Digital Twin Design Requirements for Durable Goods Distribution in Physical Internet

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Abstract: *Today the practice for distributing large products manufactured at few original equipment manufacturers (OEMs) consists of a dedicated Point-to-Point (PtP) logistics system, typically requiring long haul transport from the factory to the wholesale destination. A growing problem is the shortage of commercial drivers willing to be away from home for several days to move products cross-country. Hub relay network logistics systems are an alternative solution to P2P logistics systems that allow reducing drivers' away-from-home times. Operating a relay-based logistics system requires accounting for multiple interrelated operational decisions that become more complicated as the system becomes larger and encompasses more players. To deal with such complexity we propose utilizing a digital twin of the distribution and logistics system as a decision-making support tool to manage the system and make operational decisions efficiently. This paper explores the design and assessment of a hyperconnected relay network of transport hubs supporting the movement of durable goods from factory to wholesale destinations. It describes requirements and challenges in developing and implementing a digital twin for such systems.*

Conference Topic(s): *From Logistics Networks to Physical Internet Network, Developing the System of Logistics Networks towards the Physical Internet, Interconnected freight transport, logistics and supply networks, Systems and technologies for interconnected Logistics, PI Fundamentals and Constituents, PI Modelling and Simulation, Distributed Intelligence in Physical Internet*

Keywords: *Digital Twins, Physical Internet, Logistics System Design, Hub Relay Network*

1 Introduction

While parcel logistics has gained wide visibility and importance during the 2020-2021 pandemic, there is another logistics system of great importance that remains largely invisible to the public. Durable goods–appliances, computers, televisions, automobiles, and similar large products–are produced at a few original equipment manufacturers (OEMs) and distributed to many retail outlets, sometimes directly, sometimes through a local or regional warehouse. Today the practice is for each OEM to have a dedicated Point-to-Point (P2P) logistics system, typically requiring long haul transport from the factory to the wholesale destination or a set of nearby such destinations. In addition to long-haul transports, carriers often must break the backhaul routes to multiple legs to reduce deadheads, imposing an extended away-from-home period to drivers. A growing problem is the shortage of commercial drivers willing to be away from home for days or weeks to move products cross-country. Multiple studies, such as Hu et al. (2019), show the long driving distance causes several mental and physical issues for drivers, and is the primary culprit for high driver turnover in the trucking industry.

Hub relay network logistics systems are an alternative solution to P2P logistics systems that allow reducing drivers' away-from-home times. A hub relay network consists of multiple relay hubs where the truckloads are relayed. This includes the change of drivers, tractors, trailers, and/or loads. Smart placement of relay hubs can significantly reduce the drivers' away-from-home times while maintaining satisfactory service levels and minimizing costs and environmental impact. Hakimi et al. (2015) showed the conceptual feasibility of relay-based transportation in which drivers return home every day or after two days. Designing and implementing such a logistics system requires making several complex and interrelated design and operational decisions (Campos et al., 2021). From the design standpoint, a primary decision is designing the network of hubs. This includes finding the optimal number of hubs, their locations and capacities, while considering potential travel distances and flow between hubs, and available fleets of domiciled drivers and trucks in each region (Vergara and Root, 2013; Kewcharoenwong and Üster, 2017; Hu et al., 2019).

For illustration purposes, let us analyze a logistics system with some OEMs that need to deliver products to various retailers. If we think about a national or regional network, the retailers may be hundreds or even thousands of miles away from the OEM's, requiring long haul to distribute the goods. The point-to-point (P2P) logistics system for this example is depicted in simplified form in the left side of Figure 1.

Let us now assume that in order to address the shortage of commercial drivers we aim to implement a Physical Internet enabled hyperconnected relay logistics network which is illustrated in the right side of Figure 1. With this network we intend to allow the drivers to return rapidly to their domicile, avoid the high turnover of drivers in the trucking industry, and reduce the adverse effects of long haul on truckers' health. This network has additional hubs between the OEMs and the retailers, which we will call transit hubs, for enabling consolidation, transshipment, and crossdocking of goods. This network can be used by a single company or can be open to many companies which produce similar products, as the example shown in which the last OEM corresponds to a facility of a second company. Furthermore, the OEMs and retailers can be used as transit hubs as well depending on the context.

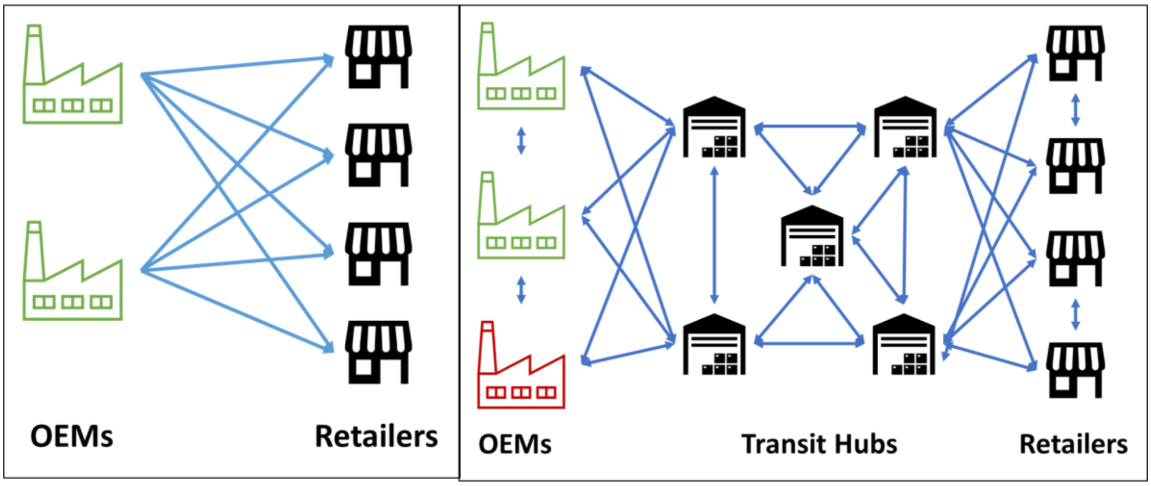

Figure 1. Long haul network vs. PI enabled hyperconnected relay network

While the hub relay network design focuses mainly on static optimization models, the operations of this system require accounting for multiple interrelated operational decisions in a system whose state changes dynamically by endogenous and exogenous factors. The decisions on how to route products in the network and when to dispatch vehicles need to be made on a daily or even hourly. This decisions are based on the status of the system and the availability of the resources, which dynamically change by exogenous factors such as traffic, weather, and breakdowns. Hence, the operating system should be equipped with proactive decision capabilities and contingency plans to react appropriately to any supply disruption and prevent propagating it to the entire system.

Moreover, relaying drivers, tractors, or trailers requires a high level of synchronization between planning and operational decisions for such resources. The system operation becomes more complicated when the logistics system is open to multiple carriers and OEMs, which offers more opportunities for flow consolidation and deadhead trip reduction but requires accounting for potential conflicts of interest between different players. To deal with such complexity, we propose utilizing a digital twin of the distribution and logistics system as a decision-making support tool to manage the system and make operational decisions efficiently.

Adapted from the works of Glaessgen and Stargel (2012), and Marmolejo et al. (2020a), a digital twin can be defined as a computational representation of a physical system that has real-time interaction with the latest state of the physical system and has analytics and simulation capabilities aimed to provide visibility, feedback and insights to be used in the decision-making process of the system, forming an improvement cycle. In logistics systems applications, the digital twin enables monitoring and scenario assessment and planning. As a real-time decision support tool, the digital twin should run faster than the real system; thus, the efficiency of the embedded algorithms is crucial.

Designing such a digital system is a complex challenge which requires considering various aspects and parameters, as shown in section 5. It also requires efficient use of available technologies such as Internet-of-Things (IoT) and sensors for efficient physical-digital communication. There have been several studies on the implementation of digital twins for logistics systems, particularly in manufacturing, warehousing, and inventory management, such as Agalianos et al., 2020; Kritzinger et al., 2018; Marmolejo, 2020b.

Nevertheless, there has not been an adequate study on the proper implementation of a digital twin of logistics systems that is connected to real-time data and used for real-time decision making. This is beyond using an offline simulation model for scenario testing. Furthermore, there are companies offering commercial digital twin software and implementations, such as Microsoft Azure, O9 Solutions, GE, Moicon, Siemens and Honeywell. These efforts together will boost the spread of digital twins in systems' assessment and improvement.

Building a digital twin for a system requires an objective definition of the system's elements and interactions. For this purpose, the domain, and conceptual models, which are often used interchangeably in system modeling, should be defined, and implemented as tool-agnostic models, meaning they should enable the complete modeling and assessment of the system without targeting a specific methodology or tool (Thiers and McGinnis, 2011). In this paper, we will make a distinction between the two. The models should be clear enough to enable building analytical, optimization, and simulation models alike with the use of any software.

This paper explores the requirements for a digital twin supporting operational control of a hyperconnected physical internet-enabled relay network of transport hubs supporting the movement of durable goods from factory to wholesale destinations. Stakeholders in this new approach include the OEMs whose product must be distributed, the retailers who want product available to sell, the carriers who require profitability through sufficient utilization of their transport resources, and the drivers who want to be fairly compensated and desire fewer days away from home. We propose developing the digital twin of such a system for efficient management of its components. We will describe the requirements and challenges in developing and implementing digital twins of logistics systems.

2 Design of physical internet-enabled hyperconnected relay logistics systems

The Physical Internet (PI) concept was first described by Montreuil (2011) as an innovative logistics system meant to tackle the global logistics grand challenge toward improvement in efficiency and sustainability. It has been defined as "an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols" (Ballot et al., 2013).

Designing a digital twin for a Physical Internet-inspired hub relay network requires inclusion of various operational decision-making tools. Campos et al. (2021) propose a toolkit for configuring and assessing physical internet enabled logistics systems. Some of the most important tools for enabling the digital twin are: Demand scenario generation, logistics zone clustering, hub network design, service network design, logistics hubs configuration, flow routing, containerization, consolidation, system description, and simulation. These tools are interrelated, forming a feedback optimization loop towards generating better overall performance.

Regarding the simulation, Kaboudvand et al. (2021) presents a simulator of a large scale hyperconnected urban parcel delivery logistics system, which could potentially turn into a digital twin due to the level of detail modeled. Similarly, Kim et al. (2021) presents the decisions and system architecture for hyperconnected urban logistics in the context of large items. Both these models are offline discrete-event simulation models of physical internet enabled hyperconnected logistics systems. These models are run beforehand for assessing different designs and operational decision making towards improving systems' performance.

Nevertheless, digital twins of physical internet enabled hyperconnected logistics systems are often difficult to implement due to the lack of capabilities of organizations to use real time decision making. Furthermore, offline policies and algorithms might not perform well under all circumstances and should be implemented based on the current state of the system, reducing with this the medium and long term of uncertainty in the system modeled.

There are three options to operate the system. The first options is that the drivers are swapped at the transit hubs, meaning they just exchange trucks going in opposite directions at each hub. The second option is that each driver keeps the tractor for the backhaul, but the semi-trailers are swapped at the hubs. The last option is that each driver keeps his/her own tractor and semi-trailer, and the products are transferred between trailers at the hub. Given the size of the products, the last option might be inefficient as the cargo can take a long time to be loaded and unloaded. Nevertheless, whenever vehicles and facilities are PI enabled, a fast unload/load process between trucks becomes feasible.

The advantage of the first option is that the swapping time is the fastest, requiring minimum time to swap trucks and reducing the handling cost. The downside is that if the drivers own the trucks, the truck swap will be hard to implement. The second option has the advantage of allowing each driver keeping its own tractor, but imposes additional handling for enabling the trailer swap, furthermore, the compatibility truck-trailer can also be a limiting factor. The last option allow the drivers to stay with both their tractor and trailer. Nevertheless, it imposes additional loading and unloading time and cost, while also risking the integrity of the products in the handling process.

If there are hard constraints on the ownership of tractors and trailers, the third option might seem the best fit, but it will require handling equipment in each hub, and additional time and resources, making the implementation more expensive than the other two options. Depending on the product, this option might be a good fit if there is a way to do the product reshuffling at the hubs fast, safe, and reliable, which could be the case for PI enabled vehicles and facilities. If the drivers own the trucks but not the trailers, the second option might seem the best. Similarly, if there is feasibility to implement the truck swapping, option one might be the best fit.

In any case, to operate options one and two there are hard problems to be solved, notably the planning and scheduling of vehicles and drivers. This scheduling requires synchronization to avoid nonvalue added times at the hubs, meaning drivers and trucks going in opposite directions should arrive to a hub during a short time window. For option three, facilities would need bigger space for storage and handling, meaning having both warehousing and crossdocking roles, needing additional resources which also need to be scheduled.

As mentioned, the operational decisions regarding this system are very complex. The main decisions to be made to design and operate such system are the location, size and capabilities of the hubs, the truck routing, the product routing, and the driver scheduling. This paper will not discuss methodologies for making these decisions. Instead, we will analyze how to assess this type of system through discrete event simulation, and how to use the simulation as a digital twin for implementing the solution in a real context.

Discrete event and agent-based simulation models can be used as an initial step towards achieving a digital twin of a system. If modelled with enough detail, the offline simulation model can be used for assessing the systems' design and operations, as well as become a digital twin when connected to live data. The use of a simulation-based digital twins enables combining the assessment of systems' design with an implementable operational real-time decision-making tool. In any case, the first step towards analyzing a system is to properly describe it, which will be addressed in the following section.

3 Domain and conceptual models

The models to be used for accurately describing the system are the domain and conceptual models. In this paper we differentiate the two, each having a particular structure and objective. These models are meant to allow stakeholders to intervene in the improvement process. As this field progresses, a standardized formal language for describing logistics systems should be implemented. Such a language should allow representing specific domains, providing a rich set of fundamental abstractions, and allowing easy computations (Thiers and McGinnis, 2011). Although using a unified language is not necessary, it is encouraged for enabling tool agnostic standardized system modelling methodologies.

3.1.1 Domain model

A good domain model, in essence, creates a *language* for discussing instances in the domain. If the domain is plant-to-customer delivery of durable goods, the domain model defines the semantics and syntax for describing any instance of such a delivery system, involving any number of plants, customers, and carriers. To do so, it must incorporate definitions for those aspects of the system that are of interest to the three main stakeholders: the OEMs (shippers), the carriers, and the system itself. Both *structure* and *behavior* must be adequately defined.

Structure refers to the observable elements of the system, their properties, and inter-relationships. What is shipped is a key element of *structure*. From the shipper's perspective a *shipment* is a set of *unitsOfHandling* (each with specific properties), with properties that include: *shipmentID*, *customer*, *tenderedDate*, *pickupDate*, *serviceLevel*, and *deliveryDate*. From the carrier's perspective, this *shipment* may be associated with one or more *transportTask*s, whose properties include the *shipment* properties but add properties such as *driverID*, *tractorID*, *trailerID*, etc. Note that *driverID* identifies a particular *driver* with properties like *domicile*, *schedule*, etc. Each resource type will have an associated set of properties. A hub relay network will require definitions for *hub* and *route*, or the ability to travel directly between two hubs. The domain model must describe these and all the other relevant components of a hub relay network.

Behavior has two key elements. The observable actions of resources like drivers and rigs are examples of resource behavior. Often this behavior can be described in a domain model using activity networks. The largely not-observable decision-making processes also are behaviors that must be captured in the domain model. State machines have proven to be one useful approach to capturing decision-making behavior. The domain model must incorporate all the generic behaviors relevant to the decisions to be supported.

Figure 2 illustrates an example of a refrigerator manufacturer that distributes its products to retailers through a relay network. Such figures would be part of the domain model defining the overall movement of flow through facilities and the system elements.

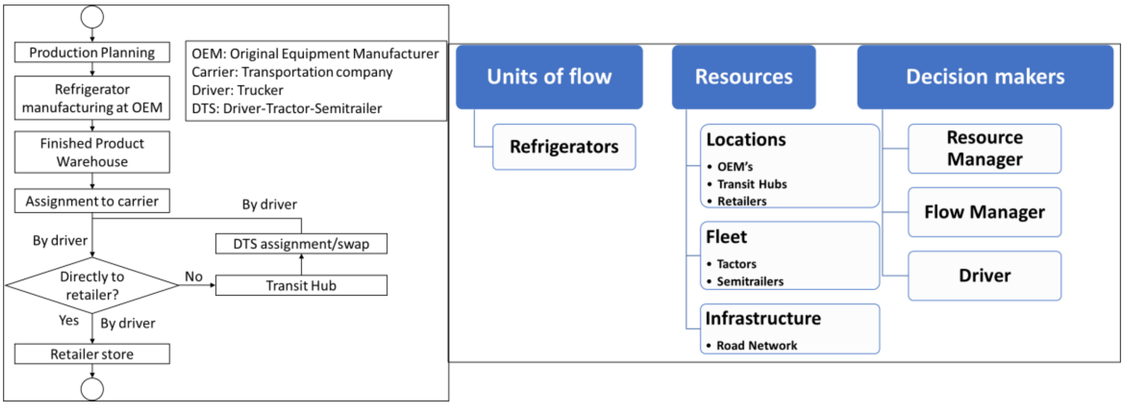

Figure 2. Domain model illustration of a refrigerator manufacturing relay network distribution

3.1.2 Conceptual model

Design and operational decision making for a hub relay network may be supported by a variety of analysis methods, from simple queuing analyses to simulation, and spreadsheets to math programming. For large scale and complicated systems like hub relay networks, it is critical that all these analyses reflect the same understanding of the system. One way to approach this challenge is through a conceptual, analysis-agnostic model, using the semantics and syntax defined in the domain model.

Each resource type defined in the domain model has a set of instances in the conceptual model. For example, the definition of *hub* from the domain model is used to identify the set of potential hubs in a proposed hub relay network, each with its own property values. The definition of *shipment* is used to create a database of shipments, both those completed, those in process and those not yet tendered. To be fully useful, the conceptual model must provide all the information needed to populate any specific analysis model that will be used to support decision-making.

The conceptual model will offer a more specific definition of the system elements and interactions, building on the domain model to describe the movement of flow in the system, the decision-making architecture, the interaction between stakeholders, resources and units of flow, and all other necessary concepts that will enable reproducing the systems' operation in a digital environment. Particularly, for the digital twins this model should also include the concepts regarding the interaction between the digital and physical systems. Figure 3 shows the flow manager decision making logic. Notice the connection between the digital and physical models is explicitly included. These types of figures would be part of the conceptual model.

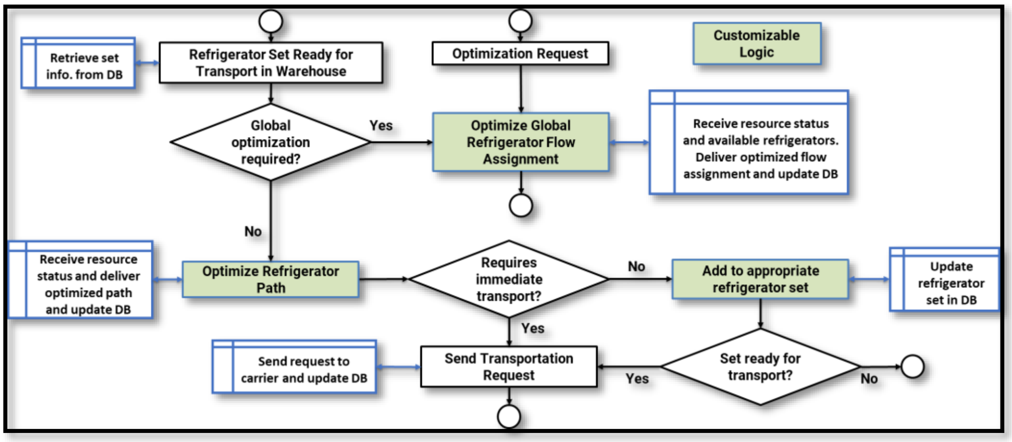

Figure 3. Flow manager decision making process.

Having these two types of models is of great help to communicate with stakeholders and guide the modeling that follows. However, in practice many times modelers skip this step, jumping directly to model the system. This practice is not recommended, as makes it hard to collaborate and allow other modelers to continue building on the existing model, especially when the original modeler is absent. Also, without domain and conceptual models it is hard for stakeholders to interact in the design process and make sure the digital model accurately represents the physical model.

4 Cyber-physical systems (CPS)

Cyber physical systems are multidimensional and multifaceted systems that integrate the virtual world and the physical world. Through the integration and collaboration of computing, communication, and networking, CPS deliver real-time sensing, feedback, control, and other services (Vatankah Barenji et al., 2020a). With intensive connection and feedback loops, physical and computing processes are highly resilient. In this way, cyber–physical integration and real-time interaction are achieved to monitor and control physical world in a reliable, safe, collaborative, robust, and efficient way. Digital twin is a paradigm for realizing the interaction and integration between the physical world and the virtual world, which has attracted full attention from the relevant academic circles and enterprises (Vatankah Barenji et al., 2020b).

Furthermore, digital twins are related to CPSs, creating a high-fidelity virtual model of the physical world, simulating objects behaviors in the real world, and providing feedback (Vatankah Barenji et al., 2020b). A digital twin is a cyber-physical system, but not all cyber-physical systems are digital twins. The concept of CPS considers the digital-physical interaction for implementing any process, which can be an isolated part of a system. The difference with digital twins lies in the fact that digital twins are digital representations of complete and well-defined systems. As the literature on CPS is also extensive, these two concepts should be analyzed together towards having a more comprehensive understanding of the implementation of digital twins.

5 Digital twins of logistics systems

One of the first challenges towards implementing a digital twin is defining the level of abstraction at which the digital system is going to represent the physical system, which is not always obvious (Singh et al., 2019). A proper system description (conceptual model) and collaboration of modelers with stakeholders will help tackle this challenge. The objective is to build the simplest version of a conceptual model which accurately represents all relevant aspects of the physical system.

After this, there are various operational decisions to be made before simulating this type of system. Some of the main models required are, the demand generation, the logistics zones clustering, hub network design, service network design, configuring logistics hubs, product routing, consolidation, and containerization. These decisions are complex in nature, and there are different exact and heuristics models to solve them. For more information about such algorithms and their interactions, see Campos et al., 2021.

For the physical internet-enabled hyperconnected relay logistics systems, there are additional challenges as mentioned in section 2. Notably, the synchronization required for both drivers and trucks imposes additional complexity to the service network design, consolidation, and product routing. This problem can be tackled using global optimization models which use heuristic algorithms to find good solutions daily. Other proposal is to find shipping protocols such as implementing chain type shipments per origin and destination with constant takt time. Other idea is trying to implement a live control tower where all vehicles are tracked, for increasing or reducing the vehicle velocity for improving the synchronization. On the simulation side, the use of global optimization models might make the run time big as the instance gets bigger, thus, dynamic protocol or algorithmic approaches are recommended if the instance gets big.

After defining the scope of the digital twin, the next big challenge is to implement the use of IoT, sensors and automation. The information from these sources needs to be compiled in a database, which needs to be updated live and must be accessible by the digital twin. The implementation of such technology can be costly and complex. There is a broad implementation of ERP systems for managing integrated processes inside companies. Some examples of areas that can be managed by such systems are the inventory, manufacturing, supply chain, dispatches, finance, etc. Nevertheless, problems have been reported with the use of ERP systems regarding real time data and identification of disruptions (Marmolejo, 2020b).

Nowadays, many organizations still have data silos managed in spreadsheets with no real time information or sharing of any kind. The information between areas is not connected, and this makes impossible the implementation of a digital twin. Furthermore, even when companies use ERP systems, such systems may not be properly integrated with partner companies such as suppliers and clients (Marmolejo et al., 2020a), due to lack of information technologies, data security and trust. This type of implementation results in myopic decision making in the supply chain management.

Novel technologies such as blockchain and smart contracts might help sorting some of the challenges with data security and trust. Nevertheless, they should be carefully implemented to make sure they do not impose excessive time for transferring the information between the physical and digital model. The next step would be to define the set of key performance indicator (KPI's) to be used in the decision-making process. Is key that stakeholders agree on the set of KPI's, the definition of how decisions will be made based on this information and the level of automation of the decision-making process. When implementing a digital twin, all these challenges need to be addressed before getting into the modeling, so that such model can be built knowing the available information, the format, and the accessibility features.

Regarding the large-scale simulation, the mix between discrete-event and agent-based simulation is the most appropriate combination of paradigms to assess the PI enabled hyperconnected relay network. On the discrete-event side, as it allows representing simple behavior efficiently and to make animations, and on the agent-based case as it allows modelling more complex proactive agent behavior and the scalability of the model through agent instance generation (Majid et al., 2016). For this type of system, being able to place agents into a GIS map is desirable for enabling realistic distance, movement, and animations. Therefore, among the existing commercial simulation software, Anylogic would probably be the best choice as it allows using together discrete-event and agent-based paradigms, and the use of GIS maps for agent's movement.

Other challenge of the simulation model comes with the size of the instance. For big instances, running such a simulation model with enough detail might take more than 80 gigabytes of RAM memory. Thus, a server with good computational power is required for running these models. For the instance generation, is recommended to create the network from input files, for liberating space in the model. In the case of digital twins, such files should be allocated in databases connected live with the model. Similarly, if the number of agents is too big, the memory required for this might be too high. Therefore, a useful modeling technique is to model flow objects (products) as data packages instead of complete agents, for reducing the model size and improving run speed. Another good practice is to turn off the automatic logs of the software and generating the output data in text files for analysis in exogenous data tools. Note in the case of a digital twin, the output generated should go directly into a database connected to the physical system, thus, storing, and computing KPI's inside of the model might be necessary.

6 Conclusion

Physical internet enabled hyperconnected relay networks will help reduce the driver's shortage and high turnover. Testing and properly managing such complex systems is difficult, so digital twins will be of great help in designing, assessing, and implementing improved operations. There are big challenges towards the implementation of digital twins, but companies will have to shift towards data driven operations to remain competitive. Academia should partner with industry regarding digital twin implementations to provide meaningful research avenues, results, and the development of the field. Simulation models with actual connections to databases for enabling digital twins are still incipient, so the implementation of such models is yet to be explored in the literature. There is need for more application cases of digital twins for proving the power of the tool; hopefully, this research will help motivate industry and academia to implement such tools in the years to come.

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