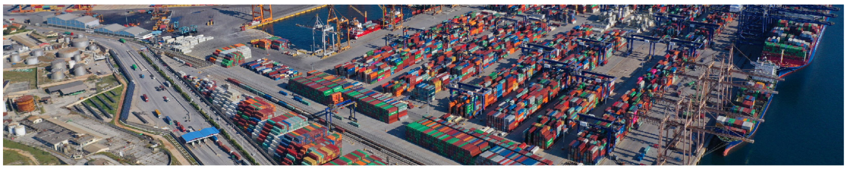

Modular and Mobile Design of Hyperconnected Parcel Logistics Hub

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Abstract: *This paper employs modularity and mobility (M^2) for designing recently introduced hyperconnected logistics hubs (HLH) for the Physical Internet, where parcels are encapsulated in modular tote-sized containers arriving in mobile racks, and these totes are consolidated by switching totes in shuffling cells to mobile racks with other totes with shared next destinations. The paper introduces the M^2 framework and its modular standard-sized cells, racks and tote containers. Building on the overall HLH concept, the proposed M^2 hub design is a major step forward with its on-the-fly transformability through operations to adapt to the dynamically changing sizes, mixes, characteristics, and flow of modular containers entering the hub and being consolidated and shipped within a short dwell time target. The paper uses a detailed case study to demonstrate the induced adaptability, adjustability, agility, efficiency, resilience, and scalability, and then it reports on an exploratory simulation experiment contrasting the performance of M^2designs.*

Keywords: *Physical Internet, Hyperconnected Logistics, Parcel Logistics Hub, Modular Hub, Adaptability, Modularity, Resilience, Scalability, Robotic Logistics, Consolidation*

1 Introduction

It is now well known that the Physical Internet induces radical transformation of logistics hubs, notably with its emphasis on universal interconnectivity; standardized modular containers enabling open flow consolidation; inter-hub logistics mesh networks; and fast, efficient, seamless, high-quality, safe, secure, resilient, and sustainable operations [1-4]. Parcel logistics hubs are particularly affected as they are to evolve from strictly performing parcel sorting and consolidation from satellite to main hub to satellite to final destination in as direct shipments as possible, toward consolidating as early as possible the parcels sharing next target hubs into modular containers, and then handling, sorting and consolidating modular containers rather than individual containers [5].

With the mesh network topology in the Physical Internet, the portfolio of active origins and destinations at each hub is greatly reduced as the main flow stems from and to nearby hubs: for example, from and to regional hubs within 4-5 hours to allow drivers to get back home everyday while the modular containers are transferred into other carriers at the hubs to keep on flowing at sustained velocity toward their next destination.

In line with [5], [6] has proposed to reimagine the design of parcel logistics hubs supporting intercity and interregional flows, such reconception affecting their physical and control architecture, and has provided such an innovative design based on shuffling, buffering, and staging cells, with minimal fixed assets and potential reliance on smart mobile robotics for supporting the moves and handlings through the hub.

This paper builds on such an innovative design, and proposes a major step forward from it by its on-the-fly transformation through operations to adapt to the dynamically changing size, mix, and characteristics of modular containers flowing through the hub and being consolidated and shipped within a short dwell time target.

We propose a new approach for designing and laying out logistics hubs that is fundamentally built upon modularity [7,8,9,10] and mobility [11,12], pushing further their application in hub design, so as to improve overall adaptability, adjustability, agility, efficiency, resilience, and scalability under high-velocity service requirements, stochastic demand and flow patterns, and streams of more or less predicatible disruptions. The resulting hubs are referred to as M^2 hubs because of their synergetic leverage of modularity and mobility.

2 Design Logic

The key M^2 concepts are to enforce a standard modular configuration of the cells and circulation spaces so that an underlying grid of potential cell locations can be defined. Because of the grid and cell modularity, and the complete mobility of all internal hub equipment (e.g., mobile robots and mobile racks), the buffer and shuffle cells can be dynamically assigned to cell locations, with the equipment smoothly moved to reflect the new assignments.

A M^2 hub is designed in response to the concept of Hyperconnected Logistics Hub (HLH) [6], including: first, consolidation of totes and racks inside standard size trailer/π-containers. As in the PI concept, π-containers designed to facilitate material handling and storage in the facilities [1], The totes and racks are designed to improve the consolidation in the trailers efficiently. At the M^2 hub, the modular cell designed for the consolidation called *DockCell*.

Consolidating the totes with the exact next destination into racks in HLH is accomplished in four operation steps, unloading the trucks, moving the racks for shuffling, shuffling totes between racks, and moving the racks for loading. *StagingCell* supports loading/unloading, *BufferCell* provides temporary rack storage during the consolidation process, and *ShuffleCell* is where actual consolidation takes place. These standard-sized cells provide adaptability and adjustability of the layouts for increasing/decreasing parcel flow through the smart design and allocation of the cells.

The third M^2 concept is robotized transportations to reduce human involvement in the process in which, the mobile robots are embedded in different cells and circulation. In our design we have been used four types of robots, *LoadBots*, *MoveBots*, *ShuffleBots* ,and *ToteBots*. Even though depicted in their robotized version, all operations done by robots in a M^2 hub can be done by humans with adequate equipment, such as lifting handling devices, and/or with human augmentation, such as augmented reality and artificial reinforcements.

2.1 Modularity of the Cells

The Hyperconnected Logistics Hub, where standard totes are sorted and consolidated by their next destination via robot-centric operations, has fewer types of working cells and thus is suitable for modularity design. An advantage of modularity is that robotic logistic hub can be designed faster via grid-based network, and the locations of working cells can be dynamically adjusted according to daily, even hourly demands. We designed the layouts as a robotic logistics hub with minimum human operation and maximum robotic technology. All the blocks have been designed in standard-sized modules for the parcels in the racks. Each rack is also designed to optimize the trucks' space in HLH. The modules design process impacts the performance of loading/unloading, shuffling, and transferring of the racks inside the facility. We hereafter describe the modular dock, shuffle, staging, and buffer cells, captioned as object-oriented *DockCell, ShuffleCell, StagingCell, and BufferCell.*

2.1.1 DockCell

In this facility, everything has been designed to be standard-sized modules ,and all the space modules are designed based on the dimensions of the racks and operational robots. The design process based on the consolidation of totes and racks started with maximizing utilization of the trucks and defining appropriate design for totes and racks for standard size trailers.

The chosen standard trailer has the dimensions of 47’7”, 9’1”, 9’8”(Figure 1). We considered the side by side orientation of the racks in the trailer relative to the door (Figure 2).

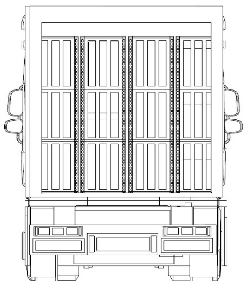


Figure 1: Side-by-Side Orientations

Figure 2: Trailer Dimensions

The design of the totes and racks starts with truck/trailer inside dimensions(47’3”, 8’3”, 9’). Considering clearances inside the truck/trailer, we determine the outside dimensions of the racks. Then we consider how the structure of the racks consumes space to determine the inside dimensions of the rack. Finally, considering clearances inside the racks, determine the actual tote dimensions (Figure 3). We are using the maximum space of the racks for the totes design, considering the ideal tote size 2x2x2 or nominal dimensions of 1x1x1.

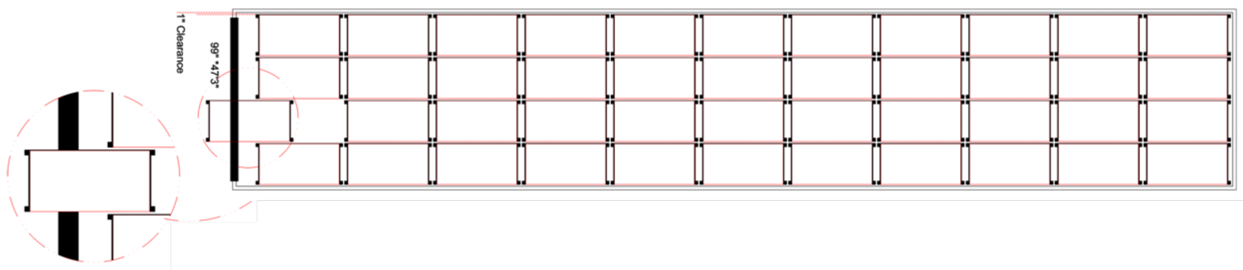


Figure 2: Rack Consolidation Inside a Trailer

The achieved racks have the dimension of 1’10-1/3”x4’x8’4-3/4” and the totes with a maximum size of 1’9”x1’9”x1’9” (Figure 4).

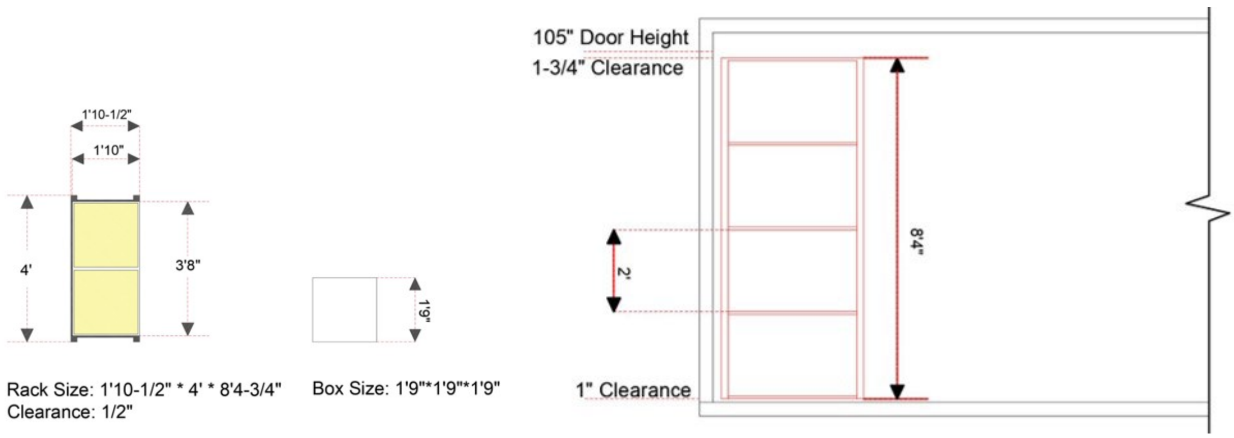


Figure 4: Dimensions of Racks and Totes

2.1.2 ShuffleCell

The shuffling process inside the HLH operates by *SuffleBot* inside the *ShuffleCell*. The process times and space requirements to move the robot arms for the shuffling are estimated through emulation using the Emul8™ software. The emulation results also indicate the optimized number of racks inside the cells. Optimized path planning for *MoveBot*, minimizing the robot's disruption in entering ,and exiting the cell and intersections are considered in all the blocks. As a result, the cell has two separate paths for *MoveBot* and is symmetrically designed to ease configuration and reconfiguration of the layout (Figure 5).

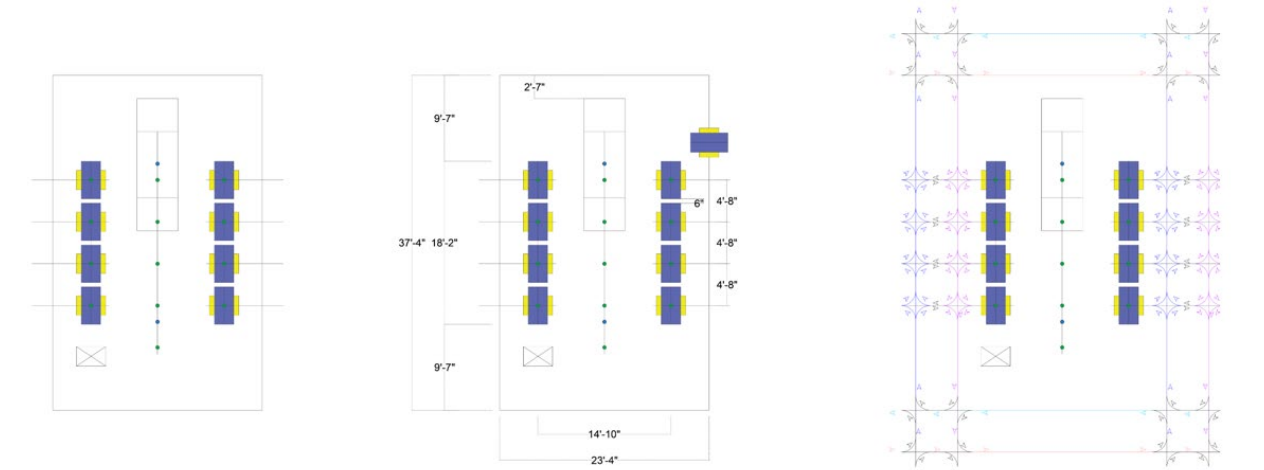


Figure 5: ShuffleCell Where Modular Containers are Shuffled from a Rack to Another

2.1.3 StagingCell

The first step to designing the *StagingCell* is the number of racks (36 racks). This number, along with the required aisle depth to move *LoadBoat* and *MoveBoat*, define the cell area. The orientation of racks inside the trucks specifies which side of the racks is grabbed by *LoadBoat* in the *StagingCell* ,and the dimension of *LoadBoat* with moving rack determines the aisle depth (Figure 6).

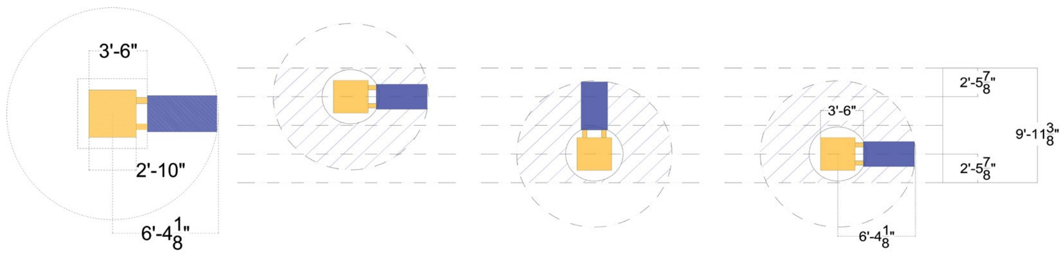


Figure 6: LoadBot and Aisle Dimensions

Figure 7 shows a standard size block for side-to-side rack orientation in the *StagingCell* with the required space for the aisle. Both *LoadBot*, and *MoveBot* uses the paths for unloading the racks and *MoveBoat* for moving the racks to the *Shuffle/BufferCells*.

2.1.4 BufferCell

The *BufferCells* are for the racks waiting to move among the *ShuffleCells*; no specific operation happens in the *BufferCells*. These cells are usually close to the *ShuffleCells* to enable efficient access. The number of these cells is also calculated by the simulation model for the operation's efficiency. *ShuffleCell*, and *BufferCell* are located in the center of HLH. They are designed to be in the same overall size with *SuffleCells* to be movable and exchangeable during the operation (Figure 8).

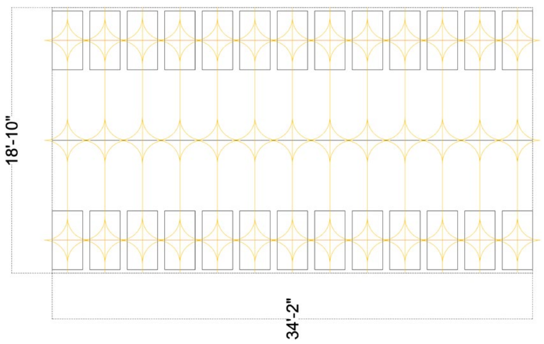


Figure 7: Modularly Dimensioned StagingCell for Mobile Racks after Truck Unloading and Before Loading

2.2 Equipment Mobility

HLH design process emphasis is on the robotic technology and the dynamics of the layouts. The detailed dimensions and behavior of the robots directly impact the design of the blocks. As it is mentioned before, the four different robots are assigned to execute the operations' tasks;

1. *LoadBots* – These robots unload/load racks from the trucks
2. *MoveBots* – These robots transport racks inside the hub between different zones.
3. *ShuffleBots* – These robots shuffle totes between racks in the *ShuffleCells.*
4. *Totebots* – These robots transport totes between the *ShuffleCells*.

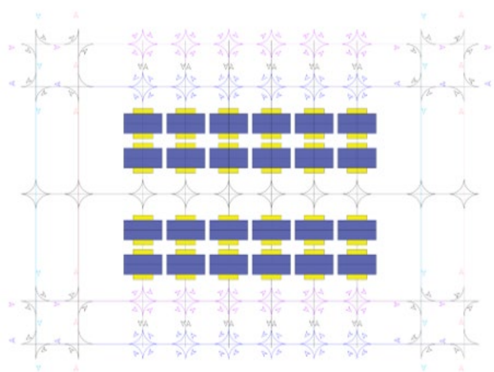


Figure 8: BufferCell

In response to the mobility of the system, the racks should be compatible with robotic technology. The mobile racks are designed with retractable legs to provide space under the rack dedicated for robotic movement. The legs open when *LoadBot* is placing the racks in the *StagingCells* to provide space for *MoveBot*. The underlying space required for *MoveBots*, path planning inside/outside the cells, and the intersections, are illustrated in Figure 9.

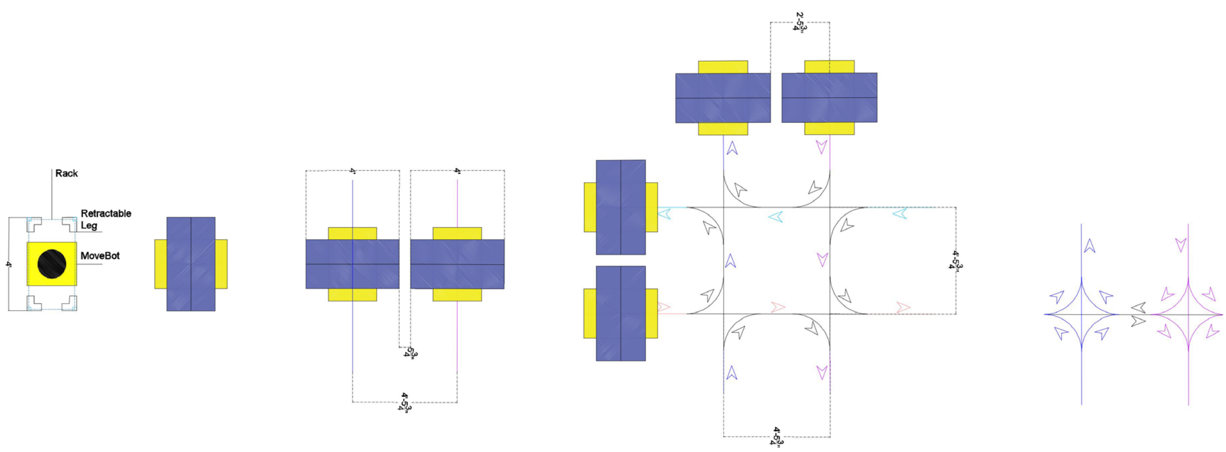


Figure 9: Standard Mobile Racks and MoveBot

Here we include some schematics highlighting some of the transformative impacts. The M^2 hub works exclusively with modular handling containers of tote and box sizes, where the totes can be handled by a human in his/her arms while the boxes are bigger than most pallet or cage sizes. Modular totes are stored and carried in mobile racks as done in goods-to-person systems such as those of Kiva and GreyOrange. Figure 10 depicts mobile racks being loaded in a truck, emphasizing the nice spatial fit of the racks into the trucks.

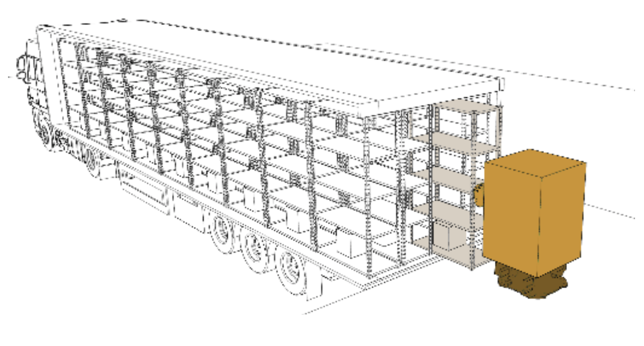


Figure 10: Loading/Unloading of the Racks-DockCell

Figure 11 shows *MoveBots* moving the mobile racks inside the *BufferCells*, it is worth noting that cells are implemented symmetrically and designed to minimize the *MoveBot* disruption considering the clearance between two loaded robots move side-by-side.

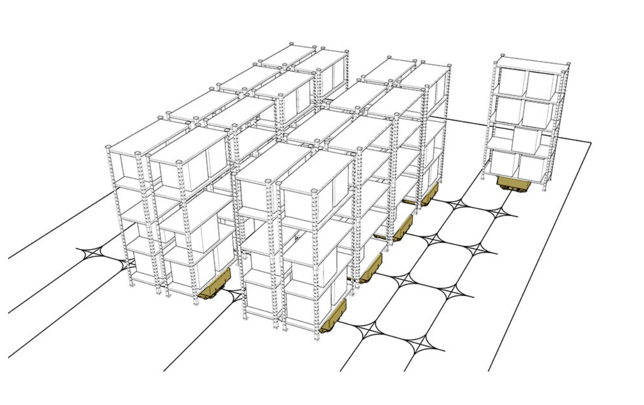


Figure 11: BufferCell with MoveBots

Figure 12 illustrates a *ShuffleBot* in a shuffling cell where totes are moved from their current mobile rack into one where totes sharing the same target next destinations and similar departure times. All constituents of shuffling cells are mobile, and the cells are themselves configured so as to fit within the modular space grid.

Figure 1**3** illustrates a *StagingCell*, where mobile racks are parked after having been unloaded from a truck while waiting for starting processing in *ShuffleCells*. Such cells are dimensioned to fit the modular space grid. Buffer cells have similar functions, yet for accomodating mobile racks between their processing in successive shuffling cells as pertinent.

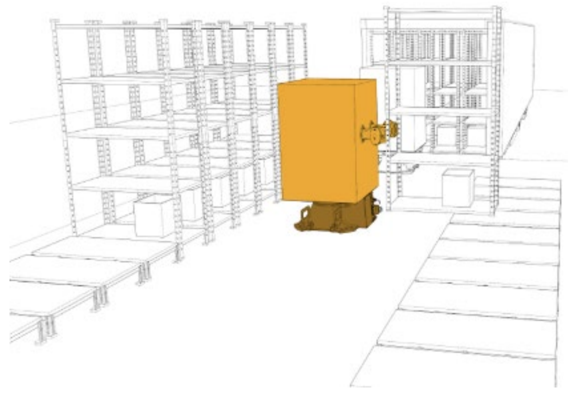


Figure 13: StagingCell for Mobile Racks after Truck Unloading and Before Truck Loading

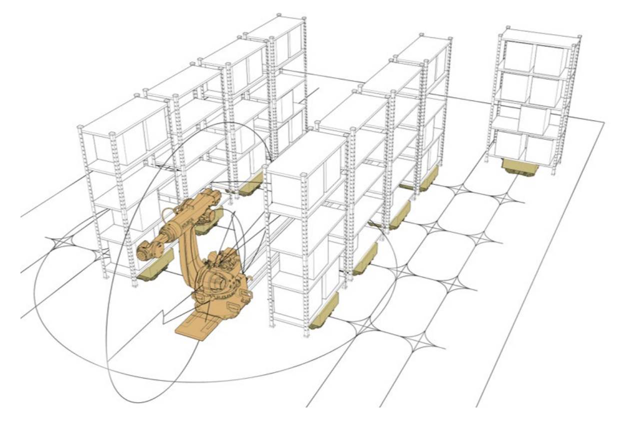


Figure 12: ShuffleBot in ShuffleCell Another

3 Layout Design

The standard size cells design eventually affects the allocation and the overall layout performance. Figure 14 provides a M^2 hub snapshot, emphasizing the spatial modularity of both the cells and the flow paths (strictly virtual, as all moving entities are not bounded by physical tracks). The cells voluntarily look similar, as they have been designed to be modular, yet each one has a specific mandate for a given time window, then are deactivated or moved to another grid module as pertinent to optimize workflow patterns.

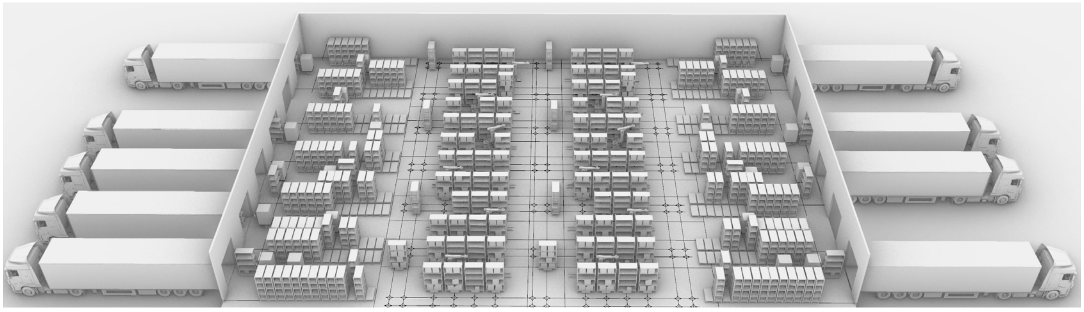


Figure 14: Hub Layout Based on a Modular Space Grid Depicting a Current Deployment of Shuffle, Buffer, and Staging Cells

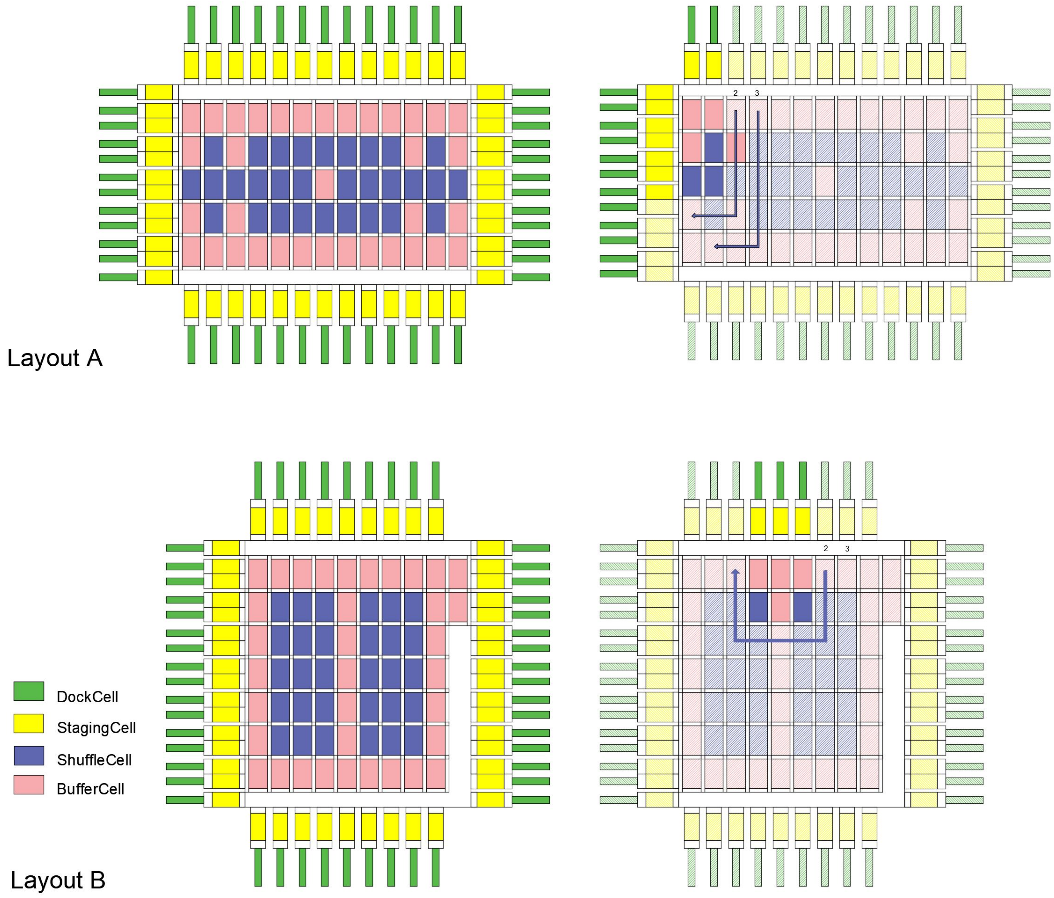


Figure 15: HLH Layouts Depicted with Dynamic Variations of Activated and Disactivated Cells

4 Simulation Experiment

This paper leverages a discrete-event simulation model in AnyLogic™ to assess the potentials results achievable by mobile and modular cell design. The experiment subjects the HLH hub to an average daily demand of 430,701 parcels encapsulated in 71,227 totes loaded on 9350 mobile racks arriving in 622 trucks and departing in 953 trucks. The parcels in a tote share the same target departure time from the hub and at least the next destination hub. In the experiment, the service requirements are such that totes have a maximum dwell time ranging from 2 to 4 hours in the hub. Demand is varying extensively through the day, with a ratio of 18.02-to-1 between maximum and minimum hourly rates, with a large peak toward the end of the day. The HLH hub is expected to meet this demand, accounting for the totes' max dwell times, with a service level of 100%.

The exploratory experiment constrats two alternative scenarios corresponding to distinct HLH hub designs, each considering that cells can be activated and disactivated dynamicall through a day. As shown in Figure 15, layout A is more elongated and puts the buffer cells mostly on the contours while layout layout B is more square and spreads more the buffer cells. This said, both layouts have the same number of activable cells: 50 StagingCells, 30 ShuffleCells, 35 BufferCells. Here, both designs impose a fixed location for each cell, a constraint that will be relaxed in further research. The designs can exploit a maximum of 250 MoveBots, 100 LoadBots, 30 ShuffleBots, and 24 ToteBots. Average speeds are 4 m/s for *MoveBots*, 30 s to move per rack for *LoadBots*, 4 s to take per tote and 5s to trasfer per tote for *ShuffleBots*, and *4 m/s* for *ToteBots*.

In this short paper, we provide empirical simulation-based evidence with key performance indicators (KPIs) on the significant performance gains enabled by M2 hub design.

The results shown in the section correspond to the calibrated version of each design, capable of meeting the service level requirements, while minimizing resource utilization (cells and robots). So KPIs are defined and measured to compare resource efficiency and utilization.

MoveBots population of 250	LayoutA	Layout B
Movement time (Minuts)	148887.4	130390.9

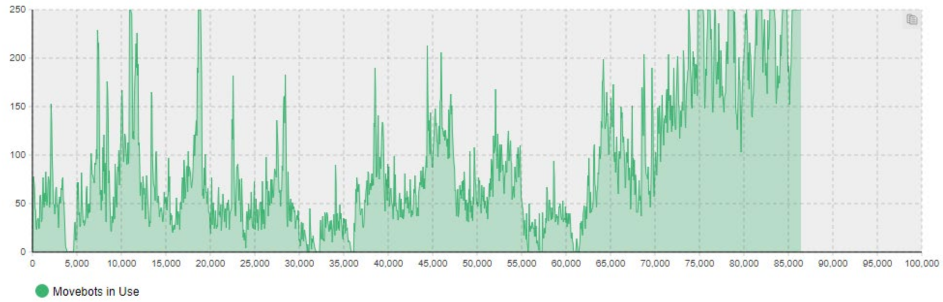
Table 1: Contrasting Robotic Utilization

The first three KPIs are the daily robotic movement time, distance travelled, and utilization rate, computed for MoveBots, LoadBots, ShuffleBots, and ToteBots, with results summarized in Table 1. Overall, layout B outperforms layout A.

The fourth KPI is the number of robots and cells of each type concurrently used in the hub. Figure 16 plots this KPI for both designs over a day, focused on the number of *MoveBots* concurrently used to transport racks throughout the hub. Design A induces two boulders of *MoveBot* transport early and mid day, which design B succeeds to avoid, smoothing more the load of *MoveBots* with less 200-250 peaks through the day. Figure 17 similarly plots the number of *ShuffleCells* concurrently in use over time. It exhibits the same induced two-boulder creation in design A, again smoothed out in in design B. Overall, this contributed to design B having better resource utilization than design A, even though both leverage the full available capacity in the latter part of the day.

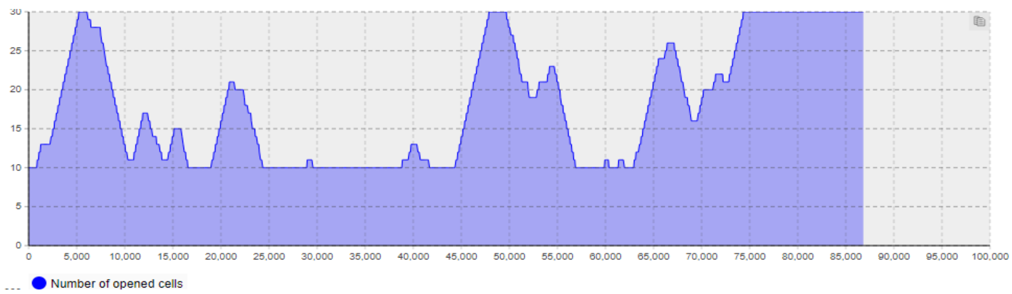
As discussed in Montreuil et al. (2021), the hub piloting architecture and algorithms also have impact on such performance, so future research is needed, challenged to further reduce these peaks while satisfying service level targets, notably exploiting the specific hub organization and layout, smart dis-activation of cells to minimize inter-cell flows.

Layout A

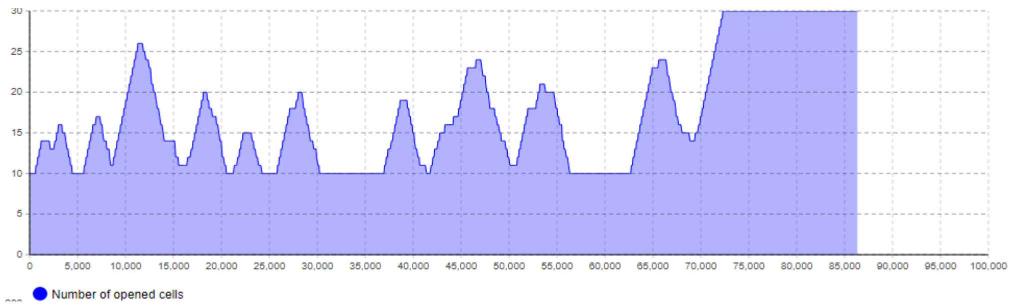


Layout B

Figure 16: Contrasting Movebot Utilization Over a Day



Layout A



Layout B

Figure 17: Contrasting ShuffleCell Utilization Over a Day

5 Conclusion and Future Design

In this paper, we have focused on introducing the modular and mobile (M^2) design of hyperconnected parcel logistics hubs that have been introduced in Montreuil et al. (2021) for the Physical Internet. We have provided an explicit fine-granularity design of such a hub, explaining and visually demonstrating each type of cells, as well as the types of robots used in its fully robotized version. We have put the emphasis on highlighting the modularity and the induced functionalities and capabilities. Given the space constraints of such a short paper, we have selected to provide empirical simulation results that contrasts two alternative designs of M^2 hubs, showing that (1) in the given instance, both succeed to satisfactorily achieve high service performance at 100% with short maximum dwell times at hubs, while doing so in a compact overall space and limited number of cells and robots; and (2) the designs differ in terms of resource utilization, with better peroformance by the design distributing more the cells to leverage the dynamic dis-activation of modular cells so as to minimize flows.

Avenues for further research include broadening the scope of performance criteria and KPIs and shaping more extensive simulation based investigation of M^2 hub capabilities and performance. This requires on one side to develop adequate decision architecture and algorithms so as, for example, better smooth utilization to minimize peaks, smartly decide on dynamic tote and rack assignment to cells, smartly decide on dynamic cell dis-activation, smartly move bots and racks to allow dynamic reconfiguration of the cells throughout the hub. It requires on the other side to extend the simulation modeling capabilities and experiment design to investigate deeper alternative M2 hub configurations and contrasting them with hubs not leveraging hyperconnectivity, modularity and mobility.

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