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Framework and Research Roadmap for a Next-Generation Hyperconnected Logistics Hub

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Abstract: Today, parcel logistics hubs, where packages come in from many origins and are sorted to their many destinations, are both capital and labor intensive, with capacity that is largely determined by investments in conveyors. In this paper, in the context of Physical Internet growth, we propose a next-generation hyperconnected parcel hub concept that leverages parcel containerized consolidation, does not use conveyors, is robot-centric, with minimal requirement for human operators. Hub capacity can be readily adjusted to accommodate changing logistics patterns. The hub concept is described along with a demonstration case study, the fundamental hub design and operational decisions are identified, and a research roadmap is defined.

Conference Topic(s): Developing the System of Logistics Networks towards the Physical Internet.

Keywords: Physical Internet, Logistics Hubs, Hyperconnected Logistics, Parcel Logistics, Modular Containers, Consolidation, Robotics, Digital Twins

1 Introduction

Today, parcel logistics at both national and international scales is enabled by large-scale parcel logistics hubs, where parcels arrive in bulk from originating hubs, are sorted and consolidated to destination hubs and leave in bulk. The UPS Worldport (https://tinyurl.com/y3bq6tur) is the epitome of such hubs, with 155 miles (250 km) of conveyors occupying 5 million square feet (464,500 m^2), and 2.6 miles (4.2 km) of tilt tray sorters, providing capacity to sort over 416,000 packages per hour. Such hubs were a natural evolution as demand for rapid parcel delivery expanded from its early days. These kinds of parcel logistics hubs, however, present significant challenges. Basic physics limits the potential for expansion, begging the question of how to deal with ever-increasing parcel volumes. They require large amounts of part-time and temporary labor and involve working conditions and hours that are less than desirable. They also engage fixed-capacity transport, which can become inefficient when parcel volumes are not at their peak levels.

This paper addresses the following question: "Can the basic precepts of the Physical Internet (PI) [1,2] be used to develop an innovative parcel logistics hub concept that overcomes the limitations of contemporary logistics hub technologies?" In addressing the question, we assume the existence of some PI technologies that already have been investigated, specifically the use of modular containers [3] to consolidate small parcels for shipment from their originating hubs and delivery to their destination hubs. For example, we rely on two types of modular-sized handling containers, termed totes for those with sides up to near 2 feet, and boxes for those with larger sides of 2, 4 or 8 feet. We rely on modular mobile racks, whose external side dimensions are consistent with those of boxes, to store and transport totes. We further assume the existence of specific robotic technologies similar to those currently available.

The paper is organized as follows. Section 2 presents the basic concept for the innovative parcel logistics hubs using modular totes and boxes to consolidate parcels for handling, and modular mobile racks to consolidate totes for transport. Section 3 provides a system architecture definition for a particular realization of the robotic logistics hub concept and section 4 summarizes initial design of the boxes, totes and racks, consistent with standard truck and trailer dimensions. Section 5 describes in detail the "Shuffle Cell", a robotic cell in which totes are shuffled between racks to improve the racks' levels of consolidation. In section 6, a complete hub design is described, based on a case study from an existing parcel logistics hub. A detailed Anylogic™ simulation is described in section 7 along with some initial computational evaluation of the hub design. Section 8 compares the results from simulating the new hub design to the observed performance from the original benchmark hub. Finally, section 9 discusses a research roadmap for this novel approach to parcel logistics.

2 Basic Concepts

The idea of hyperconnected logistics is described in several publications, including [1, 4-6] and several previously explored PI concepts motivate this work. One is the consolidation of parcels into modular containers as discussed in [3, 7-9]. An originating hub will consolidate all parcels with the same destination into one or more modular totes or boxes. In the hub concept presented here totes are consolidated into racks for transport in standard trucks or semi-trailers.

A second motivating concept is a network of logistics hubs, as suggested in [1, 2, 5, 10]. The trucks from the originating hub connect to a logistics hub that is part of this network. At each logistics hub, an arriving rack gives up totes that are not going to the same next destination as the rack and acquires totes that are until the rack is fully consolidated and ready for transport to a next hub.

At an originating hub, parcels with same destination are accumulated in a tote. A tote in a rack from a particular originating hub may visit several logistics hubs and be transferred to other racks before it finally arrives at its destination hub where parcels are removed from totes. At each logistics hub, some totes may be removed from a rack, because their appropriate next destination is different from the rack's next destination, and some totes may be added. It is possible that a rack arriving to a logistics hub will be stripped of totes and stored temporarily because it is not needed at the moment to transport totes, and all the totes it contained can be accommodated by other racks.

A third essential concept is robotic transport of both racks and totes within the hub, thus dramatically reducing the numbers of humans involved in the logistics hub operations, in line with robotic mobile fulfillment systems [11]. Further, the resources for moving totes between hubs and for temporarily storing racks between these processes are organized according to a standard footprint, resulting in easily replicated cells.

This is a fundamentally new paradigm for parcel logistics. Rather than concentrating the capacity to sort parcels, it distributes that capacity across a hub network. Because the concept depends upon robotic technology, it is readily scalable; in fact, capacity at a given logistics hub can be adjusted as flow through the hub increases *or decreases*. Further, because capacity is based on robotic technology, the number, size and location of logistics hubs can be changed much more easily than in current parcel logistics systems.

We refer to this new type of logistics hub as a *hyperconnected logistics hub* or HLH.

3 HLH System Architecture

There are three main areas of operation in the HLH, unloading inbound racks, shuffling totes between racks to achieve consolidation, and loading outbound racks as shown in *Figure* 1. Note that hereafter, for conciseness purposes, we consider boxes to be racks that simply have to be crossdocked. Physically, unloading and loading may share the same docks but operationally they are different and may have different priorities. Both the loading and unloading centers have a staging area where racks may be located after unloading or before loading. The *ShuffleCenter* contains an area where racks may be stored temporarily (*BufferZone*) and a number of cells where totes are shuffled between racks (*ShuffleCell*s). The figure also shows the flows between the three areas of operation as well as within the *ShuffleCenter*.

In the HLH there are four distinct types of robots:

- *LoadBots* are capable of un/loading racks from/to trucks
- *MoveBots* move racks from/to staging areas, and within the *ShuffleCenter*
- *ShuffleBots* move individual totes between racks
- *ToteBots* move individual totes between *ShuffleCells*

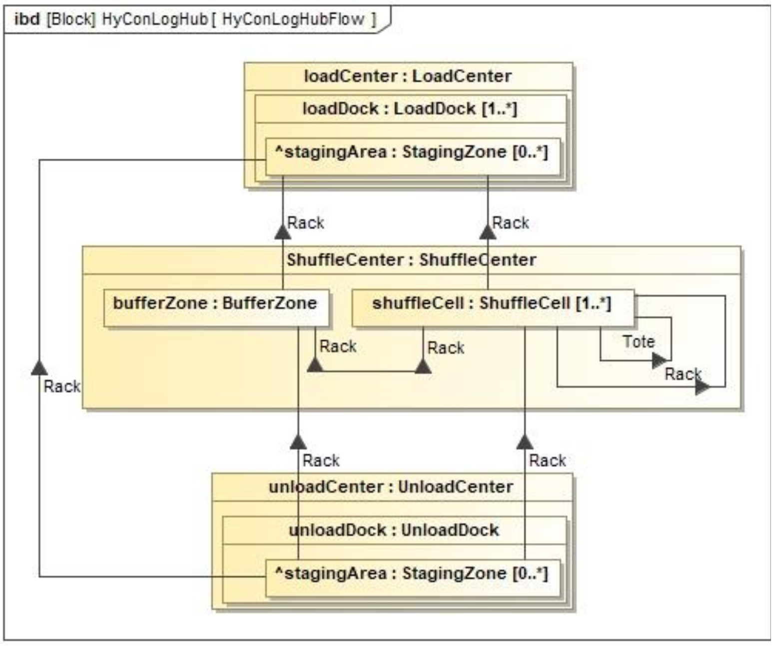


Figure 1 HLH Areas of Operation

As described in Section 4, the totes and racks are designed to maximize the utilization of standard semi-trailers and thus the racks are set flat on the floor of the trailer. Thus, *LoadBots* must be able to engage the racks, lift and move them. We assume the racks either have retractable "feet" or are placed on a specialized rack stand for movement within the HLH. Thus, *MoveBots* operate in a manner like conventional Kiva-style robots [11]. *ShuffleBots* are specialized for extracting/inserting totes from/to racks and moving totes between rack locations. Finally, *ToteBots* are conceptualized as small, quick robots that can transport individual totes between *ShuffleCells*. *ShuffleBots* can interface with *ToteBots* for their loading and unloading.

An agent-oriented control architecture for the HLH is shown in *Figure 2*. There are 11 distinct control domains. At the highest level of control is the *HLHAgent* that has visibility to the inbound trucks and the state of each of the control domains with which it directly interacts, namely the *UnloadCenter*, the *LoadCenter*, the *LoadBotPool*, and the *ShuffleCenter*.

The *LoadBotPool* has a control agent responsible for moving *LoadBots* between the un/loading operations. The *UnloadCenter* and *LoadCenter* are conceptually similar; each has a control agent, and each has an assigned pool of *LoadBots*. The center level agents are responsible for prioritizing the load/unload operations and the associated bot pool agents are responsible for managing the *LoadBots* to execute the prioritized loading and unloading.

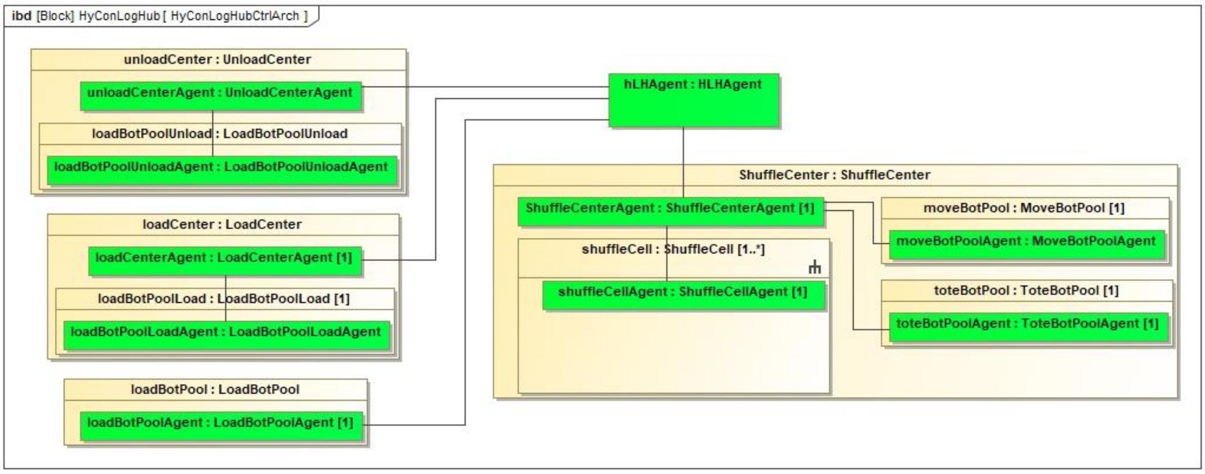


Figure 2 HLH Control Architecture

The *ShuffleCenter* has a control agent that directly interacts with the control agents for the *ShuffleCells*, *MoveBotPool*, and *ToteBotPool*. The *ShuffleCenterAgent* determines when racks should be moved and where to move them, and the *MoveBotPoolAgent* manages the execution of these moves. Similarly, the *ShuffleCenterAgent* determines when totes should be moved between *ShuffleCells* and the *ToteBotPoolAgent* manages the execution of the tote moves. Not shown in Figure 2 are the individual *MoveBot* and *ToteBot* agents that manage the execution of assigned rack and tote moves within the *ShuffleCenter*.

Within each *ShuffleCell*, the *ShuffleCellAgent* is focused on operations within the cell and determines which tote moves should be made. Possible tote moves include rack-to-rack, rack-to/from-buffer, rack-to/from-*ToteBot*, and buffer-to/from-*ToteBot*. The *ShuffleCellAgent* determines the sequence of moves and the *ShuffleBotAgent* manages the *ShuffleBot* execution of moves.

The execution of rack and tote moves are relatively straightforward and managed by the corresponding bot agents. More interesting are the operational decisions made by the agents for the HLH, the *ShuffleCenter*, the individual *ShuffleCells* and the various bot pool agents. The control architecture in *Figure 2* allows these decisions to be made using methods from simple heuristics to very sophisticated optimizations.

4 Initial Design of Totes and Racks

To make the HLH concept concrete, the totes and racks must be given physical configurations. Here we assume a single size with nominal dimensions of 2x2x2 feet, although other configurations are possible. We assume racks to have capacity for eight such totes, four high and two wide. Suppose the racks are to be transported in standard semi-trailers, with inside dimensions of 47’3”x99”x108-1/2”and rear door dimensions of 8’3"x8’9”. If the racks are placed in the trailer side by side, as shown in Figure 3, and we wish to use as much as possible of the trailer volume, then the external dimensions of the racks will be 1’10-1/2”x4’x8’4-3/4”.

Alternative designs have been considered, based on placing the racks in the semi-trailer aligned with the long dimension of the trailer, i.e., back-to-back rather than side-to-side. The two designs achieve slightly different volume utilizations within the trailer, and result in different configurations of the load/unload staging areas because of the nature of the connection between the *LoadBot* and the rack.

Assuming internal structural members with dimensions 4”, and allowing for ½” clearance around the totes, the resulting dimensions for a single standard tote would be 1’9”x1’9”x1’9”.

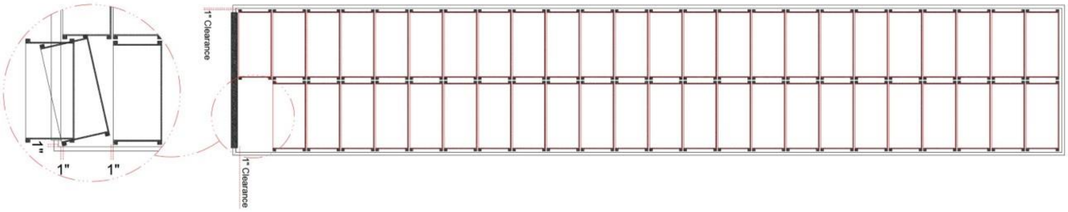


Figure 3 Racks Arranged in Semi-Trailer

5 Shuffle Cell Concept and Design

Conceptually, the ShuffleCell comprises a set of racks, ToteBot interfaces and a ShuffleBot that moves totes. The ShuffleCell operates on racks and totes but does not determine which racks or totes are assigned to it. Given a set of racks, constraints and priorities, the ShuffleCellAgent determines the specific tote moves to be made and their sequencing. From an operational perspective, avoiding deadlock conditions ([12, 13]) can be accomplished if there is always at least one empty location where totes can be placed to create opportunities for consolidation. Within this concept, the following must be determined: the number and arrangement of the racks, the ToteBot interfaces, the ShuffleBot specifications, and the operational control of the cell.

To make the concept concrete, consider a ShuffleCell configuration as shown in Figure 4. Eight racks are arranged in two rows, with space for a ShuffleBot to move between the two rows. There are locations for ToteBots that are accessible by the ShuffleBot. For this kind of configuration, the number of racks could be different from that shown. More racks would increase the chances for improving tote moves, but also might increase the dwell time of racks in the ShuffleCell.

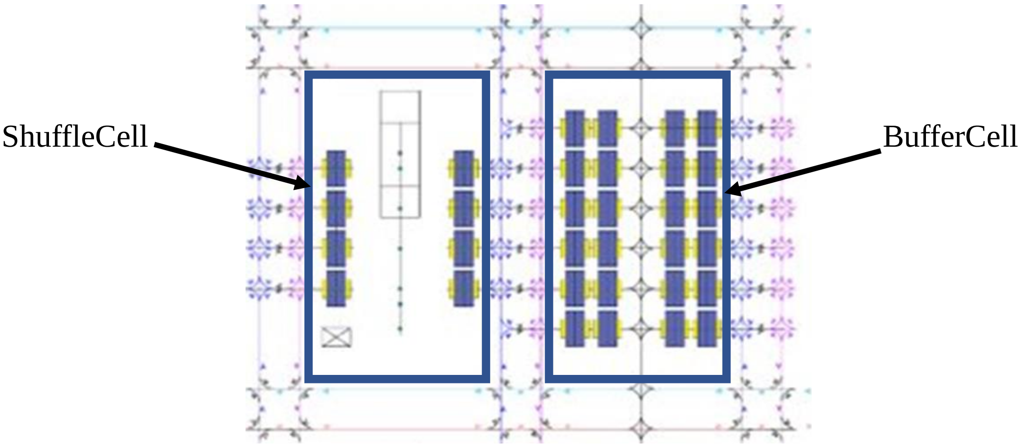


Figure 4 Example of a ShuffleCell (on the left) and BufferCell (on the right)

Conceptually, the ShuffleCell requires no “hard” physical infrastructure. The ShuffleBot is not confined to a rail and the racks do not require fixtures in the floor. Given the physical configuration illustrated in Figure 4 there are many different possible operational strategies, and the best strategy will likely depend on the nature of the arriving racks, i.e., how much consolidation already has been accomplished before the racks reach the HLH.

6 HLH Modular Design and Layout

We have designed modular components for each functional area to facilitate the overall facility design process. Figure 5 is a snapshot from a particular HLH simulation, showing the physical arrangement of the HLH. Docks are arranged around the perimeter of the building, and there is a staging area associated with each dock. The grid in the center corresponds to the *ShuffleCenter* and is configured by aisles along which the *MoveBot*s and *ToteBot*s can travel. Each space between aisles has the same footprint and can be used for either a *ShuffleCell* or a *BufferCell*. In Figure 4, the fifteen spaces on the left edge of the *ShuffleCenter* and the fifteen spaces on the right edge are used to store racks either before they first move to a *ShuffleCell* or after they have completed the consolidation process but are not yet ready to be moved to an outbound staging area.

There are thirty-five cells in the middle of the *ShuffleCenter*, of which thirty are allocated for use as *ShuffleCell*s and five for use as *BufferCell*s. *ShuffleCell*s are only active when there is a need for them, and the figure indicates that five of the potential cells are not in use when the snapshot was taken. Similarly, only two of the *BufferCell*s contained racks when the snapshot was taken.

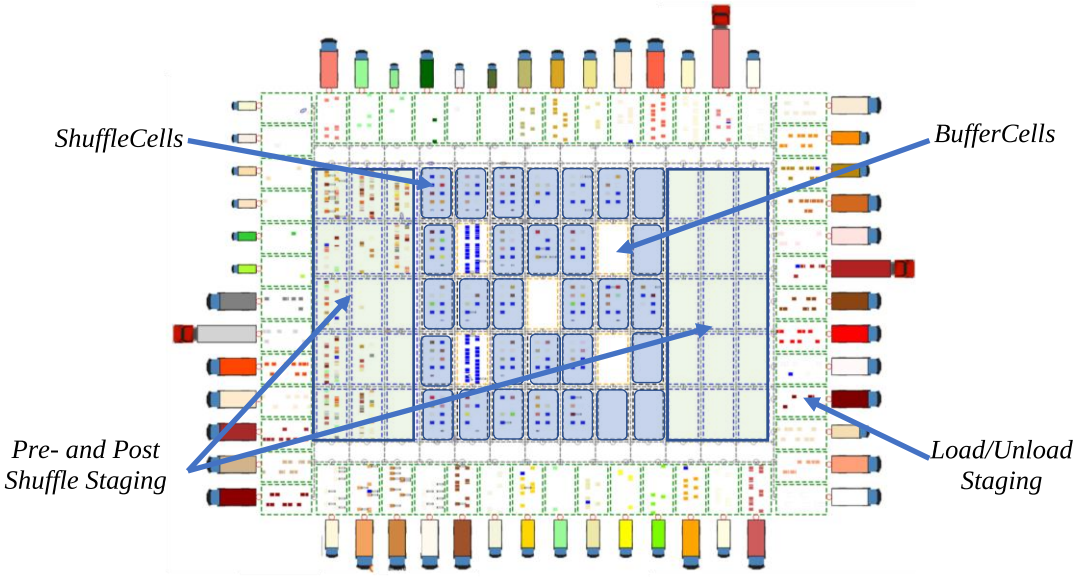


Figure 5 Simulation Snapshot for a Particular HLH Configuration

In fact, the cellular designs of the *ShuffleCell* and *BufferCell* admit a tremendous range of options with regard to the physical flow within the HLH. In Figure 5, an operational decision determines which cell location is activated “next” during the HLH operations, constrained by the predefined function (pre-shuffle buffer, in-process buffer or *ShuffleCell*). Clearly, this is not the only or even necessarily a good way to operate the HLH. For example, individual cell locations within the *ShuffleCenter* could have a predefined function, as in Figure 5, or the function of a cell location could be determined as needed. The numbers of cells of each type could be varied, as could the strategy for determining which locations to activate over the course of a day. Much more detail about the modular design is given in complementary paper [12].

7 HLH Simulation

Assessing the potential of this innovative parcel logistics concept requires a high-fidelity simulation model. Essential requirements for the simulation are the accurate representation of the operations within the *ShuffleCell*, the movements of totes and racks within the HLH, and the arrival and departure processes of trucks containing racks.

In designing the HLH simulation, three considerations were of utmost importance. First, it must be easy to modify the HLH configuration, changing the numbers of *ShuffleCell*s and *BufferCell*s and their physical arrangement. Second, it must be easy to modify the operational decision-making to accommodate experimentation with different strategies, policies and priorities. Third, it must be possible to display a visual representation of the HLH operations.

To meet the first requirement, we developed a layout specification in Excel that is processed through a Python™ script to create input to AnyLogic™ for the layout of the HLH. An example of the Excel specification is shown in Figure 6, corresponding to the simulated layout shown in Figure 5. Each cell in the spreadsheet corresponds to a standard square of defined dimension in the HLH. Cell entries indicate either a boundary of a cell or a segment of bot flow path.

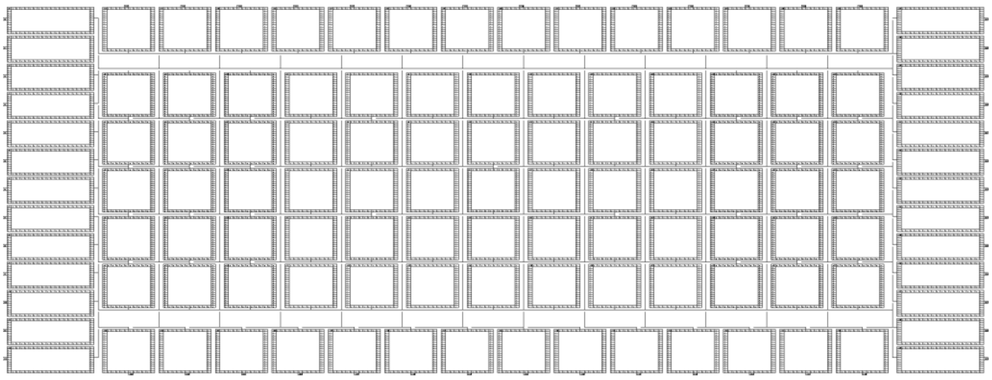
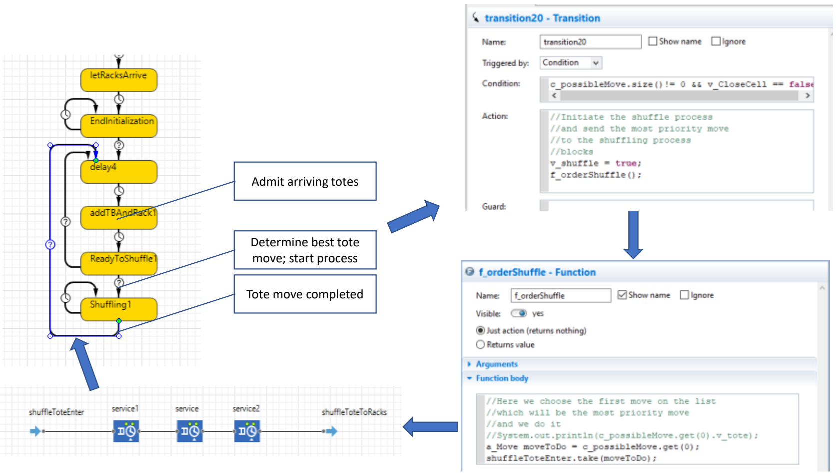


Figure 6 Example of layout specification in Excel

Our HLH simulation carefully separates modeling of the physical operations from modeling of the operational control decision making as shown in Figure 7. As discussed in much greater depth in [13], the key concept is to use state charts to model the control logic (i.e., deciding which totes or racks to move and the location to which they should be moved) and to use queues



Name: transition20 ☐ Show name ☐ Ignore

Triggered by: Condition

Condition:

```
c_possibleMove.size()!= 0 && v_CloseCell == false
```

Action:

```
//Initiate the shuffle process
//and send the most priority move
//to the shuffling process
//blocks
v_shuffle = true;
f_orderShuffle();
```

Guard:

Name: f_orderShuffle ☑ Show name ☐ Ignore

Visible: yes

● Just action (returns nothing)

○ Returns value

```
//Here we choose the first move on the list
//which will be the most priority move
//and we do it
//System.out.println(c_possibleMove.get(0).v_tote);
a_Move moveToDo = c_possibleMove.get(0);
shuffleToteEnter.take(moveToDo);
```

Figure 7 Plant-control separation in AnyLogic and servers to model the execution of physical processes, such as moving totes or transporting totes or racks between cells.

In AnyLogic™, Java-defined state chart conditions can control the transitions between states; and Java-defined actions can be executed upon entering or leaving a state. As an example, in Figure 7, the transition between states *ReadyToshuffle* and *Shuffling* occurs when the condition on the transition is satisfied by finding the best tote to move, which is done using a Java-defined function. When there is a tote to move, the condition also sends a corresponding simulation agent through the simulated "shuffle process" where the delay associated with the tote move is realized. When this simulation agent departs the service2 block, the condition is satisfied on the transition from the state *Shuffling* to the state *delay4* and the control loop repeats.

The third requirement, focused on visualization, is accomplished in two ways. First, animation shows the movement of totes in shuffle cells and the movement of racks within the *ShuffleCenter*. Figure 5 is a snapshot of the hub-level animation. Second, there are several dashboards that show real-time results from the simulated operations. Figure 8 shows part of the full dashboard, tracking the number of open *ShuffleCells* (top) and the number of racks in pre- and post-shuffle staging and in the in-process buffers.

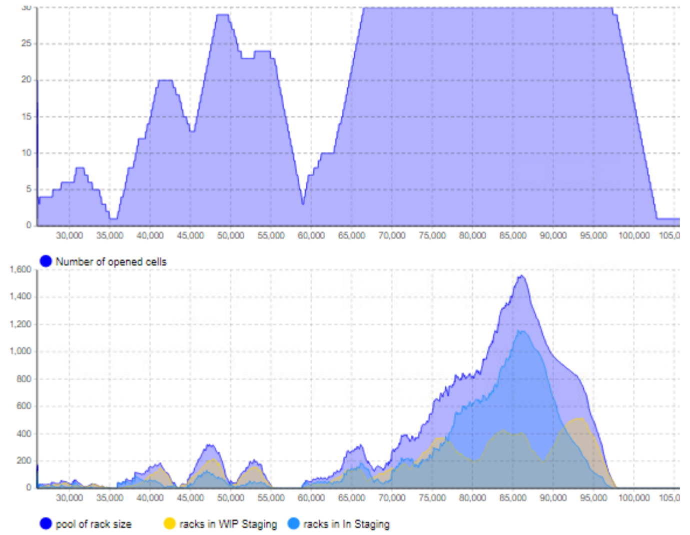


Figure 8 Dashboard Elements Showing ShuffleCells and Rack Pools

8 HLH Comparison to Conventional Hub

Our assessment starts with detailed data from an existing parcel hub, describing the arrival and departure of trucks and their parcel contents. This parcel hub handles on the order of 400,000 parcels per day. We "containerized" the parcels to convert the conventional parcel loads into corresponding loads of racks containing totes containing parcels. This resulted in approximately 72,000 totes passing through the simulated HLH per day. The baseline parcel arrival-and-departure information constitutes the performance baseline against which the simulated HLH is to be compared. In particular, the fundamental question is "Can the HLH satisfy the cutoff times for arriving parcels to be leaving the hub in a departing truck and do so efficiently?"

Our initial implementation of the *ShuffleCell* identifies racks in the cell as either "strip"—meaning the rack will only give up totes—and "stack"—meaning the rack will only receive totes. A strip rack may become empty or if not, it may return to a WIP *BufferCell*. It also may be redesignated as a stack rack if all remaining totes have the same next destination. Simulation parameters allow varying the number of strip and stack racks in the *ShuffleCells*.

Our initial experimentation is based on the HLH configuration shown in Figure 5 and reasonable parameters for the various bot operations, as well as the parcel throughput from the baseline use case. Clearly a great deal of development and experimentation remains to be done. Given that caveat, we can report that the HLH with 25 *ShuffleBots* successfully meets the parcel departure cutoffs from our benchmark parcel hub. Future papers will provide much more in-depth results from systematic experimentation of HLH performance.

9 Research Roadmap

Based on our very preliminary results, the HLH concept holds significant promise for revolutionizing parcel logistics. There are many research challenges arising from the initial proof of concept analysis and simulations. Clearly, a major category of research and development challenge is robotic technology *per se*. Given the robotic advances of the recent past, we are confident those challenges can be identified and resolved by the robotics community. Our focus in this section is on the logistics-related design and operational challenges.

Detailed design of shuffle cells. The proof-of-concept design allowed eight racks to be in a shuffle cell and assumed a specific type of shuffle robot. Overall, the best shuffle cell layout remains an open question. Moreover, the *ShuffleCell* concept as we have presented it here is only one of several, or perhaps many possible ways to employ robotics and automation to manage the destination-based consolidation of containers in HLH.

Overall consolidation strategy. In the proof-of-concept simulation, simple heuristics were used to choose racks to move into and out of shuffle cells. It seems likely that a more intelligent approach will yield better results in terms of the average time to consolidate a rack, and thus perhaps reducing the number of *ShuffleCell*s required. For example, should the shuffle cells be arranged logically into levels ranging from initial consolidation to final consolidation, where racks become more consolidated as they move through the levels? Are there other strategies that would significantly improve the time to consolidate?

Staging area design. In the proof-of-concept design, the staging area was dedicated to dock doors. It seems clear that a shared staging area approach could significantly reduce the overall staging capacity requirement, although it might impact the required number of *MoveBot*s. How to specify these capacities and how to operate the *LoadBot*s are interesting areas for investigation.

Layout. Given a shuffle cell specification, a fundamental issue is the physical arrangement of resources in the HLH, i.e., the locations of *ShuffleCells*, *StagingZones*, *BufferZones*, and dock doors. We showed only one possible configuration in the simulation results but clearly many alternatives remain unexplored. Also, we used very simple heuristics for assigning inbound/outbound trucks to docks, a decision that interacts with *ShuffleCenter* layout and operation in a very significant way to impact the total *MoveBot* travel.

Parcel de-containerization. In the proof-of-concept, boxes and totes arriving into the HLH do not have to be opened to reassign parcels to other totes or boxes, assuming adequate parcel-to-container assignment. In practice, specially at the lower-tier logistics mesh networks, there is significant probability that such sorting of some parcels into other containers may be pertinent for improving their consolidation in the next part of their journey. This requires integrating a *SortingCenter* into the HLH, potentially with *SortingCells* similar to order picking cells in goods-to-person fulfillment centers. Integrating such a *Sorting Center* has impact on the layout as well as the control of the HLH, and is a rich avenue for further research.

In summary, the HLH concept clearly is worthy of further investigation, and presents a broad range of research opportunities, both for the robotics community and for researchers focused on the strategic, tactical, and operational issues entailed in the realization of the hyperconnected logistics system and its hyperconnected logistics hubs.

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