Georgia Tech Physical Internet Center
Supply Chain & Logistics Institute

Modeling and Simulation of an Agile Assembly Center in a Physical Internet inspired Manufacturing System

Miguel Campos[1,2], Leon McGinnis[1,2], Benoit Montreuil[1,2]
1. Georgia Tech Physical Internet Center, Supply Chain & Logistics Institute
2. School of Industrial & Systems Engineering, Georgia Institute of Technology, Atlanta, USA
Corresponding author: mcampos@gatech.edu

Abstract: *Globalization, high competitiveness, and highly customized products are factors that increase the complexity of product development and production systems. Such complexity makes conventional mathematical or analytical models unsuitable for properly analyzing such systems, for which simulation emerges as an alternative for evaluating, designing, improving, and operating complex systems. This paper focuses on the design, modeling, and simulation of an agile assembly center (AAC) that produces durable big-sized products with the capacity of serving several projects and clients concurrently leveraging Physical Internet (PI) concepts while embedding the decision-making agents' intelligence. This work is the cornerstone for implementing a digital twin of an AAC that will help make operational, tactical, and strategic decisions towards improving the performance of PI inspired assembly facilities.*

Keywords: *Physical Internet, Manufacturing, Modeling, Simulation, Logistics Systems*

Conference Topic(s): *Business models & use cases; material handling; Modularization; manufacturing networks; PI modelling and simulation.*

Physical Internet Roadmap*: Select the most relevant area(s) for your paper:* ☒ *PI Nodes,* ☐ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Introduction

Globalization, high competitiveness, and highly customized products are factors that increase the complexity of product development and production systems (Ong et al., 2008). Such complexity makes conventional mathematical or analytical models unsuitable for properly analyzing such systems, for which simulation emerges as an alternative for evaluating, designing, improving, and operating complex systems (Law, 1991; Mourtzis, 2020).

One of the biggest challenges is to properly design, optimize and manage complex logistics systems at a large scale, for which Physical Internet (PI) offers a novel approach towards an order-of-magnitude improvement in efficiency and sustainability. The PI was first described by Montreuil (2011) as an innovative vision for the future of logistics where goods and materials are packaged and transported in standard containers, much like the Internet transmits data in standardized packets (Ballot et al., 2013).

For improving the performance of logistics systems, the Physical Internet concept is materialized through a multi-tier hyperconnected logistics web such as that presented by Campos et al. (2021). These types of networks can be comprised of production, storage, assembly, and transportation nodes, in which the last node in the network is conveniently located close to the end consumer. In this paper we focus, in the context of hyperconnected supply chain networks, on the design and performance assessment of that last node in the context of manufacturing. For this, the concept of agile assembly centers (AACs) is presented, as a manufacturing facility that can be open to multiple stakeholders and concurrently serve the needs of several clients for small-series production of complex and large products. Such facilities are often associated with the manufacturing of large durable goods, such as in the specialized vehicle, heavy machinery, integrated automation, energy equipment, and building industries.

Conventionally, production facilities for complex and large durable goods tend to be extensive in area and expensive to build and equip, which entails that the products need to be transported over long distances to the different clients, yielding a higher logistics cost. AACs are meant to be temporary and easy to set up in locations close to the clients, reducing the logistics costs of transporting full assembled final products.

Several studies have been published regarding simulation of conventional assembly facilities for assessing and improving performance of the system as seen in Malega et al. (2020), as well as of specific system elements such as the facility layout (Yang & Lu, 2023), or a given production line with individual stations (Afifi et al., 2016). Most of these papers develop simulations through commercial specialized software, which does not allow for full customization or embedding the intelligence of decision makers properly. This paper extends the scope and upgrades the published approaches and models, focused on the design, modeling, and simulation of an AAC with the capacity of serving several projects and clients concurrently leveraging PI concepts while embedding the decision-

2 PI Inspired Agile Assembly Centers

A typical AAC topology is presented in Figure 1. The process starts when suppliers send kitted components and materials in PI modular containers to the facility. The use of kits in modular containers is key in this context for protecting the integrity of the kits, optimizing the space in both trucks and inventory, facilitating the assembly worker tasks, and enabling reverse logistics which reduce waste induced by kit packaging. The kits are received in the inventory management center, from which they will be distributed over the different centers some time before they are required in the assembly process. One of those centers is the Subassemblies center, in which subassemblies that will be part of other assemblies are produced and distributed. The remaining centers in the facility will be operated as a hybrid between parallel

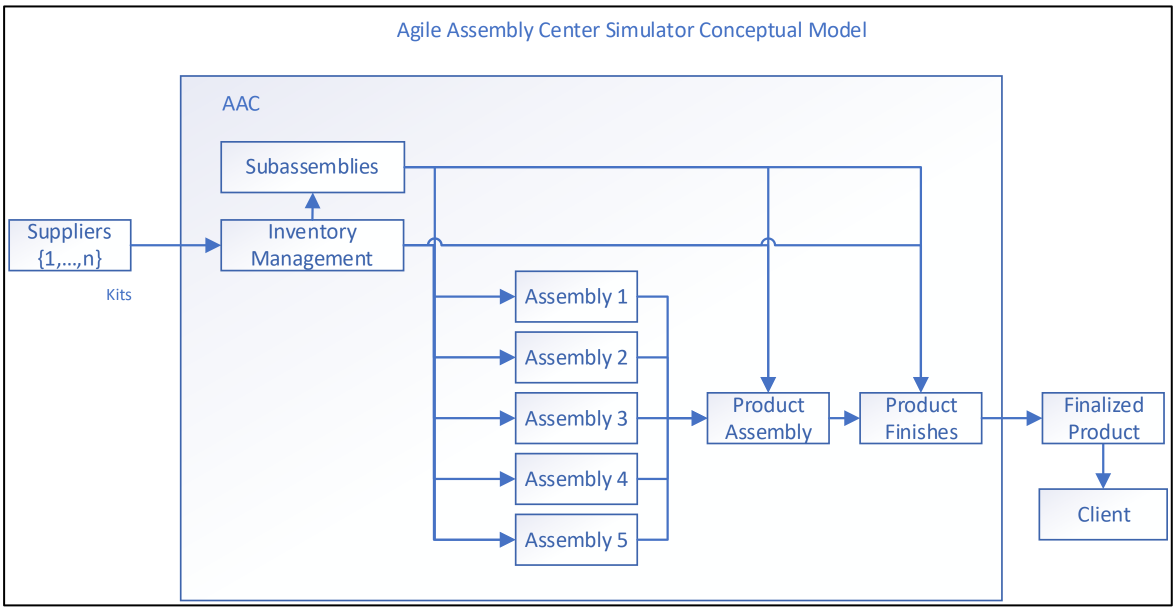

Figure 1. Illustrative Agile Assembly Center process flow diagram

moving lines for the main assemblies, a moving product assembly center where assemblies are used to build the product, plus a stationary center in charge of product finishes.

Several models are required for designing and operating such a facility. As synthesized in Figure 2, the set of models includes the product, assembly process, organization, technology, assembly capacity, assembly operations, logistic process, and logistic operations models, with the simulator as a tool to assess the performance of the system designed.

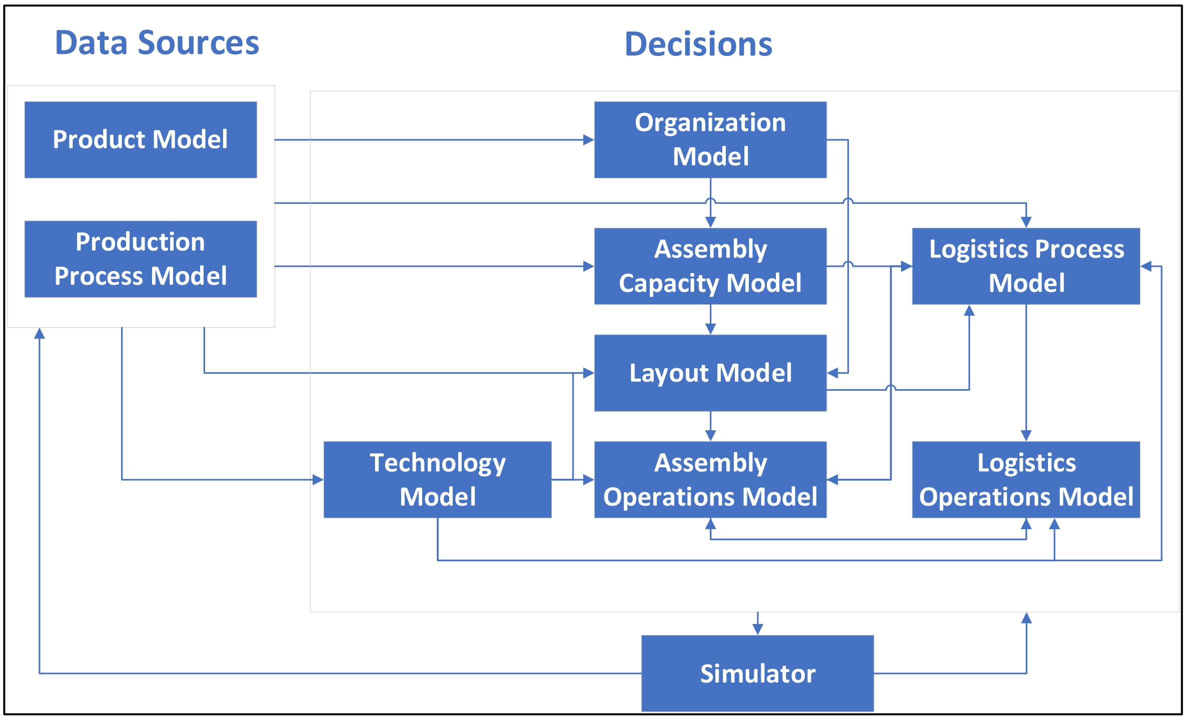

Figure 2. Model structure for designing an Agile Assembly Center

The product model defines the characteristics of the object to be assembled, while the production process model describes the tasks and resources required to assemble the product. The organization model defines the structure of the facility as shown in Figure 1 and the basic operation concepts. The technology model describes the technology available for moving and processing objects. The assembly capacity model corresponds to the line balancing, where the required number of stations is defined. Knowing the number of stations, the layout model can be built, assigning spaces to workstations in the plant floor. Once this process is done, the assembly operations model defines the schedule of the resources required to perform the assembly tasks. Similarly, on the logistics side the logistics process model defines the tasks to be performed to ensure all objects are where needed when needed, and the logistics operations model schedules the resources required for performing the tasks.

3 A high-fidelity simulator of an Agile Assembly Center

In this paper we make a distinction between a simulation model and a simulator. A simulator in this context is a simulation tool capable of modelling different designs, implementations and scenarios of a given system, while a simulation model will refer to a specific instance implemented in the simulator. This distinction is important as for implementing a simulator, the model needs to be parametrized to create various simulation models by varying the parameters without the need to modifying the simulation source code. In the context of complex systems, a simple parameter dashboard is not enough for capturing the dynamics of a full system implementation, for which external data sources are required. For instance, different operation model instances can be implemented in the simulator by changing input files that contain the workers instructions or the production plan. The AAC simulator uses a mix of two simulation paradigms: agent-based simulation and discrete-event simulation like that presented by McGinnis et al. (2021). Figure 3 shows the agent architecture, where the entities (units of flow), resources and decision-making agent are presented.

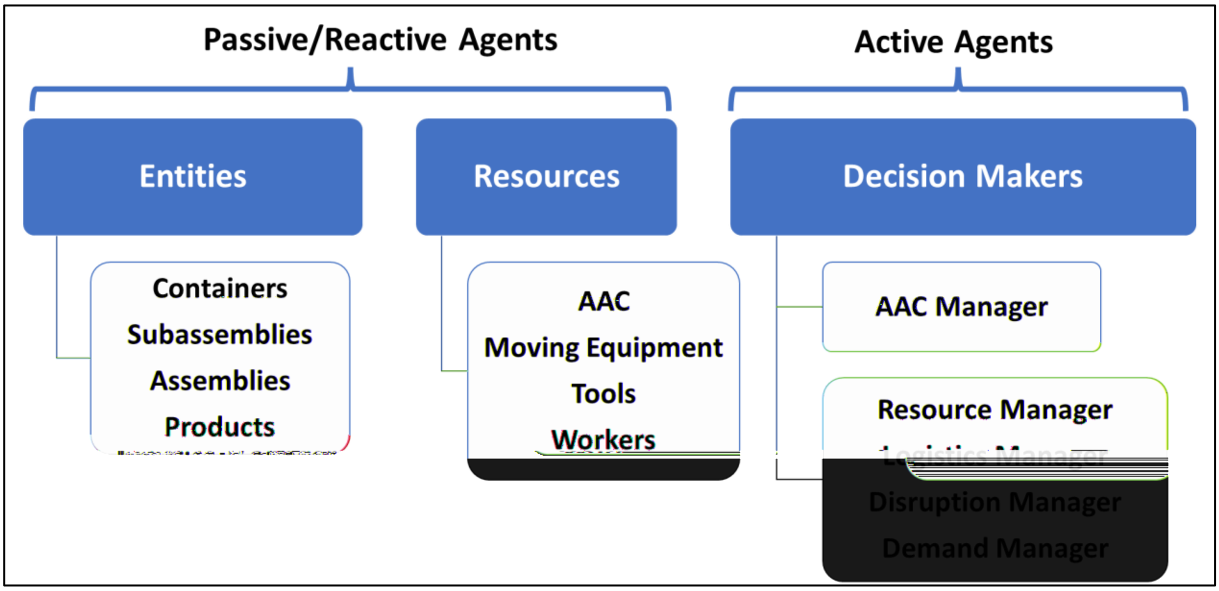

Figure 3. Illustrative Agile Assembly Center Simulator Agent Architecture

Similarly, Figure 4 presents the logic and data architecture of the model which uses external data sources that come from the decision models identified in Figure 2 to enable the decision-making agents to manage operations in the AAC. In this implementation, the product, assembly process, organization, technology, assembly capacity, assembly operations, logistic process, and logistic operations models are implemented offline and are an input to the model that is used by the decision-making agents to generate actions and tasks in the model. Although the decision logic might be hard coded in the model, this strategy enables to implement different scenarios with little or no changes in the source code.

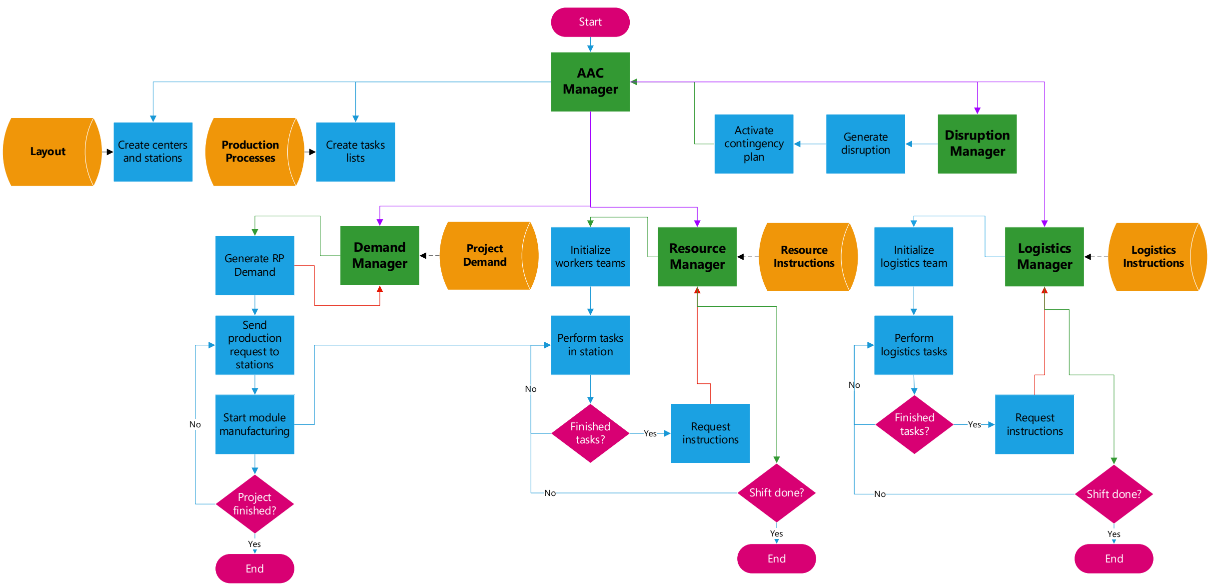

Figure 4. Agile Assembly Center Simulator Logic Architecture

Notice the layout, production process, project demand, resource instructions and logistics instructions all come from external data sources, which means the simulator is capable of modeling various instances of an AAC that has a similar operation concept just by changing the data inputs. Various experiments can be made based on this architecture without changing the source code of the model, for instance, different demand scenarios can be tested for a given facility implementation. Regarding the production process, changes in the process can be tested to assess the impact of changes in the product producibility. Additionally, different layouts for the same project can be tested, understanding changes in the layout will affect the assembly operations model and the logistics process and operations models. Another interesting experiment is to test different assembly process and operations models for the same demand and layout, to assess the efficiency of different optimization logic. Similarly, different material handling and logistics logic can be tested towards performance enhancement.

4 Simulation model implementation

The model structure presented in the previous section was implemented in the Anylogic® 8.8.0 simulation software for a large durable products AAC designed for an industry partner. The facility was designed for producing 8 assembled products a day with a takt time of one hour, assuming a single daily shift of 8 hours a day. The AAC consists of 17 centers, with a total of 54 stations distributed between subassembly, assembly, product assembly and product finishing centers, including buffer stations after certain critical stations that are more prone to disruptions. As a takt time driven facility, there is space in each station for storing two takt times worth of kits and/or subassemblies, meaning every takt time one inventory position needs to be replenished by the logistics workers, making sure every kit or subassembly will be ready at the stations two takt times ahead of when the assembly will be performed.

It is of interest for the company running the AAC to implement a pilot in the designed facility for assembling one product as a test. The product selected for the pilot is composed of 9 assemblies, which are assembled into a volumetric product which required finishing work before being ready for shipping. For this purpose, the decision models were run for a scenario producing a single product in the facility and used as input into the simulation model. For this implementation, the simulation model does not consider stochasticity on the processing times, the demand, or disruptions to the facility operations. The objective of this experiment is to validate the production process, making sure the assembly process and operations models are feasible and yield the expected performance.

5 Model Validation

The simulation model was run for 20 working hours considering a deterministic scenario without stochastic processing times or disruptions, enough time for a single product to be assembled. For validating the production process, three procedures were applied: visual verification of resource and product movement, task by task process verification and output statistics analysis. For the visual verification a 3D animation was built in the simulation model as seen in Figure 5, which allows to follow the movement of workers, assemblies, and volumetric product, verifying all objects are moving as intended when intended.

Additionally, each individual task can be revised during run time, as seen in Figure 6. In the figure it can be observed for each task is possible to know t
duration, resource requirement, start time and current status. For each individual object, the full set of assembly tasks can be individually checked to ensure all processes are being executed correctly. The output statistics analysis also helps to validate these processes overall.

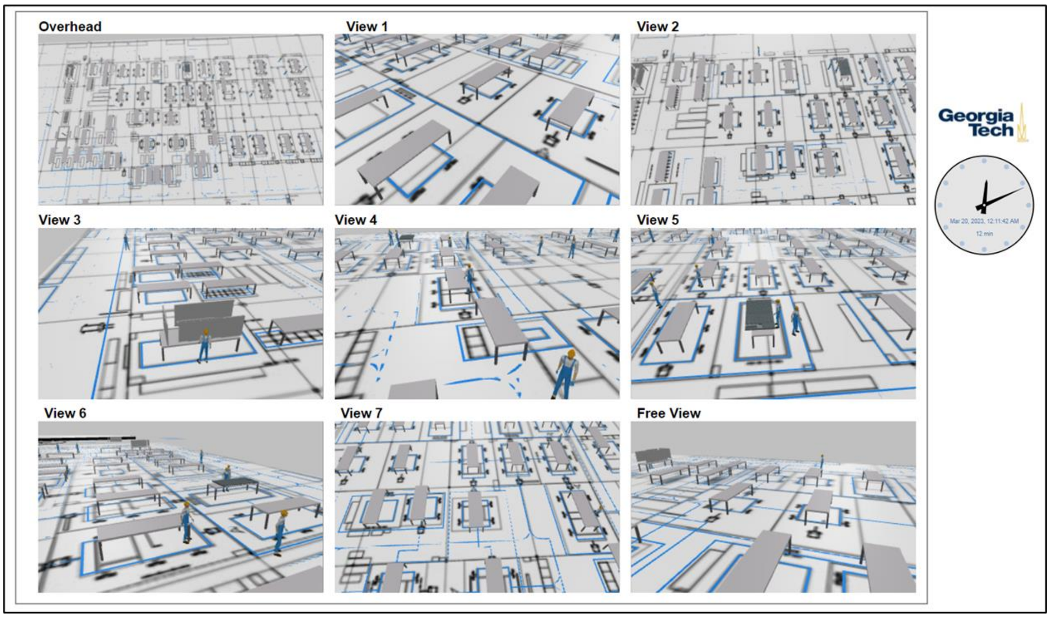

Figure 5. Simulation Model 3D Animation Snapshot

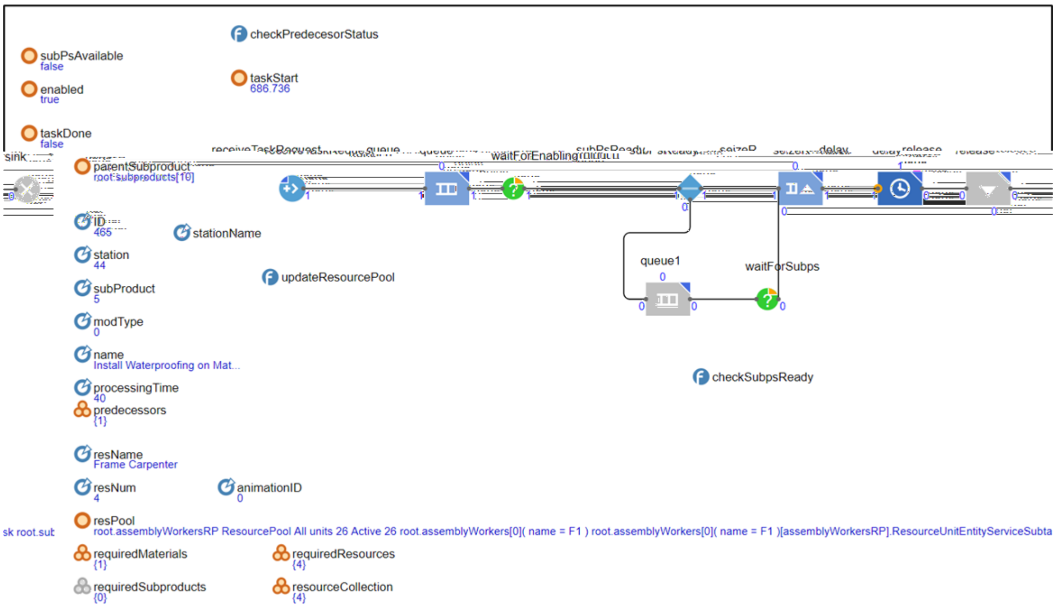

Figure 6. Individual task status

For the output statistics analysis, two main variables were studied: the labor utilization and the total worker assembly time per subproduct (assemblies, initial product, and finished product). The results of this exercise are synthetized in Table 1 below. From the results it could be verified the labor utilization and work assignment has a perfect match with the production planned, which is expected as this scenario considers no stochasticity. Nevertheless, if any process would not be implemented properly these values would not have a perfect match, thus, this analysis indicates the processing time, precedencies and resource assignment are correctly modeled. Through this analysis, we can conclude the model is valid and therefore ready to test different experimental scenarios.

Table 1. Results of Deterministic Simulation-Based Experimental Feasibility Assessment of Agile Assembly Center Design

KPI	Planned	Simulated
Labor Utilization	17.57%	17.57%
Assembly 1 Worker/Minutes	182.08	182.08
Assembly 2 Worker/Minutes	340.33	340.33
Assembly 3 Worker/Minutes	145.33	145.33
Assembly 4 Worker/Minutes	58.67	58.67
Assembly 5 Worker/Minutes	68.67	68.67
Assembly 6 Worker/Minutes	84.5	84.5
Assembly 7 Worker/Minutes	194	194
Assembly 8 Worker/Minutes	214.33	214.33
Assembly 9 Worker/Minutes	155.33	155.33
Volumetric Product Worker/Minutes	2,002.4	2,002.4
Finished Product Worker/Minutes	350	350

6 Conclusion

The main contribution of this paper consists in presenting the design, architecture, and implementation of a discrete-event agent-based high-fidelity simulator of a complete agile assembly center in the context of hyperconnected supply chain networks. The model built is parametrizable, flexible and reusable, modeled at a fine granularity level, including behavior while emphasizing in the decision-making process, how this performance, and assesses the capability of leveraging PI concepts to deal with the assembly of customized big-sized products. This work is the cornerstone for implementing a digital twin of an AAC that will help make operative, tactical, and strategic decisions towards improving the performance of PI inspired assembly facilities. This paper offers insights into the future of durable big-sized product assembly and the role that the PI could play in shaping this future.

7 Future Work

Now that the simulator has been implemented and tested, the next step is to add stochasticity to the model in terms of processing times, and potential disruptions. In order to add the disruptions, contingency plans need to be in place, such that the decision-making agents can adjust operations to deal with such disruptions. Various additional experiments can be made using the simulator, testing different demand scenarios, production processes, layouts, and optimization logic. This simulator can be used to create a digital twin of a given AAC, but an extension to the model is required where the current state of tasks, resources and objects can be used as an input to start a simulation from any given point in time.

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