

Home Delivery Logistics Networks using Driverless Delivery Vehicles

Michael G. Kay
Fitts Dept. of Industrial and Systems Engineering
North Carolina State University

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1. Introduction

A home delivery logistics network is proposed in which goods are delivered to the home in reusable containers transported by driverless delivery vehicles. Since the delivery vehicle does not have a human driver, it is cost-effective to have direct deliveries to the home and to have the vehicle wait to be unloaded. A single shipment delivered to a home can consist of either a direct delivery of a single order from a store or, more economically, several orders from stores at different locations can be sent to a small distribution center (DC) located near the home and then delivered. Each of these orders would be sent from its store to its closest DC and then transported through a sequence of DCs until reaching the DC close to the home. Orders not needing immediate delivery can be stored at the DC and the containers emptied after delivery can be returned to the DC for reuse.

In order to be cost-effective, the loading/unloading, sortation, and storage capabilities of the DC should be fully automated since each container delivered to a home might visit a dozen or more DCs while it's in transit. In order for it to be economic to locate a fully automated DC close to a home, the capacity of the storage system should be able to be specified in small fixed-cost increments so that the cost of the DC is proportional to its size. The proposed storage system design meets these requirements by using as its primary material handling device arrays of small square modules, each with orthogonal pop-up powered wheels. The arrays are used within each DC and onboard each delivery vehicle.

A home delivery logistics network, as envisioned, would make it possible to eliminate all non-recreational shopping for most people. In addition to general merchandise, meals and groceries could be delivered to the home. This would be especially important for the disabled and the elderly, and would allow them to live in a typical sprawling suburban neighborhood and still have their shopping needs met without the need to drive. Also, since empty containers would be available after delivery, each vehicle would provide a low cost means of shipping items from the home; e.g., waste requiring special recycling or sending specimens obtained at home to a lab.

Initially, the cost of this type of delivery would add to the cost of the goods purchased at the store (although it would eliminate the cost and time required for non-recreational shopping); over time, this cost would decrease because stores would be able to eliminate many of the costs associated with stocking shelves and checkout, and they could implement more efficient means of fulfilling orders, using more automated material handling equipment to receive goods and the same modular storage arrays used in the DCs to load orders directly onto self-driving delivery vehicles for shipment to customers.

2. Background

Although ecommerce spending by consumers has been growing relative to overall retail sales over the past few years, it is still necessary for most people to do the majority of their shopping in stores. Although some in-store shopping is a pleasant experience (for some, even their preferred recreational activity), for most it is a chore that, if possible, they would gladly eliminate, and, for the elderly and disabled, in-store shopping is difficult if not impossible. The overall goal of this research is to make it possible to provide low-cost delivery of goods to the home, thereby eliminating the need for most non-recreational in-store shopping. As envisioned, two key technologies are necessary: driverless vehicles for delivery and storage

devices capable of automatic loading and unloading. Together, they make it possible to create logistics networks capable of delivering goods to the home at a cost lower than the cost of in-store shopping. This work will focus on the second of these technologies, proposing a modular storage system that can be used throughout a home delivery logistics network. The expected results of this work will be estimates of many of the critical design requirements of such a network.

The first of these technologies, autonomous or driverless vehicles, has generated widespread coverage in media over the past two years. Most notable is Google’s driverless car, which has demonstrated the basic feasibility of the technology. Many observers estimate that a driverless car will be ready for market in as soon as ten years [1]. For the proposed home delivery logistics network, it is assumed that the same driverless car technology could be used to create a “driverless delivery vehicle” (or DDV). Although a DDV could be designed to be just a driverless version of the today’s typical UPS delivery van, this does not take advantage of the big reduction in cost possible due to the elimination of the driver’s labor cost. Instead, a DDV can be designed to have a small payload, making it cost-effective to provide direct delivery to the home.

Assuming that it is not going to be possible (at least initially) to have a DDV automatically unload goods at the home due to the cost of providing automated unloading equipment at the home, a person would be needed at the home to unload the vehicle. As a result, instead of the packages of an individual order being delivered, multiple packages from several orders are delivered to the home in one direct trip from a distribution center (DC) located close to the home. Reusable containers can be used for each order, with the empty containers returned immediately to the DC. In order to be located close to a home, the size of each DC has to be small, serving just several thousand people. The proposed modular storage system makes it possible to operate a DC at a small scale since no human presence is required onsite. The same module storage device used in the DC is used onboard each DDV to make automated loading/unloading possible, thereby allowing a single order to be transported between multiple DCs at a low cost. A DDV would visit a store to be either manually loaded with one or more orders (or automatically loaded if the store has the proposed modular storage system).

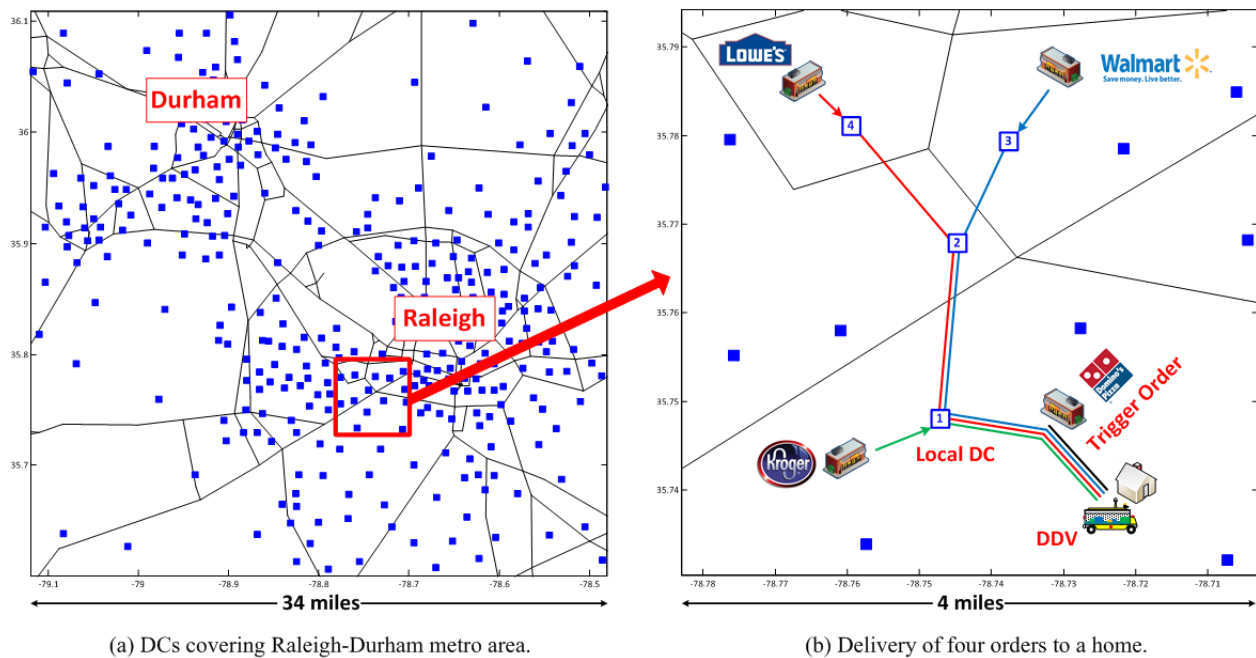


Figure 1. Home delivery logistics network example (DCs shown as blue squares).

Orders originating from a store located far from the home would be sent a DC close to the store and then transported through a sequence of DCs until reaching the DC close to the home. Orders not needing

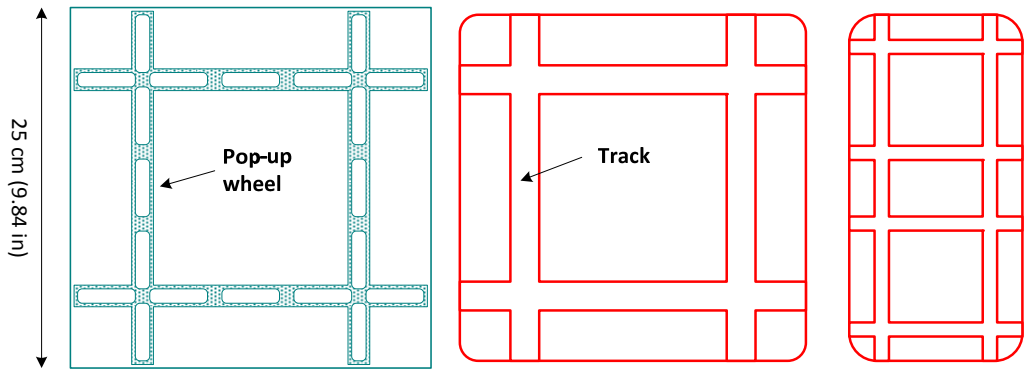
immediate delivery can accumulate at this DC and then, when a new order needs immediate delivery (e.g., a take-out order from a restaurant), it serves to trigger the delivery of all of the accumulated orders to the home in one trip. Since the final DC is located close to the home, the lead time for delivery is short and, since the trigger order is presumably of no value until it is in the hands of the person, it doesn't matter that it has to be unloaded from the DDV as opposed to it waiting for him or her on the front porch as is current practice for most parcel delivery in the U.S. (in Germany, by law, parcels cannot be left unattended outside a home). Figure 1 shows an example of how a hypothetical home delivery logistics network, consisting of many DCs, would be used to deliver a shipment of four orders to a home. Three of the orders come from retail stores and could be stored at the local DC until a take-out food order, for example, triggers the delivery of the shipment to the home.

One big advantage that such a DDV would have is that the maximum speed of travel for the vehicle does not have to exceed 25 to 35 miles per hour since the distance traveled to the home would be only a few miles. Thus, it is likely that the slow speed of a DDV would allow it to be authorized for autonomous operation before a driverless passenger car since the latter would need to be able to operate safely at much higher speeds (several states, e.g., Nevada, have already authorized driverless vehicles, but they require a licensed human driver to be onboard [2]).

3. DC Design and Control

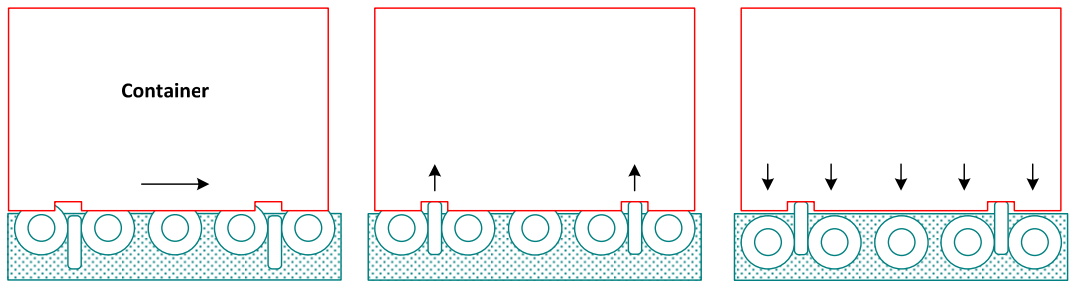
In order to be cost-effective, the loading/unloading, sortation, and storage activities in the home delivery logistics network should be highly automated since each order from a store to the home might visit a several DCs while it's in transit. Since existing automation technologies do not provide the flexibility needed to allow any size container to move to any location at any time, new DC, container, and vehicle designs are needed that integrate sortation with storage and allow for a variety of different size containers to be handled. A goal of the proposed design is to make the minimum efficient scale of operation for each DC low. Equipment that requires a large capital expenditure can only be justified for high demand volumes. In order for it to be economic to locate a fully automated DC near the home, the capacity of each DC should be able to be specified in small fixed-cost increments so that the cost of the DC is proportional to its size.

The proposed design for the DCs meets these requirements by using as its primary material handling device a small square module with orthogonal pop-up powered wheels (see Figure 2(a)). Arrays of identical modules are used to form a planar surface. Loads in containers (see Figure 2(b) and (c)) have recessed tracks on the undersides that mate with the module wheels to allow their transport along a module array using a series of orthogonal translations without rotation. The wheels of the module in each direction are raised and lowered relative to the wheels in the other direction (see Figure 3). Turns are accomplished without rotating the container by simultaneously lowering the wheels in one direction and raising the wheels in the other direction once the container has completely covered the module. The container then travels in an orthogonal direction. The length of each module is 25 cm (9.84 in.). Containers with a length greater than this would occupy several contiguous modules. These modules would operate in unison in order to transport the container. The simple actions required for each module along with using a single standard configuration should allow them to be produced in high volumes at a low cost. Montreuil [3] has proposed the concept of the "physical internet" to enable modular freight transport. The 25 cm dimension of each module meant to be compatible with the physical internet's 24 cm π -container dimension.



(a) Top view of single module. (b) Bottom view of 1 x 1 container. (c) 2 x 1 container (shown half scale).

Figure 2. Module and container designs.



(a) First pair of wheels moves container moves onto module. (b) Container stops and second pair of wheels is raised. (c) First pair of wheels is lowered and second pair moves container in orthogonal direction.

Figure 3. Orthogonal turning of a container (side view).

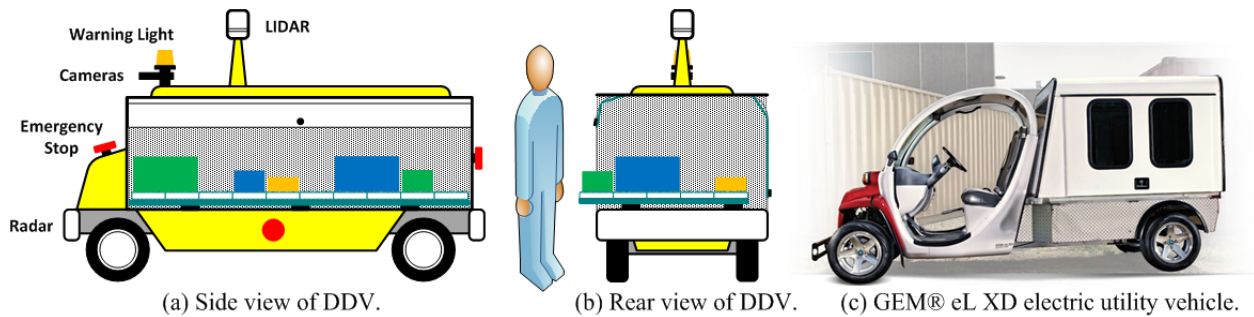


Figure 4. Proposed driverless delivery vehicle (DDV) shown in comparison to existing utility vehicle (Polaris [4]).

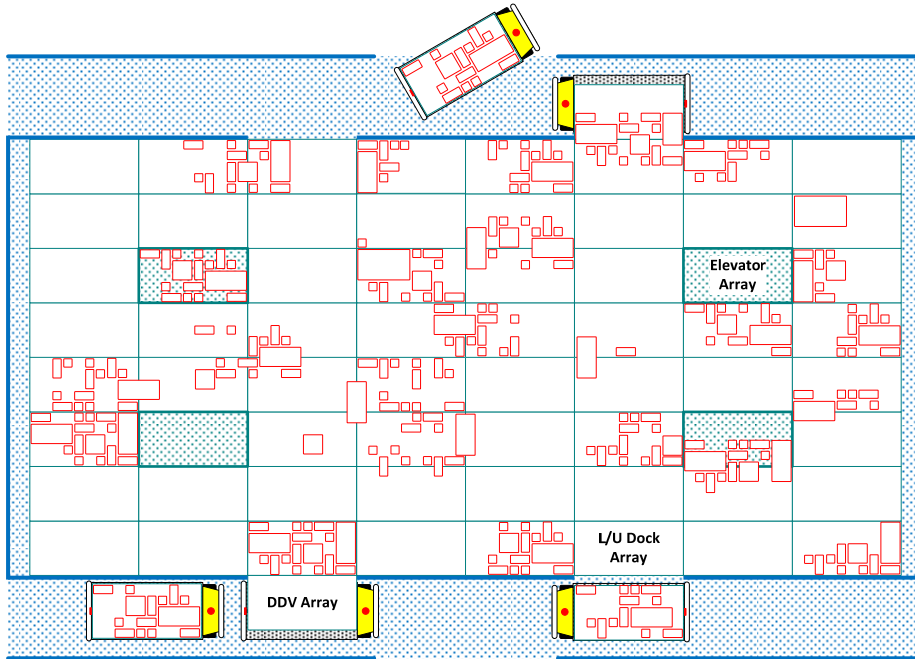


Figure 5. Top view of one level of a four-dock DC, where all loading/unloading, sortation, and storage operations are performed on a large open surface composed of arrays of pop-up wheel modules.

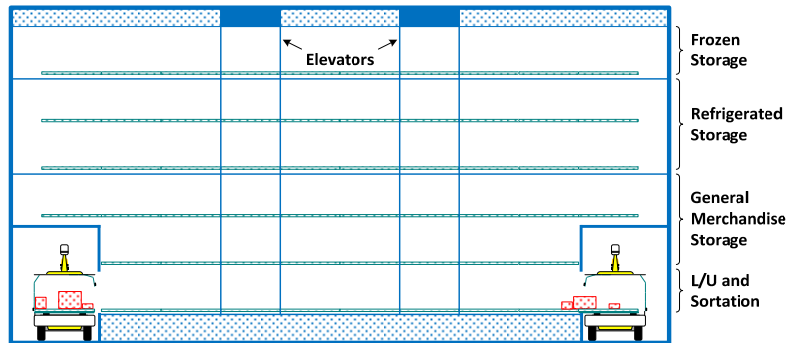


Figure 6. Side view of the DC showing the L/U and sortation level and five storage levels.

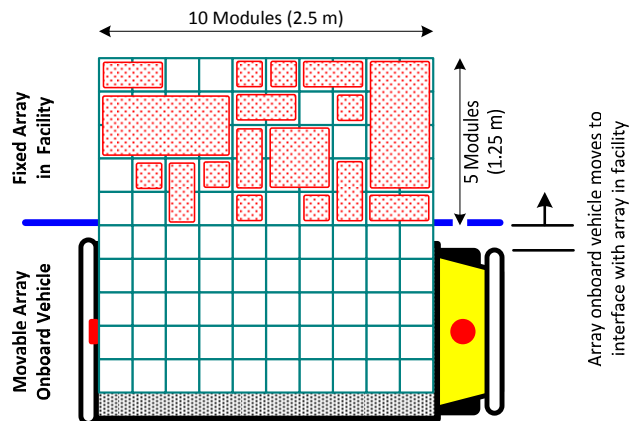


Figure 7. Detailed view of Figure 5 showing how containers are automatically loaded and unloaded from a DDV by positioning its array at the L/U dock array in the DC.

Figure 4(a) and (b) shows a possible design for the DDV. It could be built on top of the chassis of a low cost electric utility vehicle (Figure 4(c) shows the GEM® eL XD two-passenger electric utility vehicle that has an MSRP of \$11,999 and a payload capacity of 1,100 lb [4]) since it would not have to travel at a high speed or for long distances (the top speed of the GEM shown is 25 mph and its range between recharging is 40 miles). It would be fitted with the same suite of sensors and computers as used on a driverless car (see, e.g., Vanderbilt [2]), with the addition of a flashing warning light and large emergency stop buttons on all sides since a human passenger would not be onboard the vehicle to stop it in an emergency. Its only payload would be enclosed array of storage modules that would be accessible for loading/unloading from either side.

Figure 5 shows a top view of the a four-dock, six-level DC and Figure 6 shows a side view of the DC. All loading/unloading, sortation, and storage operations are performed on a large open surface composed of arrays of pop-up wheel modules. Only individual arrays are visible in the figure, not the individual modules. Individual modules are visible in Figure 7 and Figure 8. In Figure 5, DDVs are at three of the loading/unloading (L/U) docks. The DC has six levels: one level for L/U and sortation and five levels for longer-term storage. The top level provides storage for goods requiring frozen storage, and two levels provide refrigerated storage. Four elevators are used to move loads between levels. At each L/U dock, loads of containers are automatically loaded and unloaded by positioning the array onboard the DDV (see Figure 7). As compared to a design that uses traditional sortation and storage equipment (e.g., conveyors or an AS/RS), the proposed module-based design provides complete container accessibility at all times. The design differs from traditional designs by trading mechanical complexity for control complexity: each module is a simple mechanism, but each container in the system must be continuously controlled (even when it is in storage, since it will be continuously moving to provide clear paths for other loads (see Figure 8)).

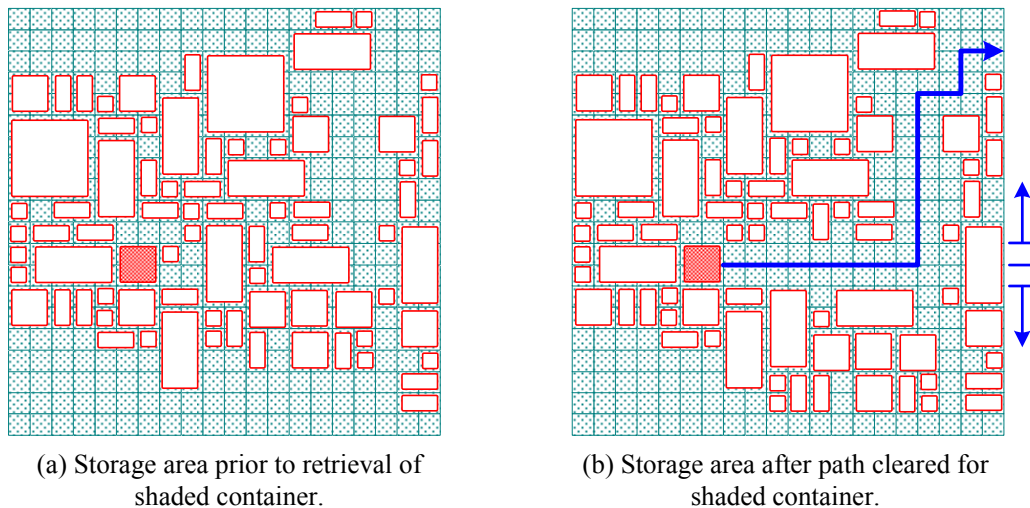


Figure 8. Containers can be densely packed together while still allowing each individual container to always be accessible because the other containers can simultaneously move to open a free path.

The proposed design provides the flexibility needed to allow any size container to move to any location at any time by integrating sortation with storage using arrays of modules. It enables high cube utilization during sortation and storage together with full accessibility to different size containers. High cube utilization reduces the amount of storage space required within a DC, while full accessibility provides the flexibility needed to re-route containers at any time and it reduces the time and cost associated with retrieving items from storage. The modules in the proposed design could be produced at a low cost due to the scale economies associated with using only a single uniform module design and the fact that each individual module would not have to be designed to handle the heaviest container because

the larger containers would occupy more modules and have their weight spread over these modules, thus lowering the cost of producing each module. Also, it is likely that several small, single-module containers will be as cheap or cheaper to store and transport between DCs as compared to an equivalent multi-module container because it would be easier for the smaller containers to find space available on a DDV for transit and within a DC for storage; this is in contrast with the economies of scale typically found when shipping larger consolidated unit loads.

The most important aspect affecting the feasibility of the home delivery logistics network, as outlined above, is cost and performance requirements of each of module in the arrays used for storage. Given the means to control such a modular storage system, the design and performance requirements for each module and the entire network can be determined. In order to provide reasonable loading/unloading and sortation performance at the DC, the biggest issues are at what speed does a module need to move a container across its surface (its cycle time) and how does the density of containers in the DC impact movement. Both issues are connected through the tradeoff of module cost versus performance. For example, the cost of the powered rollers used in each module varies with respect to the required velocity and acceleration (a module cycle time of five seconds would require 3.3 minutes to move a container from one L/U dock in DC shown in Figure 5 to a dock on the other side of the DC).

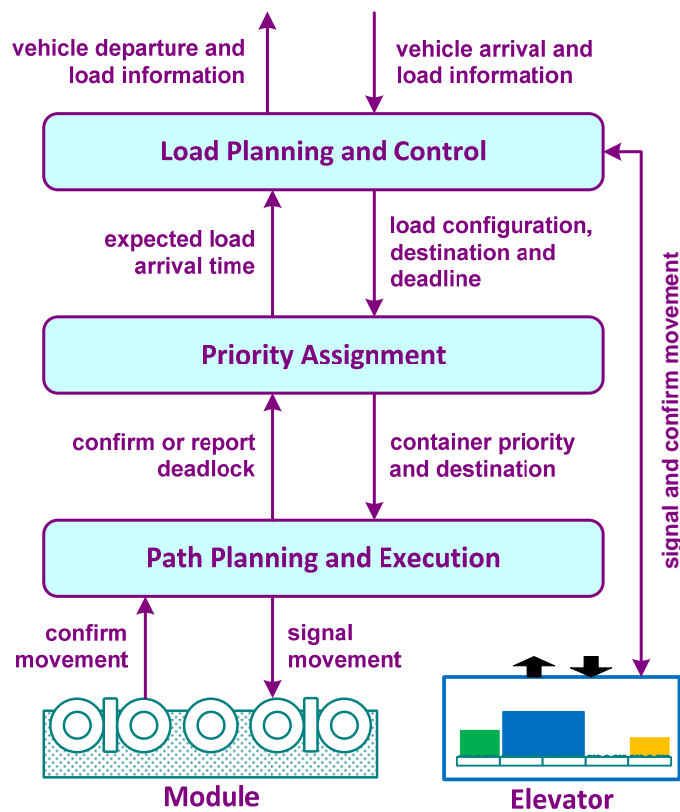


Figure 9. Three-layer storage system control.

As shown in Figure 9, three-layers are used for control of a DC. At the top layer, entire loads of containers are controlled. Each load fits onto a single array of modules and is comprised of the set containers transported by a vehicle or an elevator array within the DC. Each load arrives at an L/U dock and then its containers disperse to different destinations within the DC, and the containers departing the DC form a load on a (staging) array adjacent to the L/U dock array and then move in unison onto the dock array and onto the vehicle's array. Loads using the elevators are staged in a similar manner. This serves to decouple the control required for each level of the DC.

At each level in the DC, the movement of containers across arrays of modules gives rise to a complex multi-object motion control problem that is not adequately addressed by existing research. The goal of the proposed research is to develop efficient algorithms to handle simultaneous rectilinear movement of multiple multi-size objects (the containers) within an object-dense and limited-free-space environment (the module arrays). In order to temporally decompose the problem, the bottom layer procedures operate within the module cycle time to control each container using a priority assigned by the layer above. The priorities remain fixed for multiple cycles unless they require modification by the middle layer due to the detection of a deadlock. The middle layer translates the destination and deadlines of the loads into a unique priority level assigned to each container. If necessary, the priority levels can be used to form a desired configuration of containers for an outbound load if their unloading is required to occur in a particular sequence.

In order to control the entire DC (see Figure 9), elevator control procedures will couple each level of the DC. Representative sets of vehicle arrivals and departures and loads can be used to estimate several important design parameters (e.g., DC space utilization, L/U time, L/U dock and elevator location) and performance parameters (e.g., DC transit time for a given module cycle time and elevator speed) that together can be used to determine appropriate criteria for the design of a module and to estimate the design and performance of an entire home delivery logistics network. Previous work on “public logistics networks” (see Kay and Parlikad [5] for an early overview) has produced a rich set of modeling tools for estimating the performance of logistics networks like the proposed home delivery network and for generating representative loads. In a public logistics network, the different entities in the network (e.g., each DC and each DDV) are separated so that a single firm is not required for coordination. The results of this research will provide potential manufacturers of these modules with a tool and results to assess different design tradeoffs.

4. Cost Estimate

In order to gain insight into what the likely cost might be for a typical shipment to the home, a capacity model was developed. The results are listed in Table 1 for thirty-two combinations of parameter values. The cost of each delivery shipment (indicated by Trip in the table) can be separated into the cost of using all of the DCs visited from store to home (DC in the table) and the vehicle-related cost associated with transport from store to DC, between DCs, and from the final local DC to the home (vehicle cost is the difference between Trip and DC costs). In addition, the cost is listed on a per-module basis (Mod in the table), by dividing Trip by the number of modules occupied by the containers of the shipment. The estimated Trip costs range from \$1.45 to \$5.02, with an average cost of \$2.90 (assuming all parameter combinations are equally likely). These cost estimates are comparable to the lowest possible cost to have the smallest-size parcel delivered to the home by UPS or FedEx from a origin within the home’s same ZIP code and to what the out-of-pocket costs would be for a person to drive their car for a typical shopping trip (assuming the IRS standard mileage rate of 55.5 cents).

The capacity model illustrates now the design parameter estimates that will be produced as a result of this research could be utilized. *L/U Time* and *DC Space Utilization* are the design parameters that will be determined through testing of the DC control system. *Module Cost* would only be able to be determined after performance requirements are determined and estimates are made of what the total potential market would be for the modules. Assuming large quantities of a single module design could be produced, significant economies of scale are possible; also, the weight carrying capacity of each module would not exceed 20 lb (or 1 lb per wheel), further reducing cost. The DC shown in Figure 5 and Figure 6 has 22,400 modules (448 arrays of 50 modules each). The DCs shown in Figure 1(a) each serve a population of 2877 (derived from aggregation of U.S. census block group data), which, if extrapolated, would result in around 111,000 DCs covering the entire U.S. and a market size of about 2.5 billion modules, not including the modules onboard DDVs. Demand is specified in terms of shipment trips (deliveries) per week per household (*Household Demand*) and the number of modules occupied by the containers of each shipment (*Modules per Trip*). All of the parameter values in the table are average values, not extreme

values. Two different values were chosen for each parameter to reflect the uncertainty in what the demand might be for the proposed home delivery service (*Household Demand* and *Modules per Trip*), the minimum possible module cost when produced in volume (*Module Cost*), and the performance of the DC control system (*L/U Time* and *DC Space Util.*).

Table 1. Home Delivery Cost Estimate

Module Cost	L/U Time (min)	DC Space Util.	Household Demand (trips/week)															
			2						4									
			Modules per Trip						Modules per Trip									
			10			20			10			20						
			DC	Trip	Mod	DC	Trip	Mod	DC	Trip	Mod	DC	Trip	Mod				
50	5	0.6	1	1.46	2.27	0.23	9	2.27	3.19	0.16	17	0.73	1.54	0.15	25	1.14	2.05	0.10
50	5	0.8	2	1.29	2.10	0.21	10	1.93	2.84	0.14	18	0.64	1.45	0.15	26	0.96	1.88	0.09
50	10	0.6	3	1.46	2.27	0.23	11	2.27	3.19	0.16	19	1.32	2.13	0.21	27	1.64	2.56	0.13
50	10	0.8	4	1.29	2.10	0.21	12	1.93	2.84	0.14	20	1.32	2.13	0.21	28	1.64	2.56	0.13
100	5	0.6	5	2.51	3.39	0.34	13	4.01	5.02	0.25	21	1.25	2.14	0.21	29	2.01	3.01	0.15
100	5	0.8	6	2.16	3.05	0.30	14	3.32	4.32	0.22	22	1.08	1.97	0.20	30	1.66	2.66	0.13
100	10	0.6	7	2.51	3.39	0.34	15	4.01	5.02	0.25	23	2.12	3.01	0.30	31	2.71	3.71	0.19
100	10	0.8	8	2.16	3.05	0.30	16	3.32	4.32	0.22	24	2.12	3.01	0.30	32	2.71	3.71	0.19

(DC cost in \$, DC + vehicle cost = Trip cost in \$, Mod = cost per module delivered in \$)

DC cost per trip was determined by applying a per-module-hour DC cost to the total time that each module of a shipment spends in any DC during transit (its cycle time), which is estimated to be half the average interval between shipments. The size of the DC, in modules, is determined by applying Little's Law, where number of occupied modules (WIP) = shipment cycle time \times average demand rate in trips per hour (throughput). The total number of modules needed for each DC is then determined by dividing the number of occupied modules by *DC Space Utilization*. Total modules \times *Module Cost* investment cost is then discounted over five years at 5% and 25% salvage value to get a monthly cost to added to which is added a (\$2 per ft² per month \times DC footprint in ft²) average rental cost estimate, which is then converted to a per-module-hour DC cost. The DC shown in Figure 5 and Figure 6 has a monthly cost of \$20,800. The footprint of the DC is driven by *L/U Time*. The number of L/U docks in the DC is determined by $(L/U Time)/60 \times$ (demand rate in trips per hour). All of the DCs represented in Table 1 have either four or six L/U docks.

Vehicle cost is determined by applying a per-vehicle-hour cost to the total time that each shipment spends in a vehicle during transit and a per-vehicle-mile cost to the total distance traveled. Cost per mile includes fuel (electric power) and maintenance costs. Cost per hour is driven by *Modules per Trip* and *Module Cost*. The parameter *Modules per Trip* is used for the store-to-DC and DC-to-home portions of a trip, and a value of 40 modules is used for all inter-DC portion since the vehicles are likely have onboard multiple shipments. The base vehicle cost is assumed to be \$12,000, to which an estimated \$5,000 (Vanderbilt, 2012) is added for the driverless technology, (50 modules per array \times *Module Cost*) for the modular array, and \$2,500 for the module array enclosure. The total is then discounted to an hourly cost assuming 16 hours of operation per vehicle per day. Vehicle speed is assumed to be 15 mph. Vehicle dwell time at the store (trip origin) and home (destination) is 10 minutes, and 5 minutes at each DC. Assuming a uniform spatial demand density, average store-to-DC and DC-to-home distances are estimated as the distance to half of the DC's service area (1.3 miles for a 12 square-mile service area). The average total DC-to-DC (linehaul) distance of each shipment is estimated by finding the proximity factor [5] that results in 10% of a shipment's demand being from stores located within the service area of a home's local DC (local demand). This then results in population-weighted demand percentages for all of the DCs in the network, with demand decreasing for DCs located further away from the local DC, which result in an average linehaul distance of 6.2 miles for the DCs shown in Figure 1(a).

5. Conclusion

A home delivery logistics network, as envisioned, would make it possible to eliminate all non-recreational shopping for most people. In addition to general merchandise, meals and groceries could be delivered to the home. This would be especially important for the disabled and the elderly, and would allow them to live in a typical sprawling suburban neighborhood and still have their shopping needs met without the need to drive or own a car. Also, since empty containers would be available after delivery, each vehicle would provide a low cost means of shipping items from the home; e.g., waste requiring special recycling, sending specimens obtained at home to a lab, or goods manufactured by a home-based business.

The proposed delivery service is meant to be cost-effective even during the early stages of development for those like the elderly and disabled who would likely value the service even at a higher cost and longer delivery lead time (initially, relatively few DCs would be available in the network). The only two major factors impacting overall long-term cost would be the cost of manufacturing the modules and the cost of providing driverless technology for a DDV. A DDV is likely to provide a good test bed to first deploy driverless technology due to their slow speed of operation as compared to a driverless car, and so would be the beneficiary of nearly all early driverless car developments.

Initially, the cost of this type of delivery service would only add to the cost of the goods purchased at the store (although it would eliminate the cost and time required for non-recreational shopping). Over time, this cost would decrease because stores would be able to eliminate many of their costs associated with stocking shelves and checkout, and they could implement a more efficient means of fulfilling orders, using more automated material handling equipment to receive goods and the same modular storage arrays used in the DCs to load orders directly onto DDVs for shipment to customers. Also, as the cost of a modular decreases, many people might want to purchase a modular storage array for use inside their garage (since garage space would become available once people are able to call driverless cars on demand for their transportation needs).

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