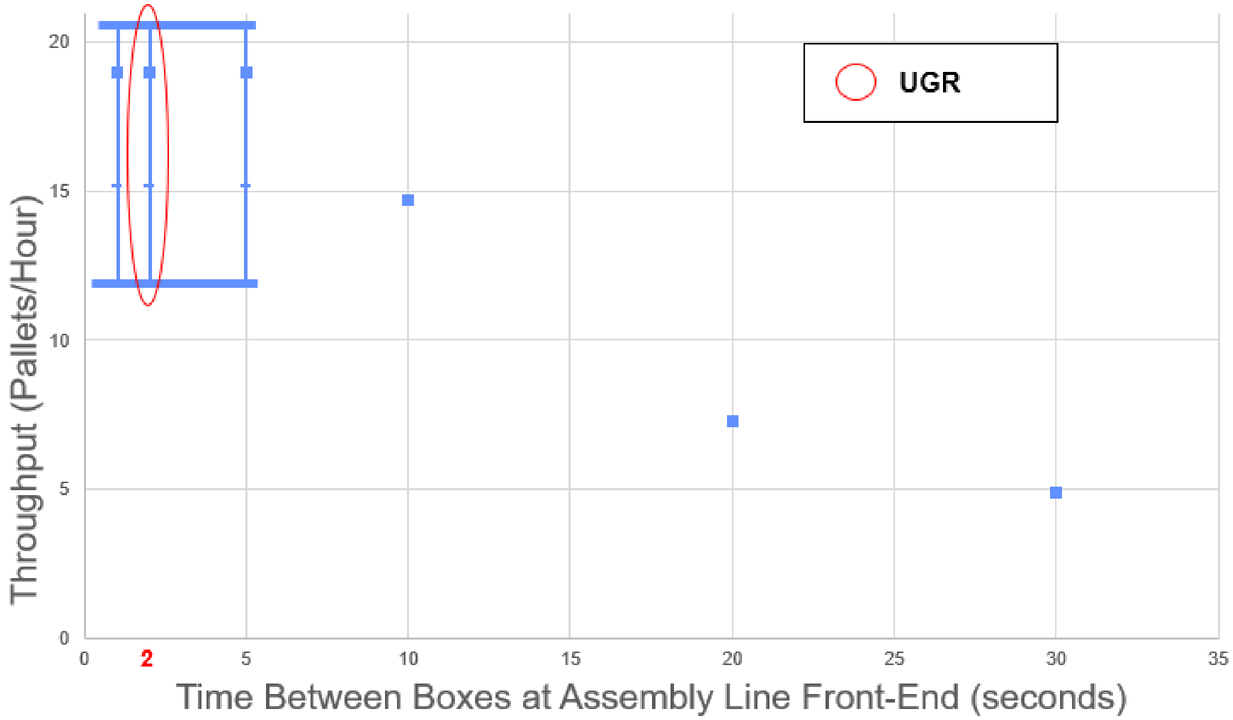


Figure 10. Time relative to throughput at assembly.

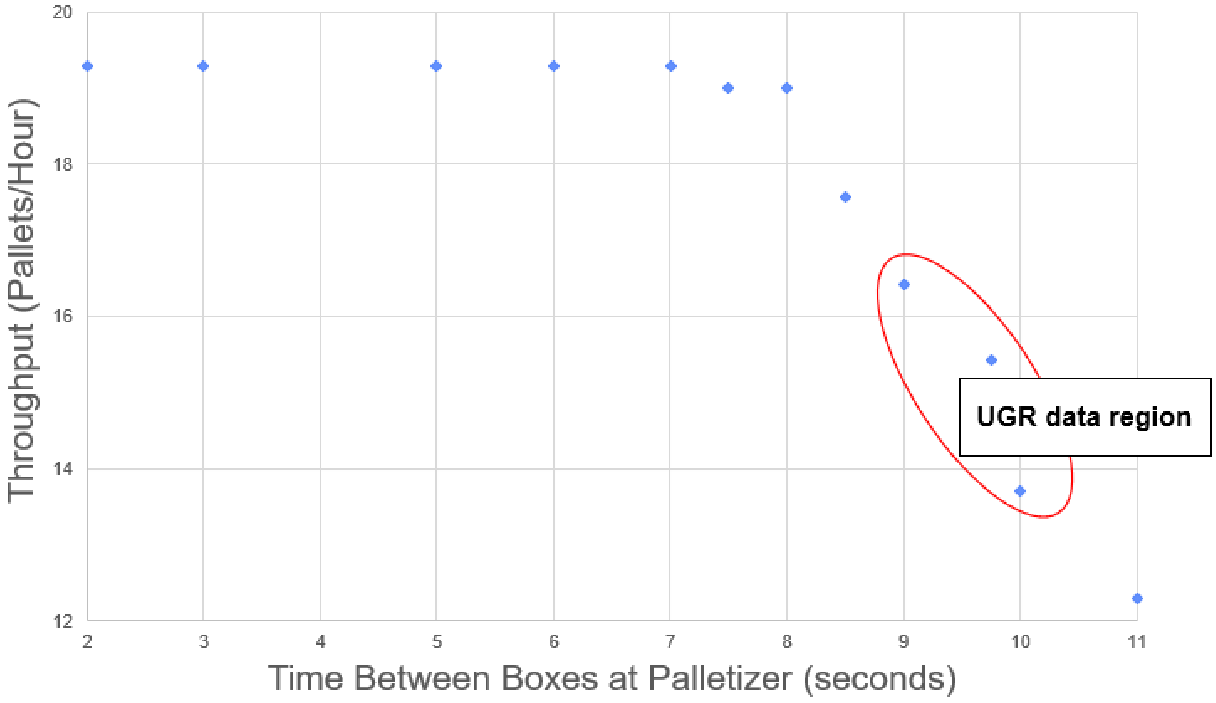


Figure 11. Time relative to throughput at palletizer.

Next, as seen in Figure 12, the line is configured to use two palletizers. However, in current practice, only one is in use. If one were to use both, a further increase in throughput would be realized, as is shown in Figure 12. In particular, if one reduces the delay at the push arm and uses both palletizers, the UGR line can meet its goal throughput. Thus, the robotic arm is not what is needed to improve productivity at UGR. The needed improvements, however, are not within the purview of R&D but of the industrial engineers.

It was fairly typical that the initial technology we set out to evaluate was not a good fit to the needs of the warehouse we examined. This happened with other technologies such as exoskeletons at DDHU and to some extent the automated tuggers at DDCT. This led us to conclude that one major gap in the R&D Distribution Modernization Program (DMP) is that it seemed focused on pushing particular technologies and investigating their applicability, rather than analyzing processes in DLA’s system, and then looking for improvements that could increase their efficiency. That led us to propose the analysis work described in the next chapter, which, alas, was not funded or executed.

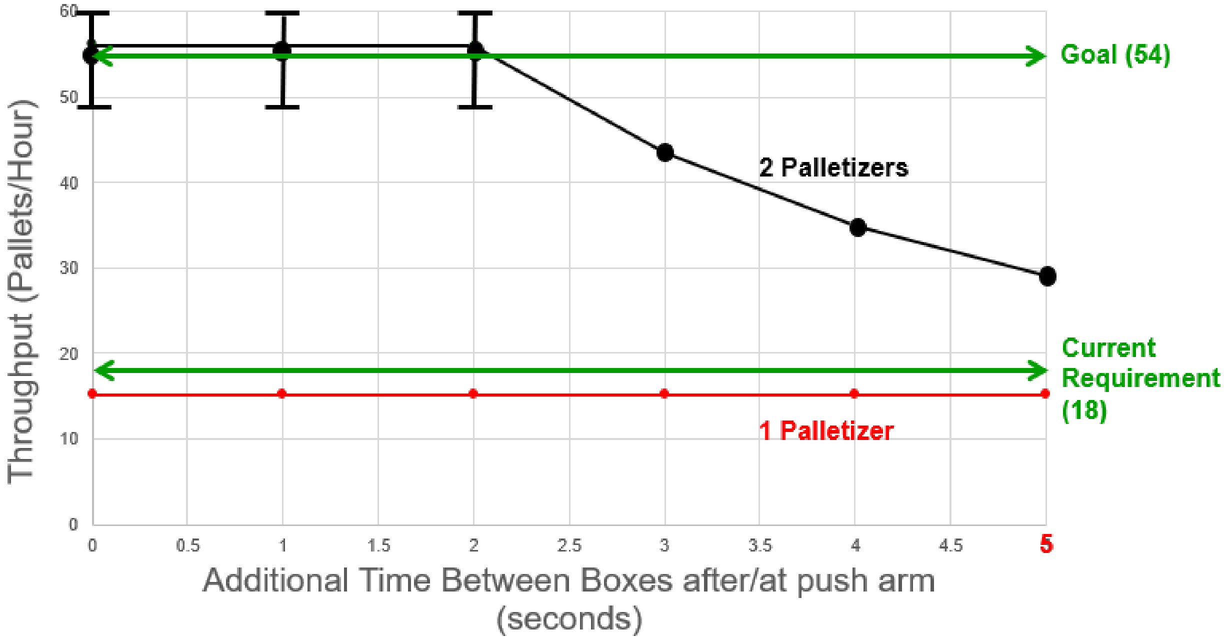


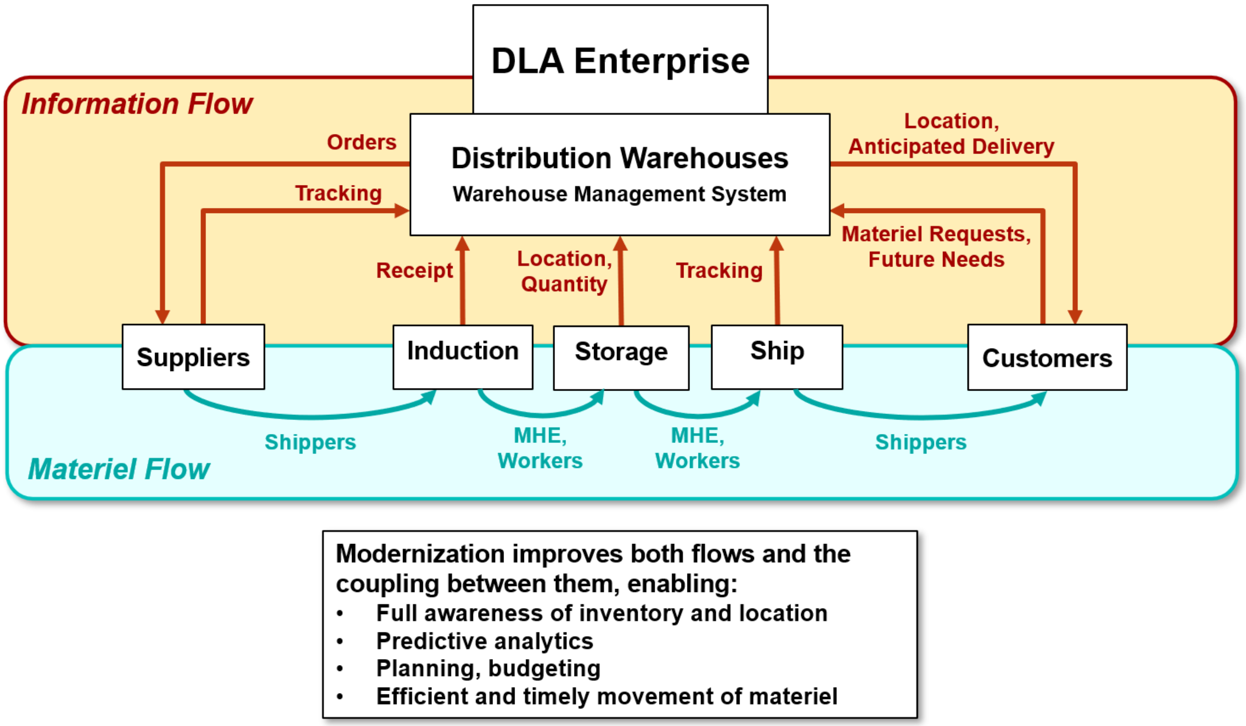
Figure 12. Time between boxes relative to throughput.

8. GAP ANALYSIS, CONCLUSIONS, AND FUTURE WORK

The DLA R&D Distribution Modernization Program (DMP) we were supporting was meant to respond to the GAO findings that the DLA was deficient in inventory management, materiel distribution and asset visibility. However, as mentioned above, DMP seemed designed to evaluate specific emerging technologies and their applicability to specific DLA facilities.

We did not find any systematic effort to model either the DLA enterprise or specific facilities in a systematic fashion so as to determine which technologies, whether available commercial, emerging or in development, would have the most impact on their specific needs and challenges. It was fairly typical that the initial technology we set out to evaluate was not a good fit to the needs of the warehouse we examined. In addition to the UGR warehouse at DDJC, this happened with other technologies such as exoskeletons at DDHU and to some extent the automated tuggers at DDCT. **This lack of systemic understanding of DLA processes as a means to identify the correct solutions is the biggest gap we identified.** We also identified gains to be had by process changes, but these are, apparently, outside the scope of the R&D effort, and, at least with regard to the ones we suggested for DDJC, there seems to be no good way of coupling the analysis to the industrial engineering efforts needed to implement the changes. We therefore recommended, and still do, that DLA undertake a systematic effort to model its facilities and processes to determine the underlying causes of the lack of performance. This will enable DLA to identify the right kinds of technology and process improvements to improve performance efficiently for the specific GAO findings.

Both the DLA enterprise as a whole, and the operation in any of its distribution centers represent coupled flows of both materiel and information. This is illustrated in Figure 13. The shortcomings noted in the GAO reports are really enterprise level shortcomings in being able to monitor and understand these flows. We therefore developed a proposal to model these flows at both the warehouse and enterprise levels, so that we could identify bottlenecks, identify both technology and process changes that can improve efficiency and/or effectiveness, and use simulation to estimate the likely return on investment. The presentation, which was previously briefed to DLA, is entitled “MBSE Framework Smart Warehouse for DLA 2021-05-12”.



Modernization improves both flows and the coupling between them, enabling:

- **Full awareness of inventory and location**
- **Predictive analytics**
- **Planning, budgeting**
- **Efficient and timely movement of materiel**

Figure 13. SOS view of DLA – Flows of Data, Information, and Materiel.

A flow chart of the proposed effort is shown in Figure 14. The idea would begin with working with DLA staff and customers to refine our understanding of DLA processes, the problems and the KPI's that would measure improvements. We would then develop models using appropriate commercial off the shelf (COTS) modeling platforms and use the models to both quantify problems and test the performance of proposed technology and process changes, either singly or in combination. The most promising candidates would be identified, and could then be tested in the field, and the performance measured. Feedback from DLA users and customers at various levels would be sought for identifying problems, defining models of both the systems and the operational constraints they operate under, and evaluating the usability as well as performance of proposed changes. This will make sure that the modeling is grounded in the operational reality and properly accounts for operational constraints.

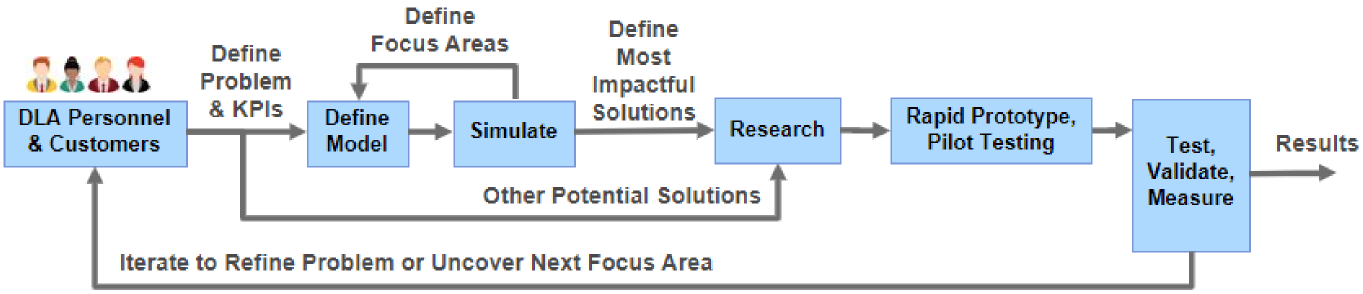


Figure 14. Distribution modernization approach – DLA as a system of systems.

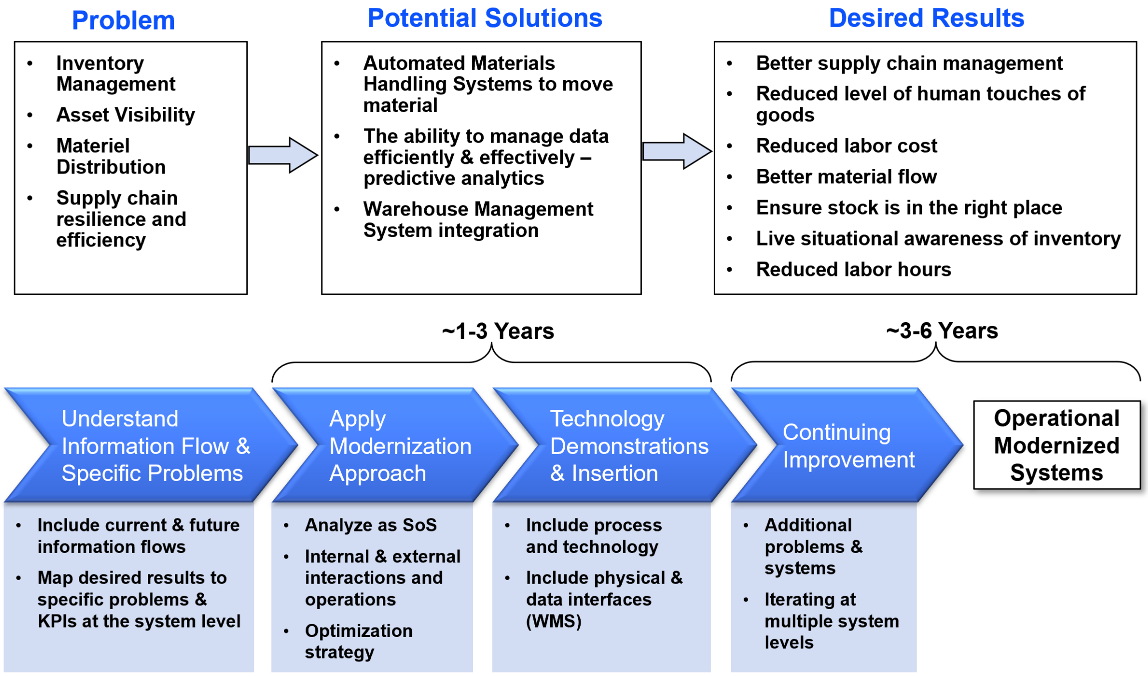


Figure 15. Roadmap to modernization and improved efficiency.

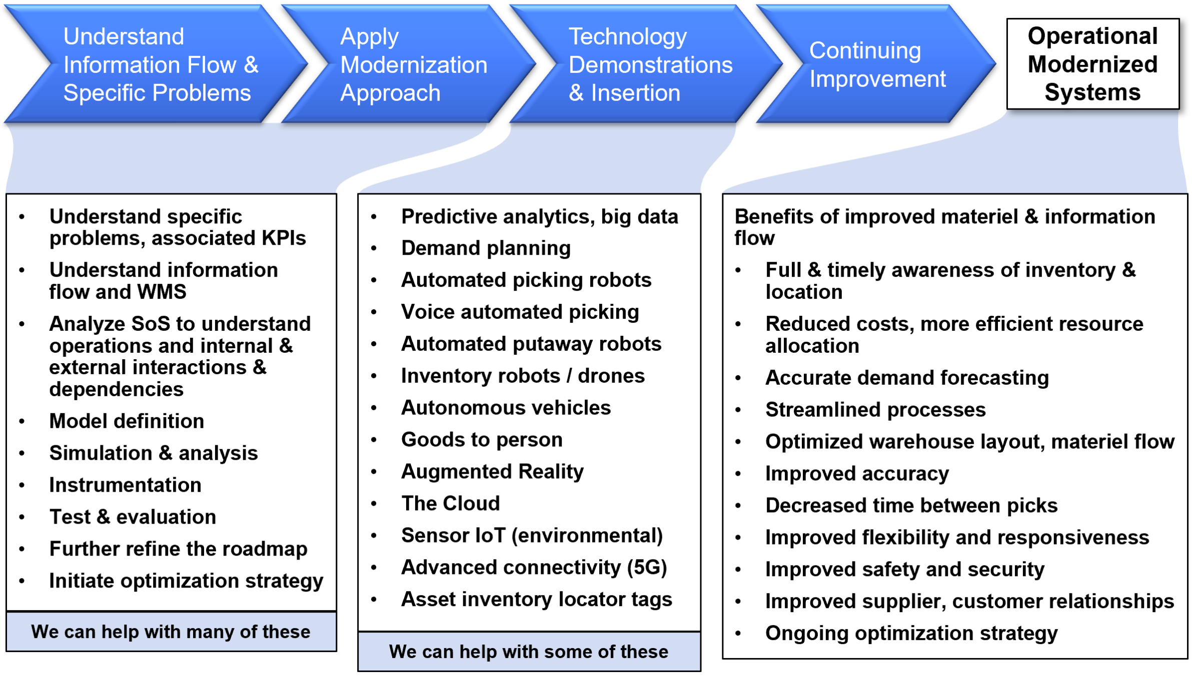


Figure 16. Roadmap details.

We recommend a high-level system model using MBSE tools, linked to more low-level detailed models, using tools like Discrete Event Simulation (DES) to model flows within a warehouse or network modeling tools to simulate detailed data flows, that can easily be linked to the MBSE model. Such a linked set of models would be in accord with the Department of Defense (DoD)'s announced digital engineering strategy. This effort would also have benefits beyond addressing the need for technology to address today's shortfalls. The linked and updated models would also provide a basis for allowing DLA to investigate continued technology refresh as technology continues to develop, and as missions and requirements evolve into the future. This will enable DLA to keep abreast of changing circumstances and invest in a controlled and efficient manner rather than in a sudden thrust to upgrade 50-year old technology, as they face now.

9. APPENDIX

Referenced documents included with the delivery of this report are:

1. Corpus Christi-AGV Data Analysis Update 2019-12-17
2. UGR Simulation Study Report 2021-01-29
3. MBSE Framework Smart Warehouse for DLA 2021-05-12
4. SoS Approach for DLA 2021-12-10

10. ACRONYM LIST

ABBREVIATION	DEFINITION
ADDER	Agile, Dynamic Distribution for Effective Readiness
AGV	Autonomous Ground Vehicle
AR	Augmented Reality
ASRS	Automated Storage and Retrieval System
AutoStore	A company brand that provides robotic ASRS
CCAD	Corpus Christi Army Depot
CONUS	CONtinental U.S.
COTS	Commercial Off The Shelf
DDCT	DLA Distribution - Corpus Christi, Texas
DDHU	DLA Distribution - Hill, Utah
DDJC	DLA Distribution - San Joaquin, CA
DDOO	DLA Distribution - Oklahoma City, Oklahoma
DDRT	DLA Distribution - Red River, Texas
DES	Discrete Event Simulator
DLA	Defense Logistics Agency
DMP	Distribution Modernization Program
DoD	Department of Defense
DSS	Distribution Support Services
ECS	Equipment Control System
IoT	Internet of Things
MBSE	Model-Based System Engineering
MIT LL	Massachusetts Institute of Technology Lincoln Laboratory
NASCC	Naval Air Station Corpus Christi
OSHA	Occupational Safety and Health Administration
POC	Point of Contact

ABBREVIATION	**DEFINITION**
QC/QA	Quality Control and Quality Assurance
R&D	Research and Development
SBIR	Small Business Innovation Research
SDD	Strategic Distribution and Disposition
SLAM	Simultaneous Localization and Mapping
SoS	System of Systems
UGR	Unified Group Rations
WIPCA	Work in Process Control Area
WMS	Warehouse Management System