Unleashing the Potential of Digital Twin-Enhanced Cellular Hyper Hubs

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Abstract

Parcel logistics hubs play a crucial role in aggregating and distributing packages, requiring significant capital and labor investments, primarily determined by conveyor infrastructure. Recently, the HyperHub concept has emerged, employing PI-Boxes and racks for parcel consolidation and transport. HyperHub functions as a cross-dock, transferring PI-Boxes between inbound and outbound trucks. However, challenges persist in developing a practical, cost-effective, and risk-free implementation methodology for HyperHub, despite advancements in its conceptualization, design, and execution system. To address this challenge, the authors present a comprehensive methodology for designing and developing a HyperHub based on the concept of digital twin (DT) in the early stages of the design process. A digital replica of the system is used in the early stages of design to create a physical layout and test the control system in a risk- and cost-effective environment. This is accomplished by integrating a model-based system into the digital copy of the real system. Firstly, we propose a concept of a generic digital twin cellular logistic hub (DT-CLH) methodology for the HyperHub, inspired by the cellular manufacturing (CM) and cellular warehousing (CW) concepts. Secondly, we formulate and define a cellular logistic hub (CLH), considering the objective of minimizing total movement.

Keywords: *Physical Internet, Hyper Hub, Logistic hub, Parcel logistics, Digital twin and Cellular manufacturing*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan:* ☒ *PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories),* ☐ *Transportation Equipment,* ☐ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Vertical Supply Consolidation,* ☐ *Horizontal Supply Chain Alignment,* ☐ *Logistics/Commercial Data Platform,* ☐ *Access and Adoption,* ☐ *Governance.*

Targeted Delivery Mode-s*:* ☐ *Paper,* ☐ *Poster,* ☐ *Flash Video,* ☐ *In-Person presentation*

1 Introduction

In recent years parcel logistics has been strongly impacted by globalization and the pandemic, which has resulted in increased global competition. This logistics competition has acted as a driving force for utilizing modern technologies, systems, and paradigms that have better capabilities to help enterprises increase their agility and responsiveness to meet end-user expectations regarding service levels and costs [1]. In this respect, the Physical Internet (PI) has been formulated as a new paradigm for improving economic, social, and environmental [2]. The PI is defined as an open global logistics system founded on physical, digital, and operational interconnectivity, through encapsulation, interfaces, and protocols. PI is not something on the cloud or just on the server, but rather a structure made of physical objects: parcels, containers, hubs, routes, trucks, and robots are just some of the elements that make PI concept-based parcel logistics possible.

Most recently for parcel logistics purposes, a multi-hub parcel logistic web underprint of PI concept is proposed with interconnecting meshed transportation networks along four different hubs[3, 4]. Zero-point hub; linking original destination customer locations and pickup-and-delivery points. e.g., household, office, factory, and parking. First-point hub is the access point hub. It facilitates the direct transfer of parcels between sources and destinations in nearby zones. The second-point hub is an inter-area network that consolidates parcels to the PI containers or tote. Third-point hub or gateway hub is the main interface between areas of a megacity. In this paper, our main aim is to design and develop the HyperHub that could support the gateway hub responsibility. HyperHub uses modular containers or totes to consolidate parcels and racks to consolidate containers for transport.

The idea of HyperHub is expressed in most recent publications, including [5, 6] underprint of PI concepts that motivate this work. The consolidation of parcels into modular containers is discussed in [7, 8]. An originating hub will consolidate all parcels with the same destination into one or more modular totes then totes are consolidated into racks for transport in standard trucks or semi-trailers to HyperHub. Besides a network of logistics hubs, as suggested in [3, 9, 10]. The trucks from the originating hub connect to a HyperHub that is part of this network. At each HyperHub, 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 the next hub. 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. At each HyperHub, some totes may be removed from a rack, because their next destination is different from the rack's next destination, and some totes may be added. It is possible that a rack in a HyperHub is stripped of totes and stored temporarily because it is not needed at the moment to transport totes, and all the totes it contains can be accommodated by other racks. The last essential concept robotic transport of both racks and totes within the HyperHub, thus dramatically reducing the service time and number of humans involved in the HyperHub operations, in line with robotic mobile fulfillment systems. 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.

Despite the contributions of existing works in terms of conceptualization, design, and the execution system of HyperHub, there remains a challenge in achieving a practical, cost-effective, and risk-free design and implementation methodology for HyperHub. It is obvious that design and implementation of HyperHub for the real industrial applications require risky, careful decisions to ensure that the system and technology will successfully satisfy the demands of an ever-changing market. The behavior of a HyperHub is not deterministic. Yet the direct experimental testing of it with the physical system/control environment being involved is not only extremely expensive, but non-realistic as well. Hence, the companies need methods and tools for modeling and emulation of such complicated systems in a quick, cost-effective, error and risk-free way with complete physical configuration and human in loop perspective [17].

An important question that follows from research in this area is, given that HyperHub system is dynamic, robotized and human friendly in nature, how to define and validate the most appropriate physical layout and execution architecture for any given HyperHub without really implementing it into the operations? This decision corresponds to defining ways of implementation and the level of integration within the system through digital twin tool. Researchers evolved several specific simulation methods in the literature for modelling and simulation of complex systems for industrial applications. However, conventional simulations approaches and tools support users in understanding the process characteristic but often suffer from limitations in the detailed analysis necessary for accurate system adoption and in capturing visual details of implementation []. In addition, most existing tools after evaluation cannot be used for implementation of real system for example the code with used to simulate control robotic system cannot adapted to real system which are considered for simulation respect [18, 19]. The digital twin can be considered as a solution for such problems, as the user and the information support elements are put in direct relation with the operation of the system in a virtual physical environment to provide a sense of reality and an impression of 'being there', which is considerably effective in representing the activities. Using a digital twin of the physical system to perform real-time execution, scheduling, and optimization. The breakthrough is achieved from three aspects: 1) Calculation time has gone from hours to minutes, which has made it possible to explore the solution space searching for the global optimum; 2) Increased use of sensors and on-line measuring equipment [11] are making it possible to reuse simulation models during both pre-production and production phases, now with real context data rather than estimated or historical data as input [12]. This will allow for adjustment of machine settings for the work-in-process in line based on simulations in the virtual world before the physical changeover, reducing machine setup times and increasing quality.3)Testing and implementing different types of configuration as well as automation in order to full feel the factory layout problems such as the confusion of logistics, overlong distance and accumulation of WIP and the low utilization rate of tooling due to the unreasonable material distribution route and the low accuracy of material distribution.

In this paper, a methodology that uses a digital twin-based cellular logistic hub (DT-CLH) for modeling and implementing a HyperHub in the early stage of design has been proposed to test and evaluate the proposed execution architecture and physical systems in the natural practical industry environment. This work is motivated by the need for HyperHub that are able to adapt to internal and external disturbances. In this system, new robotic human friendly systems can easily be added or removed, and different demands can be met by re-configuring the system.

2 Overall methodology

The conceptual methodology of DT-CLH is shown in Figure 1. It consists of three main subsystems: system design, real world and cellular logistic hub. Each subsystem is described as follow:

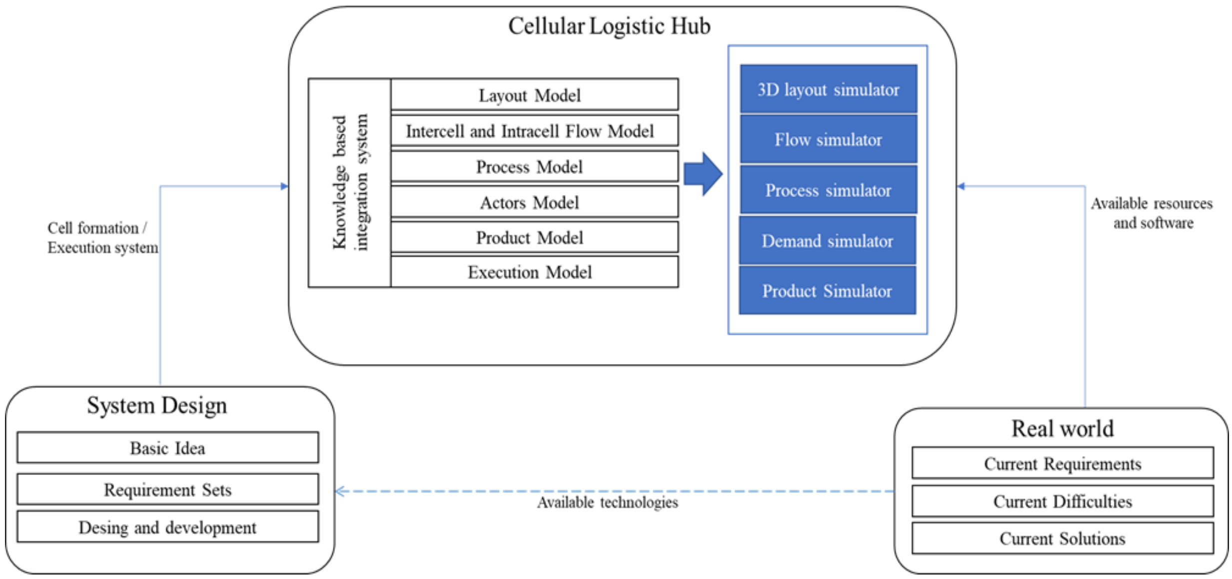


Figure 1 Conceptual architecture of DT- CLW

2.1 Real world

The real world (RW) encompasses three primary dimensions: firstly, the existing technological landscape and solutions; secondly, the prevailing challenges, difficulties, and issues that act as motivating factors prompting individuals to seek resolutions; and thirdly, a broad overview of current solutions or strategies employed to address these problems. In terms of 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 of fixed automation which are not reconfigurable and agile, therefore currently most of the hub suffering from low utilization through the day. This happened because the whole hub could be active as a full system for a couple of hours to fulfill the high demand in the system. Therefore, most of the days and time they are not active. HyperHub would be able to answer this problem by employing CM and CW approaches. The RM responsible to provide existing resources and physical requirements of the HyperHub by examining current technologies, for example which types of robotics manipulator could be best solution to handle the shuffling process or what are the best cell definition as well as intracell and intercell operations. Therefore, RM contains two main sections;(1) primary physical cell definition section, this section is responsible for defining types of cells, intercell and intracell paths as well as layout perspective of cells, in order to provide reconfigurability and agility between cells and system. (2) Resource definition section, it is responsible to provide physical requirement and capabilities of resources which would be possible to use in the cells. The main components of the resource definition section are divided into two parts: hardware/worker specifications and software specifications. Hardware specifications comprise machines, robots, and the material handling system. Software specifications consist of computational models, low-level control software, data gathering software, etc. Figure 2 illustrates the main concept behind the RW subsystem in the DT-CLH. The output of the resource definition is divided into two categories based on the level of automation: first, the pool of available resources and technologies for fully robotized and automated cells, and second, the pool of available resources and technologies considering human in the loop for cell operation which is highly align with industry5.0 concept [13].

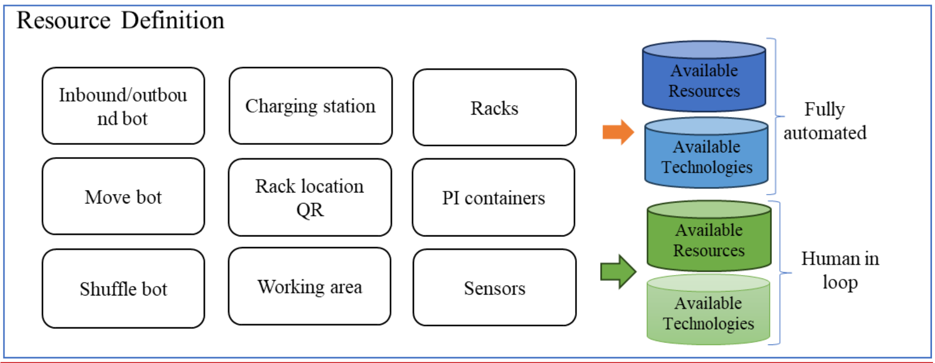


Figure 2 Real world of Hyper Hub modeling

Consequently, RW yields a reservoir of available resources, software, system capabilities, and requirements. These resources are subsequently disseminated to other subsystems, thereby contributing essential elements to the system design, and cellular logistic hub.

2.2 System design

System design mainly deals with design and development of whole system. The systematic process of system design encompasses three key phases: Basic Idea, Requirement sets, Design and development phase. In adherence to recognized standards, particularly the ISA95 standard, our approach to the design and development of the HyperHub [14] is guided, ensuring a rigorous and industry-accepted methodology. Each phase is defined as follows.

2.2.1 Basic idea is formulating the possible solution to deal with problems which are highlighted by RW. For example, what are the best bots to use in the HyperHub or what is the best and most practical cell layout and intracell flow algorithm to minimize total movement in the system. This phase is responsible for providing basic ideas and definitions for the next phase regarding existing technologies and possible existing solutions based on the CM and CW. Figure 3 shows the possible basic idea for formulation of HyperHub. It highlights the types of cells and first step to formulized cell definition.

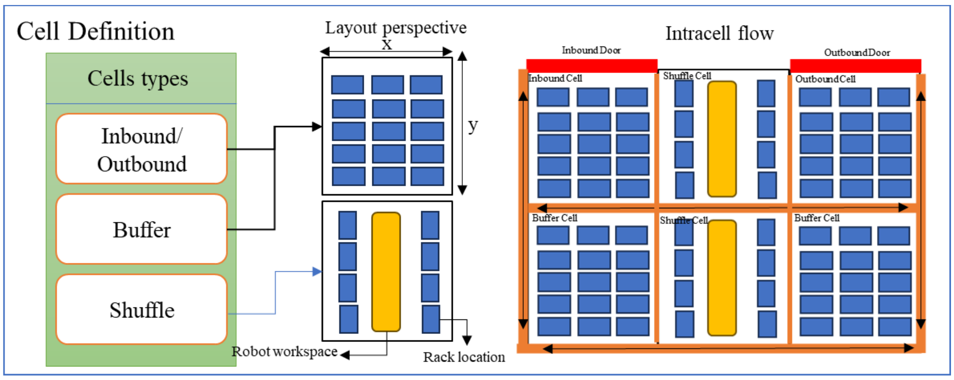


Figure 3 Basic cell definition of HyperHub

2.2.2 The requirement sets receive the output of the basic idea and RW and provides the set of the requirements of each resource, cells, and possible execution system. It is the conditions that a proposed requirements for a solution or applications must meet to solve the problem. Both scenarios based modeling and behavioral modeling are applied in order to extract the requirements of the cells in the HypreHub[6]. The main goal of the requirements set is to decompose the system in order to identify the initial problem domain, and solution domain. Figure 4 shows our method for capturing requirement sets.

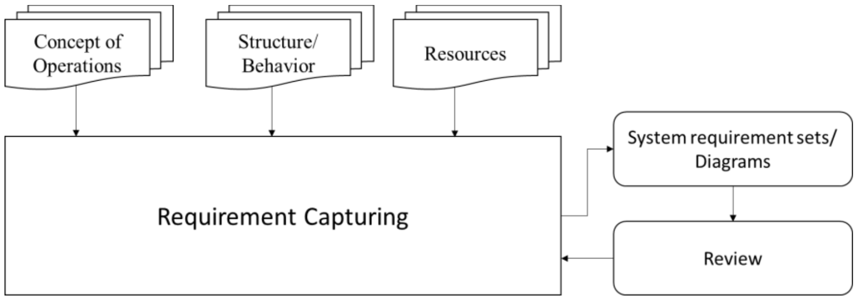


Figure 4 Steps in capture requirements

The cells in the HyperHub consist of structure and resources that act together to produce behaviors, or observable transformations. The cells and resources have their own behavioral capabilities which are invoked by execution system at the level of the cells and HyperHub. Such as resource for movement of racks (move bots or pallet jack), shuffling of PI-Boxes (shuffle bots or human) and loading or unloading rack to trailer (inbound bots or forklift). The resources may themselves contain sub resources, which will have their own structure, behavior and low-level control unites. Physical layout cells structures are also part of structure and behavior of Hyperhub. The structure and behavior of each operation with associate resources and physical layout of cells is to make sure that PI-Boxes from inbound racks are transferred to outbound racks, and the outbound racks loaded into the outbound trucks whose destination is the same as the truck's destination. System behavior and structure are based on the HyperHub main concept, which enables the system to be highly flexible in terms of agility and reconfiguration to handle different disturbances, such as demand disturbances. Figure 5 SysML requirement diagram of HyperHub based on the three main types of cells and its operation, physical layout and execution system.

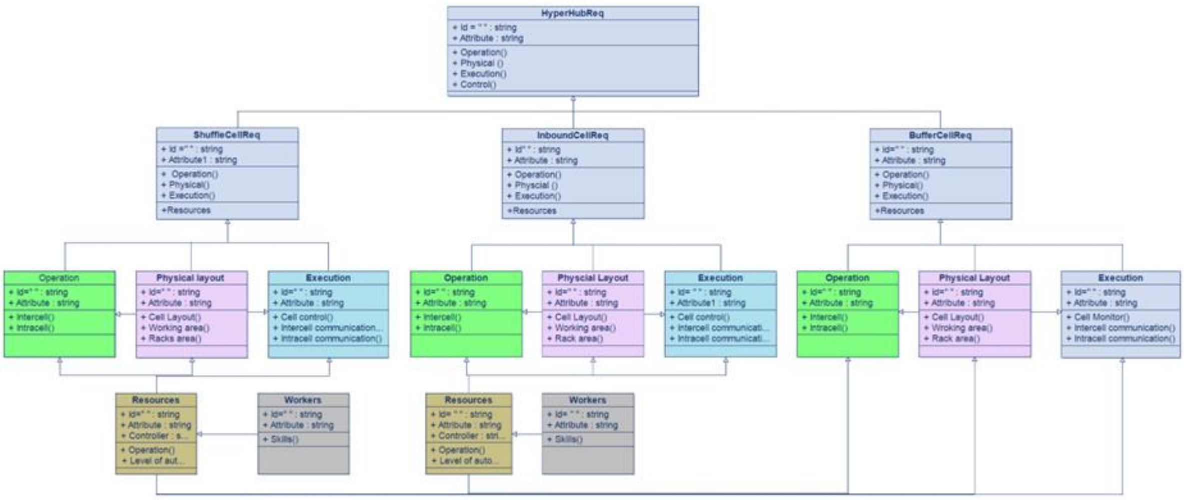


Figure 5 High level example of SysML requirement diagram for HyperHub

The HyperHub employs both active and passive resources and they are also clustered based on fully automated and human in loop perspective. The passive resources are the various PI-containers that are processed in the HyperHub. The three relevant concrete container types are the transport container, the rack, and the PI-box(tote), which are kinds of container and thus inherit all the properties of container.

2.2.3 Desing and development phase

The output of the requirement sets, encompassing both system and subsystem functionalities of the HyperHub, are inputted into the design and development phase. This process emphasizes the operational, structural, and behavioral characteristics of the HyperHub. A crucial aspect of the design and development phase is to furnish an abstract representation of the system's resources, activities, and decisions. To achieve this objective, we adhered to the ISA95 standard in designing the execution system for the HyperHub. This standard is divided into three main levels. In this context, Figure 6 illustrates the proposed architecture of execution system, which is aligned with the standard.

Level 1 encompasses physical resources such as robot and cell structures and pertains to the perception layer, or the types of sensors utilized in each resource. Level 2 addresses supervisory control or the types of internal controllers for each resource. Lastly, level 3 denotes the location of the execution system, which is responsible for executing tasks within the HyperHub. This architecture gives us a level of agents. The HyperHubs's execution system has three main agents with its operations and relations. Namely Hub controller agent, shuffle cell controller agent and inbound/ outbound controller agent. Both the inbound and outbound cells have a StagingZone where racks may be located after unloading or before loading. The activity and decision diagram of execution system is shown in Figure 7 and illustrates the flows between the three cells of operation as well as within the cells. There are three levels of decisions that exist in the HyperHub, hub level, shuffle center level and inbound/outbound level. The main decisions of HyperHub execution system highlighted at decision diagram based on the racks point of view. There are three levels of operational execution & control level, Figure 6 shows this level in the details.

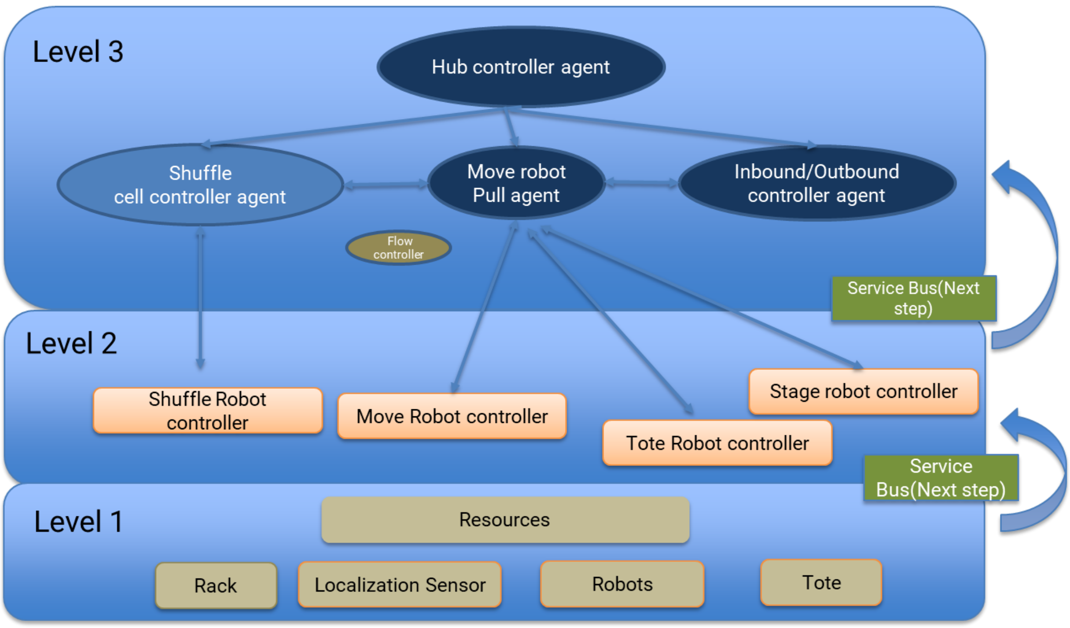


Figure 6 The proposed architecture of HyperHub's execution system

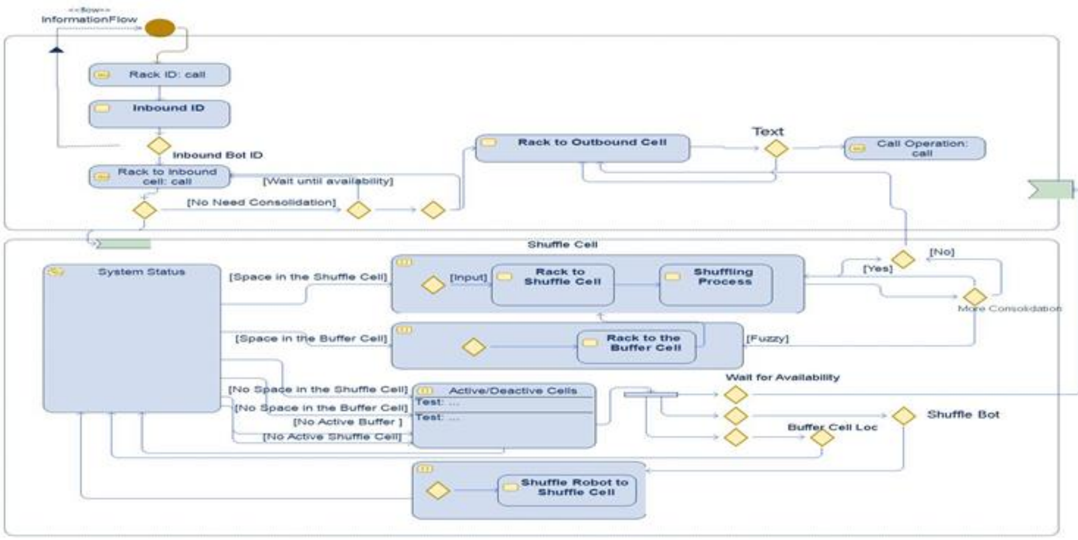


Figure 7 Activity and decision diagram of HyperHub's execution system

3 Cellular logistics hub

CLH receives knowledge and information from real-world and system design sections in order to create control systems and a digital model with its functionality and integration platform, key factors in the design and implementation of desired HyperHub goals. CLH consists of two main sections: the first section focuses on information integration to form cells and allocate resources, establishing direct or indirect relations between cells. This relationship, based on organized information, serves as the foundation for cell formation, moving to the next step of integrating modules together to run the system as a whole unit. Figure 8 shows the information and data integration framework with key modules that belong to CLH, namely, Layout Planning, Material Flow, Actors or Resources, Product, Control System, and Data Modules. All of these are integrated with each other through knowledge-based system integration to act as a union.

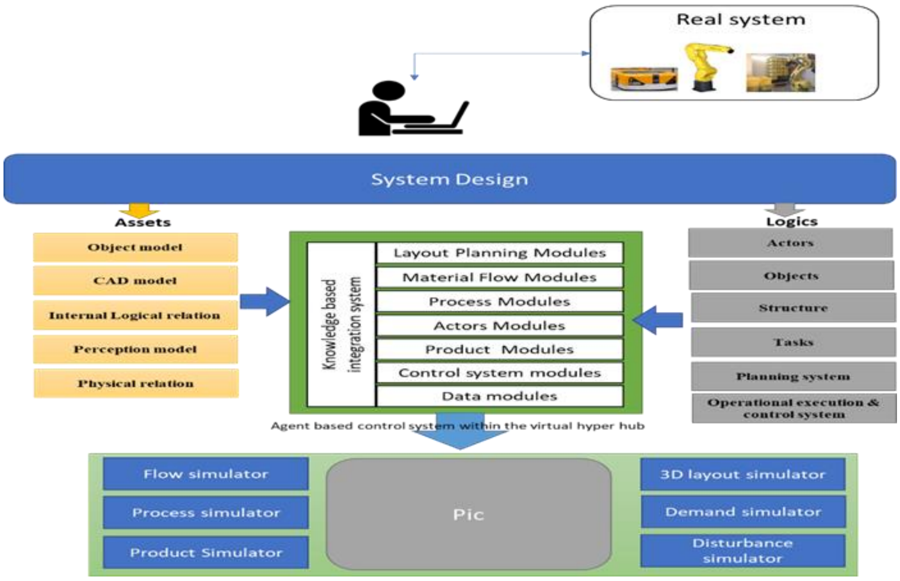


Figure 8 Framework for cellular logistics hub

The CLH was conceptualized as a virtual representation of a real factory, depicted through an integrated simulation model that encompasses the factory and its subsystems. In this regard, Table 1 illustrates the resources required at HyperHub.

Table 1 Resources in HyperHub

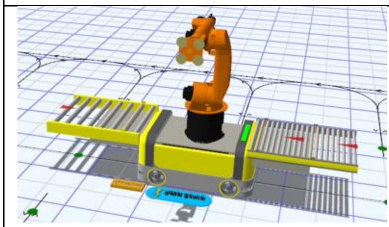
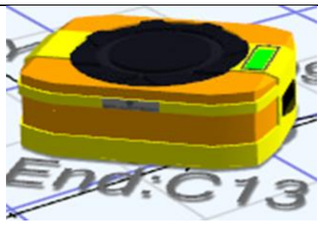
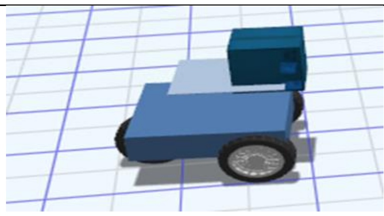
Shuffle Bot	Move Bot	Tote Bot
		
• Acceleration: 6.56 ft/s^2 • Declaration: 13.1 ft/s^2 Speed: 190 ft/min • Tote Capacity: 4 • Manipulator: Kuka600	• Speed: 196.8 ft/min • Declaration: 13.12 ft/s^2 • Acceleration: 6.5 ft/s^2 • Rack Capacity: 1	• Acceleration: 6.5617 ft/s^2 • Deceleration: 6.5617 ft/s^2 • MaxSpeed: 195 ft/min • Tote Capacity: 1
• Avoid Collision: True • Front Offset: 2 mm • Distance per charge: 60 km	• Avoid Collision: True • Front Offset: 2 cm • Front Sensor Range: 2 cm • Distance per charge: 100 km	• Avoid Collision: True • Front Offset: 1 cm • Front Sensor Range: 1 cm • Distance per charge:200 km

Figure 9 illustrates the implemented HyperHub through the proposed methodology. It comprises five shuffle cells, four buffer cells, and four inbound or outbound cells. While the cells are fixed, the system can add or remove new cells to the HyperHub with minimal changes in the control system, based on demand. Unity3D platform used as main platform for CLH and C# programming language was used for implementing proposed control system and functionality of subsystems.

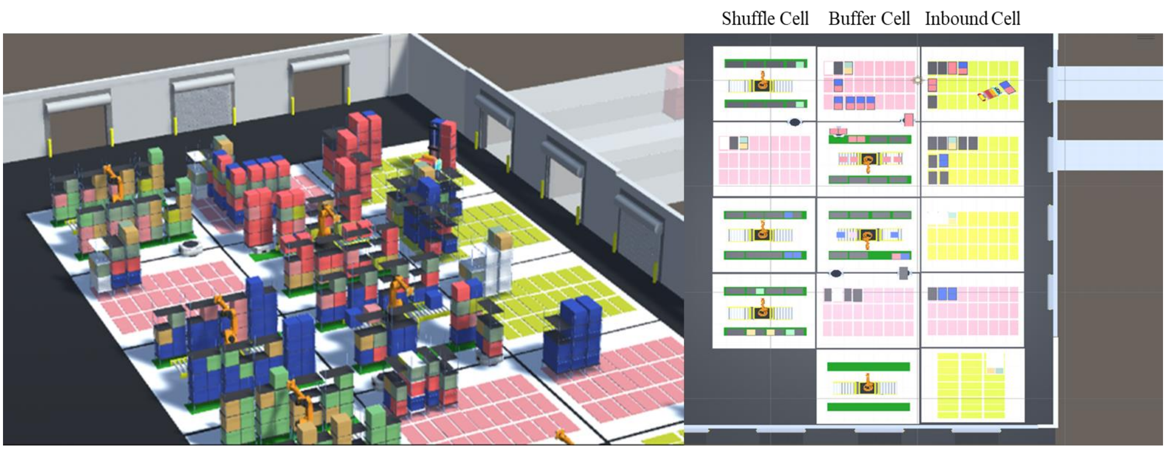


Figure 9 Developed HyperHub

Conclusion

A methodology based on digital twin for implementation of the HyperHub for early stage of design for parcel logistics has been presented in this paper. The digital twin cellular logistic hub concept has been introduced, which integrates real world and system design modelling into a virtual cell definition in order to realize the HyperHub within a system modeling environment. The DT-CLH concept introduced in this research serves to illustrate the use of digital twin to interface with existing modeling approach. Although each cellular logistic hub has been designed specifically for ISA95 standard and unity platforms, the methods presented here could be applied in general to other digital twin and multi-agent software development platforms.

The methodology outlined in this paper offers several contributions. It provides a systematic approach to HyperHub design and development, encompassing system design, real-world considerations, and cellular logistics hub components. Through the integration of digital twin technology, the proposed methodology enables adaptability to internal and external disturbances, allowing for the addition or removal of robotic systems and meeting diverse demands through system reconfiguration.

Furthermore, the paper introduces a conceptual architecture for DT-CLH, emphasizing system design phases such as basic idea formulation, requirement sets, and design and development. The DT-CLH framework integrates information from the real world to define cell structures, resource capabilities, and execution systems, facilitating a holistic approach to HyperHub implementation.

In conclusion, this paper lays the foundation for a robust methodology leveraging digital twin technology for the design and implementation of HyperHub in parcel logistics. While the presented approach is tailored to specific platforms and standards, its principles can be adapted to other digital twin and multi-agent software development environments, offering potential applications beyond the scope of this study.

References

- Barenji, A.V., et al., Intelligent E-commerce logistics platform using hybrid agent based approach. Transportation Research Part E: Logistics and Transportation Review, 2019. 126: p. 15-31.
- Montreuil, B., *Toward a Physical Internet: meeting the global logistics sustainability grand challenge.* Logistics Research, 2011. **3**: p. 71-87.
- Montreuil, B., et al., *Urban parcel logistics hub and network design: The impact of modularity and hyperconnectivity*. 2018.
- Montreuil, B., R.D. Meller, and E. Ballot, *Physical internet foundations*, in *Service orientation in holonic and multi agent manufacturing and robotics*. 2013, Springer. p. 151-166.
- Benoit Montreuil, L.M., Shannon Buckley, Sevda Babalou, Wencang Bao, and Ali Beranji, *Framework and Research Roadmap for a Next-Generation Hyperconnected Logistics Hub*, in *8th International Physical Internet Conference*, A.-t.E.T.P. ALICE, Editor. 2021, ALICE - the European Technology Platform ALICE: Paris,. p. 15-21.
- McGinnis, L., S. Buckley, and A.V. Barenji. *Designing and implementing operational controllers for a robotic tote consolidation cell simulation*. in *2021 Winter Simulation Conference (WSC)*. 2021. IEEE.
- Sallez, Y., et al., *On the activeness of intelligent Physical Internet containers.* Computers in Industry, 2016. **81**: p. 96-104.
- Treiblmaier, H., et al., *The physical internet as a new supply chain paradigm: a systematic literature review and a comprehensive framework.* The International Journal of Logistics Management, 2020. **31**(2): p. 239-287.
- Ballot, E., B. Montreuil, and Z.G. Zacharia, *Physical Internet: First results and next challenges*. 2021, Wiley Online Library. p. 101-107.
- Tran-Dang, H. and D.-S. Kim, *An information framework for internet of things services in physical internet.* IEEE Access, 2018. **6**: p. 43967-43977.
- Dias, J., et al., *Introducing the next-generation operating model.* Washington, DC: McKinsey & Company, 2017.
- Yildiz, E., C. Møller, and A. Bilberg, *Conceptual foundations and extension of digital twin-based virtual factory to virtual enterprise.* The International Journal of Advanced Manufacturing Technology, 2022: p. 1-17.
- Vatankhah Barenji, A., et al., *A digital twin-driven approach towards smart manufacturing: reduced energy consumption for a robotic cell.* International Journal of Computer Integrated Manufacturing, 2021. **34**(7-8): p. 844-859.
- Scholten, B., *The road to integration: A guide to applying the ISA-95 standard in manufacturing*. 2007: Isa.