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Kit Fulfillment Centers Serving Distributed Small-Series Assembly Centers in Hyperconnected Supply Chain Networks

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Abstract:

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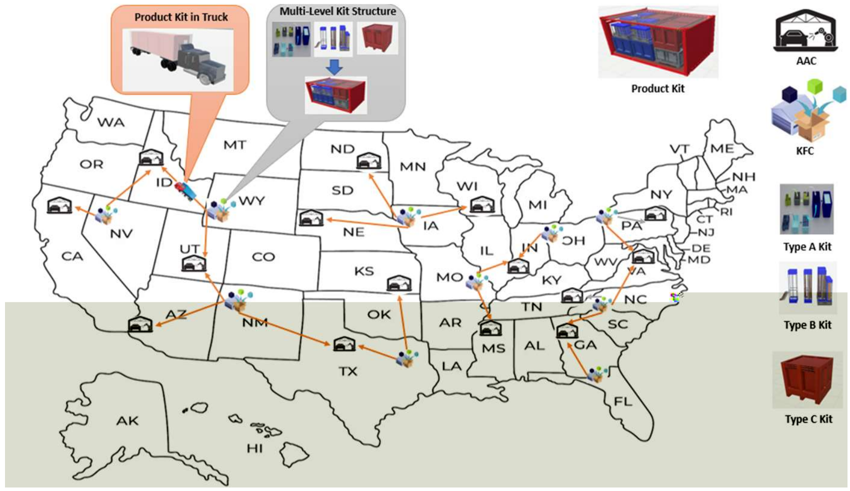
1 Introduction

This paper is about designing Kit Fulfillment Centers (KFCs), kitting facilities that are distributed over a territory and capable of serving multiple vicinity agile assembly centers (AACs) in a hyperconnected supply chain network, as shown in Figure 1.

Bozer and McGinnis (1992) defined kitting as the practice of preparing kits containing predefined quantities of parts that serve specific assembly efforts in the manufacturing plant. There are two ways in which manufacturers can feed materials to the assembly line: line-side feeding and kitting. Assembly line feeding methods can be selected depending on product customization and storage space constraints in a facility (Hu et al., 2020). In general, line-side feeding requires more space around the assembly line, while kitting is more labor intensive. In the context addressed by this paper, the AACs assemble complex, large products with many parts. This means we need several different parts for each assembly station, which could make line-side feeding impractical.

Challenges in designing the KFCs include: (1) due to the dynamic nature of demand from the AACs, the designed KFCs must be able to readjust and reconfigure quickly to changes in demand; (2) due to the complex and large nature of the products of the AACs, the scheduling of kit production and the compactness of kit structure in the KFCs must be designed to be space efficient; (3) under the setting of the hyperconnected supply chain networks, the designed KFCs must produce kits that are

(a) easy and safe to transport between KFCs and AACs, (b) easy and safe to handle, distribute and use in AACs, and (c) efficiently recycled in the hyperconnected supply chain networks.



The full paper is structured in the spirit of (Meller et al., 2014; Babalou et al., 2021). We first analyze the related literature to position our research contribution. Second, we define performance and capability criteria driving KFC design. Third, we address the design of kitting processes and operating models for the multi-level kitting. Fourth, we elaborate on the roles, benefits, and challenges of modular multi-level kit containerization. Fifth, we address the design of modular kitting cells enabling operational efficiency and easy quick reconfiguration. Sixth, we elaborate on takt time driven resource balancing and scheduling, which are done by the KFC configuration and labor scheduling model (KFC-CLSM). Seventh, we describe key KFC layout concepts. Finally, we provide conclusive insights and avenues for further research.

2 Literature Review and Contribution

Kits can be categorized into stationary kits and traveling kits (Schmid and Limère, 2019), and the kits produced by the KFCs are stationary kits, not traveling kits. However, the fact that KFCs produce kits for multiple AACs in an order fulfillment fashion makes the KFCs fall in the intersection between kitting facilities and fulfillment centers. Both kitting facilities and fulfillment centers involve order picking, but fulfillment centers fulfill demand from customers, whereas kitting facilities serve assembly plants, thus fulfillment centers typically have more dynamic demand than kitting facilities. Like the fulfillment centers, the KFCs also have more dynamic demand from multiple short run AACs.

Bortolini et al. (2020) allocated parts in warehouse aisles for kitting by first allocating parts to aisles according to their size and weight and then assigning kits with most commonality to the same aisle. Under the setting of kitting for mixed-model assembly, Fager et al. (2019) conducted experiments to compare different picking information systems: pick-by-HUD (Head-Up Display), pick-by-paper, pick-by-light, and pick-by-voice, under different kitting batch size and picking density. Two tabu search based heuristics for order batching have been proposed by Henn and Wäscher (2012). Schmid et al. (2021) presented an optimization model for designing a single U-shaped kitting cell, assuming deterministic picking times, given kit demand pattern generated according to historical data, with the objective of minimizing investment, walking and replenishment cost. Proposed by Montreuil et al. (2021), the robotization idea of movebots moving racks to shufflebots in shuffle cells for sorting in logistics hubs can be easily adapted in order picking scenarios.

First mentioned by Montreuil (2011), the π-container is an important pillar in the Physical Internet concept. Montreuil et al. (2015) conceptualized the π-containers as world-standard, smart, green, and modular containers, and categorized them into three tiers: transport container, handling container, and packaging container. In our case, task kits may be put in packaging or handling containers; skill and workstation kits in handling containers; product kits in either handling or transport containers. Grover and Montreuil (2021) presented a mixed integer programming model for the containerization of π-containers under dynamic environment of logistics hubs. Making the π-containers smarter, Tran-Dang et al. (2017) presented a container tracking system via wireless sensor network.

In this paper, we present a use case of π-containers in kitting. The focus of this paper is on the design of a kitting facility, including organization, layout, process, configuration, labor scheduling, and final product. To the best of our knowledge, there are several points of innovations in this paper: (1) the final product kits are multi-level kits contained in π-containers; (2) the stations in the designed KFCs are modular for quick reconfiguration under dynamic demand; (3) the designed KFCs reside in π-enabled hyperconnected supply chain networks, which, along with the modular station design, allows efficient resource sharing in the network.

3 Performance and Capability Criteria

The KFC is designed based on four performance and capability criteria: space efficiency, produced kit ease-of-use, reconfigurability, and labor efficiency.

Space efficiency (discussed in section 4): The space required to operate a KFC should be as small as possible, given the required maximum capacity, to save on the fixed costs.

Produced kit ease-of-use (discussed in section 5): The produced multi-level kits must be easy to transport and easy to handle and consume at AACs. The produced kit must be easy to load onto a trailer or truck. The workstation kits inside product kits must be easy to move inside the AACs. The skill kits inside workstation kits must be easy to take out for assembly workers. The task kits inside skill kits must be easy to access for workers when performing the corresponding tasks.

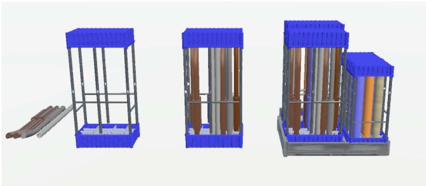
Reconfigurability to different demand (discussed in section 6): Since the KFCs need to serve multiple short-series AACs with variable demand patterns, the success of the designed KFCs depends significantly on their reconfigurability to respond to changing demand patterns from AACs.

Labor efficiency (discussed in section 7): Given the demand, the number of workers required should be as small as possible to save operational costs, meaning that the average worker utilization rate should be as high as possible.

4 Kitting Process and Operating Model for Multi-Level Kitting

Ideally, for each product, there should be a product modular container kit that contains multiple workstation modular container kits, and each workstation modular container kit contains multiple skill modular container kits, and then each skill modular container kit contains multiple task modular container kits. However, the assembly of a product may require parts that come in significantly different shapes, sizes, and weights. For example, elongated parts may lead to inefficient space

Part Category	Definition
A	Parts that fit in a modular packaging container and are not heavy.
B	Parts that are elongated but are not heavy.
C	Parts that are large and heavy.



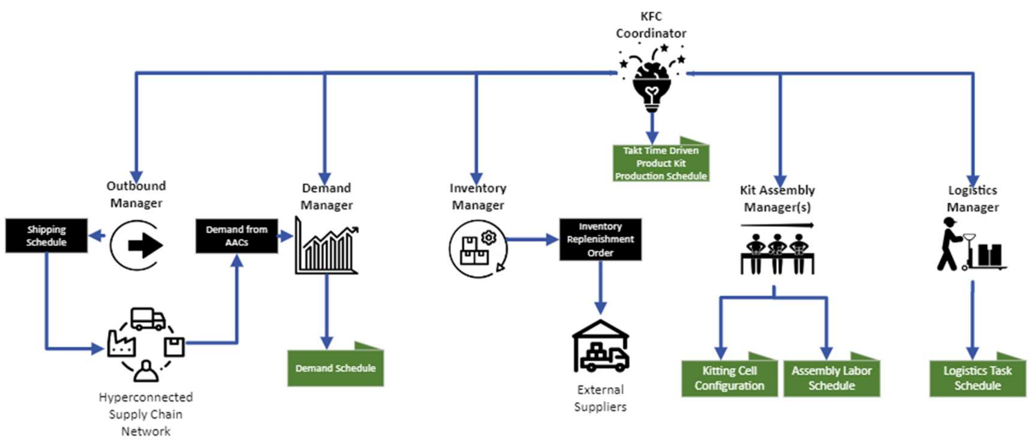
utilization inside cube-shaped modular containers. Taking a large and heavy part out of a modular container task kit in an AAC assembly workstation may be inefficient and possibly lead to injuries. Defined in Table 1, the kitted parts were categorized into three types: A, B, and C. The type A parts, like the electronic parts for an automobile, are kitted into modular task kit containers, then modular skill kit container, then modular workstation kit container. The type B parts, like the long exhaust pipes in an automobile, in one task kit are bundled together and then kitted into modular type B workstation kit containers, shown in Figure 2. Each grid separated by the gray separator is a position for a type B skill kit. For ease of handling, all the type B workstation kit containers are further combined into one as shown on the right side of Figure 2. These type B workstation kit containers are designed to be easily combined to transport or split to distribute to workstations in AACs. The type C parts, like the wheels and engines of automobiles, are kitted directly into the modular product kit container in their original packaging. Each of the individual type C parts in its original packaging is a workstation kit container. The containerized workstation kits of Type A, B and C parts are then kitted into the modular product kit (transport) container for easy transportation to the AACs.

The overall organization of a typical KFC is presented in Figure 3, with the model on top showing the high-level organization, and the model on bottom showing the detailed organization. In the detailed organization, there are three streams of workstation kit containers for type A, B, and C parts meeting at the product kitting center to be kitted into a modular product kit (transport) container. The flow of materials in KFC starts from receiving parts. Then, the parts are stored in either type A/B part inventory or type C part inventory according to their part types. The type C part inventory is separated from the type A/B part inventory because the heavy and large type C parts require wider aisles for the replenishment to the product kitting center. Out of the inventory, the type A parts flow to the Type A Part Kitting Center to be kitted into multi-level modular container workstation kits; the type B parts flow to the type B part kitting center to be kitted into multi-level type B modular container workstation kits; the type C parts directly flow to the product kitting center to be kitted into the modular product kit container. After workstation kitting, the type A and type B workstation kit containers flow to the product kitting center to be kitted into modular product kit container with the type C parts. After the product kits are produced, the modular product kit containers will be moved to the Product Kit Staging, and then shipped to their destination AACs. According to the demand, there could be multiple multi-level kit assembly centers working in parallel.

The multi-level kit production is takt time driven, which is a lean manufacturing concept aiming to pace the manufacturing process to meet customer demand. Each multi-level kit assembly center has its own takt time, which is calculated by $T_k = T_a/d$, where is the resultant takt time, is the amount of available manufacturing time, and is the demand. For example, assuming the available manufacturing time in a day is 8 hours and the demand for the day is 8 product kits, the takt time would be 1 hour, meaning that each hour there will be a product kit finished. The production of a product kit takes two takt times. All the type A and B part workstation kitting will be done in the first takt time, and then in the second takt time, all the type A, B, and C workstation kit containers will be kitted into the product kit container and moved to staging.

4.1 Operating Model

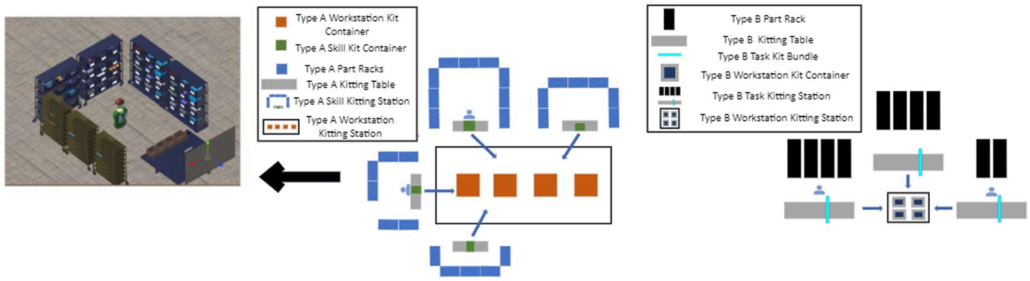
The operating model of the KFC in Figure 4 shows the main decision makers in the KFC and their responsibilities. There are six main decision makers: KFC coordinator, kit assembly manager, logistics manager, demand manager, inventory manager, and outbound manager. The demand manager receives kit production orders from vicinity AACs in the supply chain network. The KFC coordinator then assigns kit production tasks to kit assembly centers and generates takt-time driven kit production schedules for each kit assembly center. In the meantime, the KFC coordinator coordinates communications between other decision makers. According to the kit production schedule, the kit assembly manager of each kit assembly center generates kitting cell configurations and labor schedule. During kit assembly, it assigns the assembly tasks to workers according to the schedule. According to the assembly labor schedule, the logistics manager then generates logistics task schedule and assigns them to workers. With the information of current kit production schedule and finished product kits, the outbound manager schedules outbound trucks to make sure all product kits will arrive at their corresponding AACs on time. Throughout the operation of a KFC, the inventory manager constantly monitors and manages the stock level and storage position of each part type in the inventory and sends inventory replenishment orders to external suppliers when necessary.



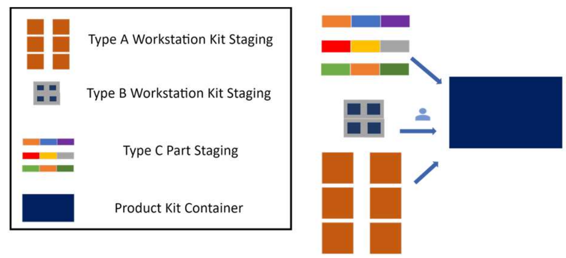
4.2 Type A, B Part Workstation Kitting (Takt Time 1)

Figure 5 shows the conceptual drawing of the type A and B part kitting centers. The type A and B part workstation kitting are done by first setting up the workstation kit containers in the workstation kitting station that is surrounded by a set of modular kitting cells. The modular kitting cells then produce task and skill kits to put into the workstation kit containers. To improve space utilization, the finished task kits are put directly into skill kits and the finished skill kits are put directly into workstation kits, which prevents double handling and requires no intermediate inventory for task and skill kits under this design.

According to the synthetic automobile assembly data provided by our industrial partner, we calculate the required intermediate inventory space if intermediate inventory was used. We assume all type A task and skill kits are stored in three-level racks, all type B task kit bundles are stored in 16-position elongated part racks, and aisle width is 5 ft for easy access. The intermediate inventory space requirements for type A part kitting are 295 ft^2 for task kits and 212 ft^2 for skill kits. For type B part kitting, the intermediate inventory space requirement is 32 ft^2 for task kit bundles. There is no intermediate inventory required for type B skill kits, since the skill kits in type B part kitting are positions in the type B modular container divided by the gray dividers. According to the calculated results, our design reduces the space requirement by 539 ft^2 per kit assembly center.

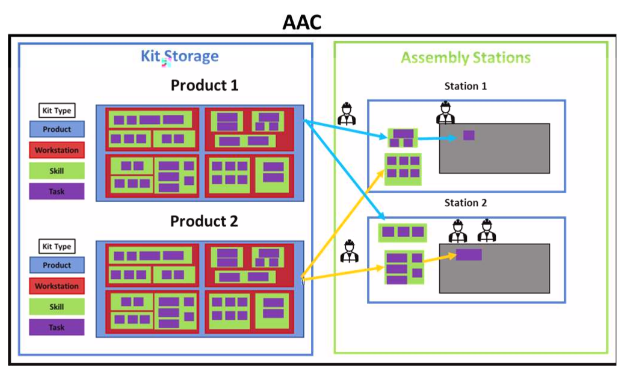


4.3 Product Kitting (Takt Time 2)



As the last step of the multi-level modular container kitting, the product kitting requires putting all type A, B, and C workstation kit containers for one product into a modular product kit container. As shown in Figure 6, there are three staging areas: type A workstation kit staging, type B workstation kit staging, and type C part staging. The type A and B workstation kit staging are replenished at the end of takt time 1 from the type A and B kitting centers. The type C part staging is replenished every x takt times from the Type C Part Inventory.

5 Modular Multi-Level Kit Containerization



The main role of the multi-level kitting is to facilitate the assembly work at the AAC. Therefore, the kits need to be easy to identify, manipulate and access. For achieving this, the objects inside of the container should be kitted in the reverse order of the assembly process, meaning the worker should be able to open a kit and access the objects in the order in which they will be needed for assembly. Figure 7 shows an example of an AAC that has two assembly stations. In this example, product kits (blue) will arrive at the AAC and be stored in a kit storage area. From the storage area, the kits will be transported to the respective staging areas by logistics workers. From staging, the assembly workers will open the workstation kit, grab the skill kit (green) corresponding to his skill and then grab one by one the task kits (purple) to be used in each one of the assembly tasks.

There are various benefits of using this kitting strategy. First, it makes the assembly process easier and faster for the workers. This allows a higher throughput, a lower overall labor requirement and the need for smaller AAC facilities as the space is used efficiently, enabling higher production rates in the same space compared to other feeding strategies. In some cases, land will be less expensive at the KFC compared to the AAC, as the AAC would normally be located closer to the clients and urban areas, another factor for using space efficiently. Additionally, the labor cost tends to be more expensive at the AAC, as it might require specialized labor, making the transfer of work hours from the AAC to the KFC cost effective.

There are some challenges as well for implementing this kitting strategy. One is the space utilization of the containers. As space is key in both the inventory at the facilities and the trucks that will transport the kits from the KFC to the AAC, the container selection needs to be optimized such that the empty space inside the containers is minimized. For this purpose, the two-stage parcel containerization optimization proposed by (Grover and Montreuil, 2021) was implemented. An important input to such a model is the set of potential containers, so this selection must be carefully made for the containers to be modular and easy to nest. These containers need to be strong enough to protect the integrity of the kit, should be labeled in a way that is easy for the workers to identify, and should be flexible enough to allow smooth reconfiguration in case kit contents change. Another challenge comes with the reverse logistics, as the containers are meant to be reusable, there are additional processes required to deliver empty containers from the AAC to the KFC, for which collapsible containers are recommended.

6 Modular Kitting Cells Design

Due to the variable demand from multiple AACs, the takt time for multi-level kit assembly could vary with the demand. To achieve operational efficiency, the kitting cells for lower-level kitting, which takes majority of the work, are designed to be modular, as shown in Figure 4. This modular design enables easy quick opening, closing and reconfiguration of kitting cells. The racks and tables in the modular kitting cells are all designed to be mobile, so that it can be quickly moved for opening, closing or reconfiguration of kitting cells. The specific number of kitting cells and the configuration of each kitting cell that achieves most economic efficiency under a specific demand is determined by the KFC-CLSM.

7 Takt Time Driven Resource Balancing and Scheduling

The KFC’s production rate is designed to be takt time driven, as shown in Figure 9, and the KFC kitting cells are designed to be modular. To benefit from the takt time driven production schedule and modularized kitting cell design, proper resource balancing and scheduling is required for operational efficiency. This is achieved by KFC-CLSM, a mixed integer linear programming model. The objective of the KFC-CLSM is to minimize operational costs including assembly worker costs and kitting cell replenishment costs.

As shown in Figure 8, the KFC-CLSM takes in multi-level kit definitions of different product, precedence relationship defined in process design, time parameters of tasks, part dimensions to assign rack for parts, and product kit assembly sequence to determine produced kit in each takt time. The model output includes station configuration, worker assignment, and labor schedule. The station configuration includes the opening or closing of each candidate kitting cellrin equebed lgu pr e M required and the replenishment cost. The worker assignment means assigning tasks to kit assembly workers. The labor schedule specifies the schedule of tasks for each worker. It is possible for a worker to work in multiple kitting cells in a takt time. The KFC-CLSM finds the optimal combination of number of open cells, kitting task assignment of cells, and labor scheduling to save operational costs.

7.1 Experiment

To demonstrate the performance of the KFC-CLSM, a two-stage optimization model is designed to compare with the KFC-CLSM. The main difference between KFC-CLSM and the two-stage model is that KFC-CLSM does kitting cell configuration and labor scheduling at the same time, whereas the two-stage model does it in two stages. The first stage is kitting cell configuration. Instead of determining the configuration of kitting cells by a mathematical programming model, we have kitting cells designated to one or multiple skills. If due to short takt time, the kitting tasks cannot be finished with one set of kitting cells, another parallel set of the same kitting cells will be opened. Since different skills have distinct sets of parts, this method of kitting cell configuration would keep kits with most part commonality in one kitting cell to reduce the replenishment cost and minimize the movement in kitting. The second stage is labor scheduling. For labor scheduling, the same formulation as the KFC-CLSM will be used.

The synthetic kit definitions for two types of automobile product were provided by our industrial partner. It was observed that the number of skill kits of skill a and b in type A kitting are both around 30% of all the skill kits. Thus, for the configuration of type A kitting cells in the two-stage optimization model, we have one kitting cell designated for skill a, one for skill b, and one for the rest of the skills for each set of type A kitting cells. For type B kitting, since there was only one skill that had type B parts, we have one kitting cell for each set of type B kitting cells.

The performance of the two optimization models in terms of kitting cell replenishment and kit assembly costs will be compared under the demand scenarios of 4, 8, 12, 16, 20 and 24 product kits per 8-hour shift. The demand for the two types of products is assumed to be the same. The cost of workers is assumed to be $21 per hour per worker. The frequency of kitting cell replenishment is once per 8 takt times. The experiments were run with the Gurobi optimizer version 9.1.1 in Python on a computer with an AMD EPYC processor (2.5 GHz, 2 processors) and 230 GB of RAM. The time limit for all the experiments was set to be two hours.

7.2 Results

The two plots in Figure 10 show the comparison between the resultant costs from the KFC-CLSM and the Two-Stage model. The plot on the left for kitting cell replenishment costs shows that the KFC-CLSM has a smoother increase with the demand, whereas the Two-Stage model shows a sudden increase when the demand is 16 product kits per day. Although for the scenario of 8 and 12 product kits per day, the replenishment cost of KFC-CLSM is slightly higher than that of its counterpart, only by negligible amounts of $2 and $9 per day respectively. This is because when demand is high, the Two-Stage model had to open two sets of type A kitting cells, whereas the KFC-CLSM model smartly utilizes the modular design of kitting cells to assign kits with most part commonality to the same kitting cells to reduce replenishment costs while making sure the workload can be finished in a takt time. The plot on the right shows that the kit assembly costs for the two models are the same in all demand scenarios. This is as expected, since having all part types of each skill available in the designated kitting cell gives the Two-Stage model more flexibility in labor scheduling. For example, when there are two kitting cells for skill a, the skill a skill kits can be assigned to either one of the two kitting cells, meaning that the workload in each kitting cell can be easily changed to accommodate for the purpose of generating a labor schedule that will minimize the number of workers used. This proves the performance of the KFC-CLSM on finding the optimal labor schedule that achieves the minimum kit assembly cost while maintaining the replenishment cost at a much lower level.

8 KFC Layout Concepts

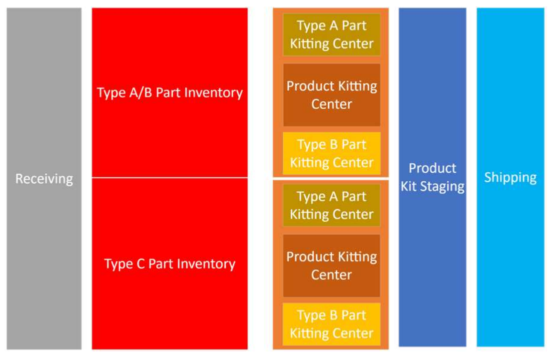


Figure 11 shows the high-level conceptual layout of a KFC with two kit assembly centers. Each kit assembly center consists of a type A part kitting center, a type B part kitting center and a product kitting center. According to the predicted demand from AACs, a KFC could have multiple multi-level kit assembly centers working in parallel to fulfill the demand from AACs. Each kitting cell inside the type A and B part kitting centers and type C parts in the product kitting centers will need to be replenished with parts from either type A/B part inventory or type C part inventory, so the inventory areas should be near to the kit assembly centers, and there should be enough aisle space for the replenishment tasks. Inside each assembly center, the type A and B part kitting centers should be near to the product kitting center, since the finished workstation kits from type A and B part kitting centers will need to be moved to the workstation kit staging areas of the product kitting center. The product kit staging between kit assembly centers and shipping needs to have enough space to act as a buffer for the finished product kit containers to be stored before departure.

9 Conclusion

In this paper, the design of a kitting facility, KFC, that serves multiple AACs in a hyperconnected supply chain network was presented. The KFC produces multi-level kit π-containers which due to their modular design are easy to transport and handle and economic efficient, and due to their multi-level structure are easy to distribute to AAC stations and provides easy and quick access to parts down to task level for the different skilled workers in the AAC stations. The KFC kitting process has been categorized into A, B, and C types according to the size, shape, and weight of parts. The designed multi-level kitting process has been optimized to prevent intermediate inventory between different levels. The kitting cells are designed to be modular enabling easy and quick opening, closing, and reconfiguration under various demand from multiple AACs. The KFC-CLSM finds the optimal combination of kitting cell configuration and labor scheduling to save operational costs including kit assembly and kitting cell replenishment costs.

Avenues for further research and innovation include design improvements and validations with discrete-event simulation, instruction feeding for the multi-level kitting process, resource sharing in the hyperconnected supply chain network, and robotization of the kitting and inventory processes.

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