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Abstract: *Significant expansions have been reflected worldwide in business reports of major E-commerce players such as Alibaba, Amazon and JD.com. Omnichannel retailing is an evolutional variant of E-commerce by providing consistent, unique and contextual brand experiences across multiple customer-aware touchpoints. Despite all the efforts, goods still move slowly and damages are a concern along with the booming omnichannel retailing. Meanwhile, high variety and variability of omnichannel retailing orders complicate the implementation of automated facilities. To deal with these phenomenal and challenging problems, a new warehousing paradigm named cellular warehousing is proposed. The concept of cellular warehousing is adapted from cellular manufacturing, taking full advantage of the similarities between online-offline orders and/or their items as well as standardization and common processing. To sum up, the paper will firstly introduce the key processes within the IoT/PI-based cellular warehouse, and then cover the major elements to support the operation. Finally, three representative case studies of Alibaba, JD.com and COSCO will be presented to verify the necessity to transform the existing warehouses to cellular warehouses.*

Keywords: *Omnichannel Retailing, Logistics, Cellular Warehousing, Cellular Manufacturing, Internet of Things, Physical Internet*

1 Introduction

Omnichannel retailing refers to combining and integrating various sales channels to meet the comprehensive experience needs of customers' demand on shopping, entertainment and social networking (Piotrowicz et al., 2014; Verhoef et al., 2015; Cummins et al., 2016). These types of channels include tangible and intangible stores as well as the information media such as the websites, emails and the social media (Fei 2013). In the age of omnichannel retailing, the entire supply chain system becomes customer-oriented so that the enterprises are required to put the customers' needs in the core position when designing all strategies and operations such as warehousing operations and goods delivery (Picot Coupey et al., 2016). The customers may place an order consisting of any types of goods at any time in any place by any methods, which sets a quite high requirement on the warehousing operation especially (Cummins et al., 2016). The warehouses are expected to handle the omnichannel orders of large quantities and varieties very efficiently in a short time window to meet the customers' promise such as "same day delivery" or "next day delivery".

The e-commerce enterprises and the logistics players, however, have not kept up the pace of its development of the warehouses, even though the major e-commerce players worldwide have cast a lot of efforts on improving their warehousing performance. For example, Amazon has introduced the Kiva system (Bhasin et al., 2016; Xinhua, 2017) and JD.com has put into use of a highly automatic fulfillment center in China. Whereas, the automatic warehouse is only capable of dealing with the goods of similar properties in terms of sizes and weight.

Considering the challenges, there is an urgent need for an innovative warehousing paradigm. Our paper comes up with the concept called Cellular Warehousing (CW), which is adapted from Cellular Manufacturing (CM). CW will take full advantage of the similarities among the online-offline orders and their items as well as standardization and common processes. A cellular warehouse is composed of multiple cells, each of which is optimized in terms of layout, space, internal scheduling, operations and facilities. The order items with strong similarities are handled in the same cell. To facilitate automating the flow of information, driving the synchronization among the cells and visualizing the operation, Internet of Things (IoT) and Physical Internet (PI) will be applied to build up the technological infrastructure. This article will focus on discussing the concept, building blocks and case studies of the cellular warehousing that driven by PI and IoT technologies.

CM is proposed as the panacea for dealing with more personalized and changeable customer needs; and meanwhile to strengthen the flexibility of production workshop. There have been mature theories guiding the design and operations of cellular manufacturing, which can be taken as reference when designing the cellular warehousing framework. Each stage for implementing CM has been well discussed in theory, including cell formation (Selim et al., 1998; Mahdavi et al., 2009; Gonçalves et al., 2004), the cell layout design (Salum, 2000; Tavakkoli-Moghaddam et al., 2007; Solimanpur et al., 2004) and inter-cell/intra-cell scheduling (Tavakkoli-Moghaddam et al., 2010; Golmohammadi et al., 2009). In the complicated onmichannel retailing environment, demand-driven supply chain also urgently needs a similar warehousing solution to hedge against risks and costs while providing sufficient agility. Although some scholars who have set about discussing similar concepts (Shafer et al. 1993; Huang et al. 2015), there is little research exploring how to match the concepts or theories from cellular manufacturing to cellular warehousing. Also, little literature has formally established the concept of cellular warehousing. The application conditions, constrains, methods, advantages and disadvantages to apply cellular concepts to warehousing have not been discussed, not to mention the verification of the idea.

This research will come up with a preliminary conceptual model of cellular warehousing considering the typical characteristics of e-commerce logistics from the following three aspects. Firstly, the research will examine the matching relationship between CW and CM to bring about CW paradigm. It can be conceived as a primer on the cellular warehousing concept. A generic workflow within a PI/IoT-enabled cellular warehouse will be illustrated. Secondly, key building blocks for PI/IoT-enabled cellular warehouse are introduced in terms of physical dimension and cloud cyber dimension. Finally, through three representative case studies, industrial motivations and current frontiers for CW will be discussed. Future works are also identified for open exploration.

It is expected that a theoretical framework of a cellular warehouse in the context of IoT and PI will be established. The paper aims to make both theoretical and practical contributions to the ecommerce warehousing field. From a theoretical point of view, the study is among one of the early articles to apply cellular concepts to the warehousing design and operation, which might be regarded as a promising research stream. With regards to the practical contribution, the model proposed could serve as a reference for designing new warehouses, which will benefit various stakeholders. By referring to the paradigm, it is possible that the warehouse operator could further improve their efficiency and accuracy when dealing with ecommerce cargo of large volumes and varieties. The logistics automation service provider can possibly figure out new services and earns a higher market share in the future. Last but not least, the customers can be better satisfied with higher service levels and reduced costs

In the following, the paper will firstly introduce the key processes within the IoT/PI-based cellular warehouse, and then cover the major elements to support the operation in section 3. Section 4 will present three case studies of Alibaba, JD.com and COSCO to verify the necessity to transform the existing warehouses to cellular warehouses. Finally, future works are given in section 5 for open discussion.

2 Key process within a PI-enabled cellular warehouse

In addition to the traditional functions of materials storage, warehouses now are equipped with more functions, including materials receiving, order put-away, picking, sorting, packaging, consolidation, dispatching and etc. By implementing the cellular warehousing with the major support of IoT and PI, the warehouses can achieve these objectives much more efficiently.

The framework of cellular warehousing is composed of the physical warehouse and the cyber decisions to better manage the physical warehouse. These two layers of systems are simultaneously operating based on the philosophy of physical internet and cyber-physical system as well as IoT technological architecture. The processes in the physical warehouse will be reflected in the cyber space that will be monitored by the qualified planners or schedules for global optimization and operational synchronization. Especially, any unusual event in the physical warehouse will be highlighted so that the scheduler will be informed via cyber decision sub-system. Meanwhile, the scheduler can make changes on the parameters or variables of the cyber decisions to dynamic (re)configure the operations of physical warehouse back on track.

A clear insight over the key processes within a PI-enabled cellular warehouse is shown in Figure 1, from the time when the items come into the warehouse until the time when the items are shipped to the customers. The entire process consists of three major stages, inbound, warehousing and outbound. The operations directly related with the items flow take place in the physical warehouse. All the dynamic conditions will be uploaded to the cloud real-timely, which can be accessed by the authorized staff of the warehouse for (re)planning, (re)scheduling and controlling. The instruction on the physical warehouse will be placed through the cloud as well. In a PI-enabled warehousing / cross-docking environment, standardization is a critical premise and fundamental principle in terms of cargo, material handling facilities and even software protocols or data formats. CW is structured and operated based on this environment.

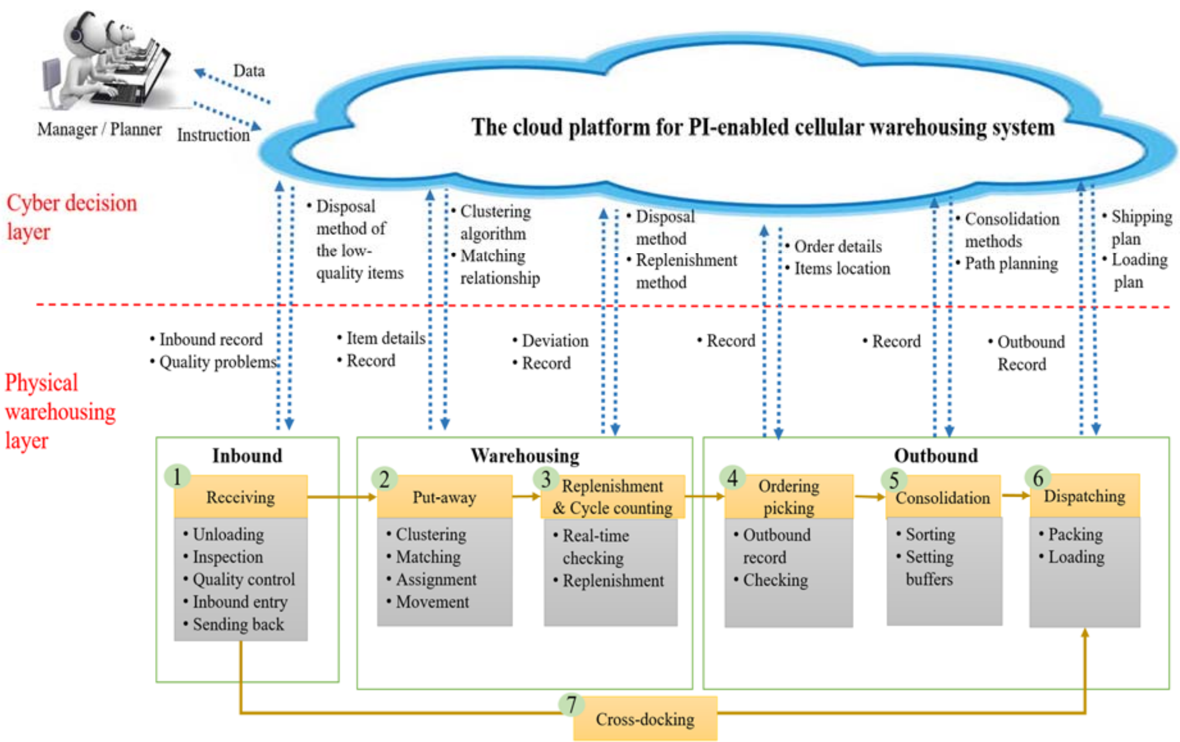

Figure 1: The process within a CPS-based cellular warehouse

The entire CW main stages are illustrated in following 7 steps:

(1) CW begins with receiving. Careful inspection will be conducted when receiving the goods according to detailed information listed including the names of the goods, categories and required quantities. In the traditional warehouse, inbound entry is usually written by the warehouse keepers. On the contrast, the entries will be recorded when the items come into the system via AutoID-based automatic scanning. Based on these real-time information, CW system can automatically assign appropriate cargo to suitable temporary buffer for further processing. The items that arrive without prior notices or do not meet the requirements will be sent back.

(2) The step following receiving is put-away, in which step the items from the same batch will be broken up and put on the shelves of different cells. Firstly, the goods will be clustered pursuant to their properties such as categories, sizes, weight, functions, surface characteristics or even sales volume. The methods to cluster these products will be made referring to the clustering approach in cellular manufacturing field. However, it might be more complex in cellular warehouses since the items will be more diverse. Then the product families will be matched with the machines or workers to handle or store them. With the relationship, it can be determined which cell they will be assigned to. For example, the items of regular appearance such as the standardized boxes coming in large quantities will be assigned to the completed automatic cell, where the machines will handle these items readily. On the other hand, it is likely that there are not appropriate automation systems to deal with the items of anomalous shape or size. Therefore, such items will be assigned to the manual cell. There will be semi-automatic cells as well for several medium-volume cargo with not too urgent delivery requirements. The items will be transmitted to the corresponding cell by conveyors or smart AGVs. The materials will be put neatly on the shelves and bounded with the corresponding shelves. The information recording the operation on the item, the exact location of the item and its every movement will be recorded in the IoT device/tag and uploaded to the cloud.

(3) The items will be kept as stocks before they are scheduled to deliver to the customers. Cycle counting on the status or changes of the items will be conducted. Given there are any deviation between the record in the cloud and the physical warehouse, the reasons will be figured out by specialized employees and the problem will be tackled according to the instruction received from the cloud. The missing parts, damaged, spoiled or the overdue goods will be replenished in due course. Every change including the dispose, replacement and addition will have a faithful account in the cloud. In the cellular warehouse, products of different categories, shapes, sizes and functions will be stored in different shelves or cells so that the system can locate the items easily. With the inherent priority scheduling algorithm, the system will check the products regularly at different frequencies for a higher efficiency with a lower cost. Important or special products will be counted more often, such as the items ordered by customers of higher priorities, the products stored in thermostats, the perishable goods, and the high-value goods.

(4) The order can be placed by the various channels in Omni-channel retailing, including the website, mobile APP and the market. These orders will be integrated on the cloud and processed in a unified framework. The details of the orders will be released to the physical warehouse, including the name of the items ordered, the promised delivery time and the address of the end-customer. Accordingly, the employees or the machines can prepare the related order fulfillment operations. In the traditional pick-and-pass warehousing system, there will be a picking line that has multiple pickers and each picker will pick the items of an order located in the shelves. The order pickers will be guided by the light indicator quickly to the picking locations. The items will move along the entire picking line to arrive at the consolidation location. When one order is finished, the data of the next order will be sent to all modules in the zone. On contrast, in the cellular warehousing system, the picking

process can be more flexible to save time dramatically. The items will be firstly picked from the shelves. Given some items do not need to be clustered with the other items in the picking zone, these items will be directly moved to the consolidation by the smart AGV and prepared for dispatching. The AGV will generate the shortest path from the location of the items and the destination, while there is no need for the items to go along the entire picking line. Assuming the items need to be combined with other items belonging to the same order, the AGV will also walk along the shortest path to collect all of them before going to the destination. In this way, the transportation time is saved to a large extent. What is more, multiple orders can be deal with at the same time, because the AGV can help cluster the items of the same order. Given the items of different orders will not pass the same picking line, they will not be mixed up. All these movements will be computed on the cyber layer.

(5) The items picked from the shelves will be transmitted along the planned path to the consolidation. As mentioned, usually, in the traditional pick and pass system, the items are moved along the conveyor belt, so the items have to pass all the zones even if some do not need to be consolidated with the other items, leading to a waste of time. In the PI-enabled cellular warehousing system, smart AGVs will play a more important role. Before arriving at the goods will only go through some pre-determined cells where they will be operated on or aggregated with the other goods. In the consolidation cell, the goods are sorted and clustered again. To save the waiting time in the consolidation station, it is important to establish the appropriate intra-cell synchronization algorithms. In this way, different cells can operate on the items belonging to the same order simultaneously. When they arrive at the consolidation station within the same period, they can be aggregated quickly for the following packing and dispatching. The synchronization algorithm will include synchronized order release, order assignment, order scheduling and machine scheduling to support the combination and partition of the orders as well as the concurrent operations of orders. The smooth process will rely on the buffers and smart AGVs. The AGV will move the items to the consolidation along the optimized path and some buffers need to be set in each cell and the consolidation station to avoid the congestion. When some items arrive early, they will be assigned to the buffers to wait for the late-coming items of the same order. With appropriate synchronization algorithms and buffering control tactics, the deviation in the arriving time can be shortened as much as possible to save time and the space needed by buffers. The consolidation efficiency should be high enough so that the consolidation station will not become a deadlock of the warehouse, since the operation speed and the transit speed have been increased a lot in the PI-enabled cellular warehouse. With the support of synchronization, it is possible to achieve the concurrent or parallel cross-cell operation on multiple orders or multiple jobs with minimized throughput time.

(6) The goods will be packed and loaded to the vehicles at the dispatching bay. The cloud will inform the warehouse keeper or the machines of detailed shipping plan, including the assignment of the goods to the vehicles, the planned delivery schedule, the paths, the addresses of the customers and other specific requirements of the customers. The whole intelligent loading and dispatching process will be supported by PI. Each vehicle, item, and loading machine can be tracked and traced by the cloud. The cloud will guide the loading machine to automatically move the item to the corresponding vehicle. The outbound record will be uploaded to the cloud.

(7) It is noteworthy that cross docking is still allowed in a PI-enabled cellular warehouse. Given some items are ordered at once when they arrive at the warehouse, they will be directly moved to the dispatching location by the smart AGVs to save operation time and storage space.

3 The key elements in a PI-enabled cellular warehouse

To support the above processes, a general PI-enabled cellular warehouse is shown in Figure 2 with two layers: the physical warehouse layer and the cloud cyber decision layer.

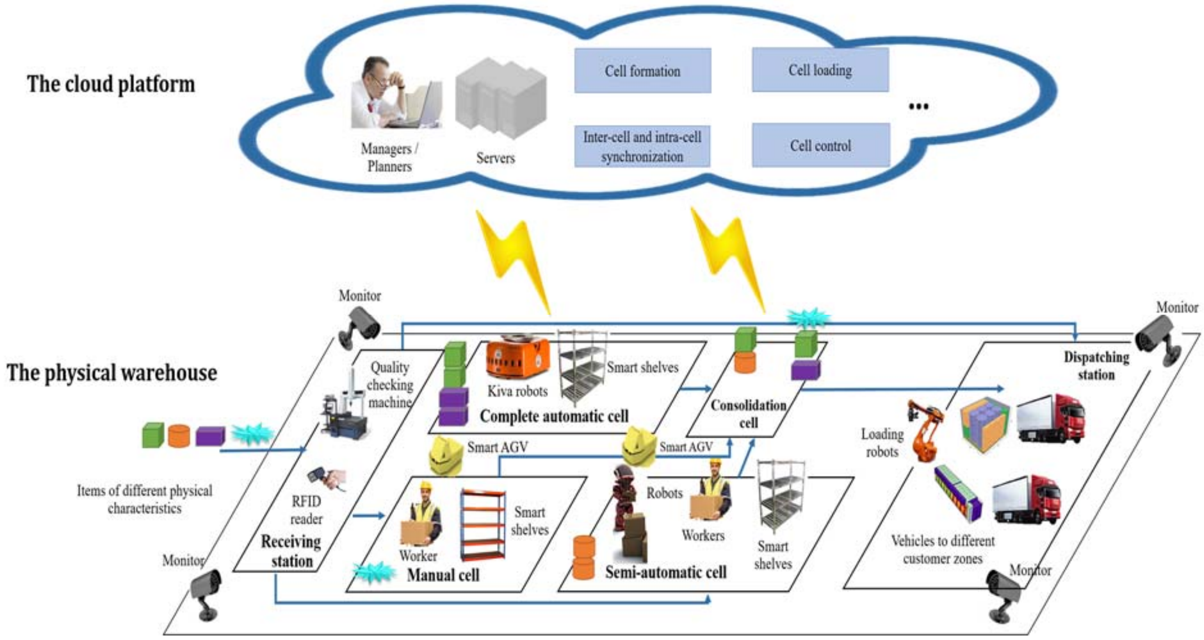

Figure 2: The key elements of a cellular warehouse

3.1 The physical warehouse layer

As illustrated in Figure 2, the physical warehouse consists of “smart” opertors, facilities and materials, which are distributed in the receiving station, warehousing cells, consolidation cells and dispatching stations. Every item is “smart cago” enabled by IoT device/tag, recording and updating the corresponding information, such as the name, quantity, quality, location and logistics status. All men and machines within the warehouse are equipped with a transceiver to achieve interoperability with surrounding environment. They can upload the data to the cloud real-timely while receiving the instructions from the cloud. In addition to the transceivers, the monitors are spread all over the CW so that the managers or planners can keep watch on the process in the physical warehouse easily. The intercell and intracell movement of the materials are mostly completed by smart AGVs, since they can move more flexibly compared with conveyors. The path of the AGVs will be planned via the cloud in advance. The blue arrows in Figure 2 stand for the material flows among the cells. The detailed introduction to the elements within each cell is as follows:

(1) Receiving station: smart IoT devices will be implemented in the receiving station, so the tags of the inbound items will be read efficiently, which carries a lot of information of the items, which vary from one to another in terms of physical characteristics. The information will be uploaded to the cloud quickly a. The smart devices including the quality checking machine will be installed in the receiving station as well. In case any bias is detected, the problem will be uploaded to the cloud and the items will be rejected.

(2) Warehousing cells: there are different cells within the warehouse to operate on and keep the inventory of various items. The exact numbers and sizes of the cells as well as the specific design of cells depend on the needs of the individual warehouse. Generally, there are three types of warehousing cells in the conceptual model of the cellular warehouse. Generally, there are three types of warehousing cells in the conceptual model of the cellular warehouse. The first one is the completely automatic cell. The items of regular shapes in large amounts will be deal with in this cell. High-end automation facilities are installed in this cell, such as the Kiva robots of Amazon. These machines can complete the job with a high efficiency and a low error rate, compared with human beings. However, the major drawback of the automation facilities is that they are usually especially designed to handle some standardized products/boxes. Therefore, the second one is the manual cell that is more like the traditional warehouse. The items of very irregular appearance may not have corresponding automation machines. Given they do not have a high sales volume and come out not very often, it is not worthwhile cast high investment for the design, test and manufacturing of the automation machines to handle them. In this case, the workers will be assigned to deal with the goods. The third kind of cell is the semi-automatic cell, where the automation degree is lower than 100%. The machines and robots are not as advanced as those in the first cell, so the efficiency is relatively low. However, they are designed in a more general way so different goods can be handled within the same cell. The most innovative parts of the warehousing cells are reflected in three aspects: the smart operator, the smart facilities and the smart materials.

- **Smart operators:** In PI-enabled cellular warehousing system, every operator will be equipped with intelligent IoT devices, such as wearable sensors and scanners. They can scan the information and learning about the items easily while operating on the items. Each operator has a good command of multiple skills and is not fixed in one location. They can complete various operations on the item and offer a help to other operators when needed. All their operation data and the data collected by their sensors or scanners will be uploaded to the cloud and be accessible by others.
- **Smart facilities:** The major smart facilities in the PI-enabled cellular warehousing systems include smart trolleys, smart AGVs and smart robots. The trolleys are movable shelves. After the items are well received, the items will be put away on the smart trolleys. They will be bound with the corresponding trolleys and their data will be uploaded to the cloud, describing their name, location and condition. Each trolley has some joint components on their side with which they can be hooked with other trolleys. In this way, the storage facilities can be configured, assembled, expanded and disassembled with ease as needed. The smart AGV can pick some items from the trolleys and move them. Alternatively, the smart AGV can also drag the entire smart trolley to the destination. The basic process is as follows. When some items on the trolley or the entire trolley need to be picked or moved, the trolley will send a request to the cloud. The cloud will look for the most appropriate AGV to complete the job with a consideration of the capacity of the AGVs, their distance to the trolley, the obstacles on the way, the basic transportation needed, the energy to be consumed and the operation cost. The appropriate AGV will be assigned to pick the items or trolleys. This is called centralized decision. In some decentralized scenarios, the assignment and matching job may be completed by the AGV itself. The cloud will only serve as an information sharing platform in the process, and every AGV will receive the request from the trolley. Multiple AGVs will compete for the request on the basis of their own conditions. The trolleys will select the most appropriate AGV which will take the shortest time. Alternatively, other selection methods can be considered. For instance, the first AGV taking action of competing for the task will be assigned to pick the order. The third type of smart facilities is the smart robots. In addition to the robots in receiving station and dispatching bay, most robots are distributed in the warehousing cell. They moved around the warehouse to help in operation, movement, and storage. The smart robots will be equipped with some IoT devices, such as the intelligent tags and sensors, so that the real-time sensing on any status change can be achieved. The managers and supervisors can monitor and control the progress of the smart robots in real time via the cloud with the help of these IoT devices. The seamless communication and operation can be better guaranteed.
- **Smart materials:** Each item should have a smart tag, such as the RFID tag. On arrival in the system, the data of the item will be uploaded. During the entire process, the item will be tracked and traced.

(3) Consolidation cell: in this cell, the machines will consolidate the orders according to the instruction from the cloud. The orders to be sent to the customers in the close zones will be sorted and consolidated. Especially, some intelligent sorting systems have been established, such as the Sure Sort system, t-Sort system and Celluveyor.

- **Sure Sort:** Sure Sort (OPEX Corporation, 2018) is an intelligent extendible sorting system (see Figure 3) for sorting small items, such as the nail polish, potato chip bags and water bottles Sure Sort system is a smart automatic system designed by OPEX Corporation on the basis of mature iBOT delivery technology. The working mechanism is as follows. The Sure Sort will first scan the replenishment and wave or batch picked small items by reading their barcodes. The barcode reading can be completed from any angle regardless of the size, packaging or orientation of the items. The barcode data will be uploaded to the iBOT system and then to the warehousing management system (WMS). The WMS will send the assigned order locations to the Sure Sort in return. The items will be accurately delivered to the end location on a single pass accurately and easily. When the order is completed, the shipping container is transported to a packing station preparing for the shipment. Compared with the traditional sorting system, Sure Sort reduces the number of transfers and conveyors required to complete the sorting work so that the sorting efficiency and accuracy is improved dramatically. 2,400 items can be handled by a single pass per hour. What is more, it is highly scalable in size and throughput. The expansion modules can be added simply to adjust to the growth in demand. It is worth noting that the Sure Sort is mainly designed targeting as the small items, while it does not work well for handling the items in large sizes.

Figure 3: The Sure Sort system (OPEX Corporation, 2018)

- **t-Sort:** t-Sort (Tompkins Associates, 2018) is a sorting, picking and consolidation system (see Figure 4) designed mainly for medium-sized items, such as containers of liquids, bags, boxes, mailers, apparel, footwear, general merchandise, single items and inner packs. It is established collaboratively by Tompkins International and lab Z. It is the first portable automated parcel sortation system in the world, which brings unmatched flexibility and throughput. The uniqueness of t-Sort system is that it uses completed independent robots without tracks. These robots are allowed to travel to any satiation independently along the pre-determined shortest path, just as the smart AGVs mentioned in the last section. Such robots can help greatly enhances the efficiency to maximize the operational capabilities of warehouses. In the system, the free-moving and independent robots are adopted to replace the traditional conveyors, sorters and tilt trays. The space utilization will be increased dramatically so that the required space is reduced. The robots can be modularly added without interrupting or stopping the operation of the system. By offering more flexibility, the system will not face the risk of downtime of the entire system because of a single point of failure anywhere, because the elements are plug and play.

Figure 4: The t-Sort system (Tompkins, 2018)

- **Celluveyor:** The Cellular Conveyor (Celluveyor) is a flexible conveying and positioning system (see Figure 6) that has distinctive advantages when dealing with items of large sizes and complicated shapes, such as mega boxes and some furniture. The Celluveyor is composed of small hexagonal modules, each of which is supported by omnidirectional wheels. These wheels are controlled by an electric motor via the controlling software, and each wheel can be turned into different directions independently. In this way, the wheels in the hexagonal modules can be combined to form a path of any shape that fits the needs. The items can be transported to the destination through the Celluveyor system automatically and the direction of the item can be changed by simple operations on the controlling software. With the innovative design of the wheels and the selective control methods, even large parcels can be moved along any path to any destination via the system easily. Several items can be moved simultaneously on the track, saving a lot of transportation time and the footprints of workers.

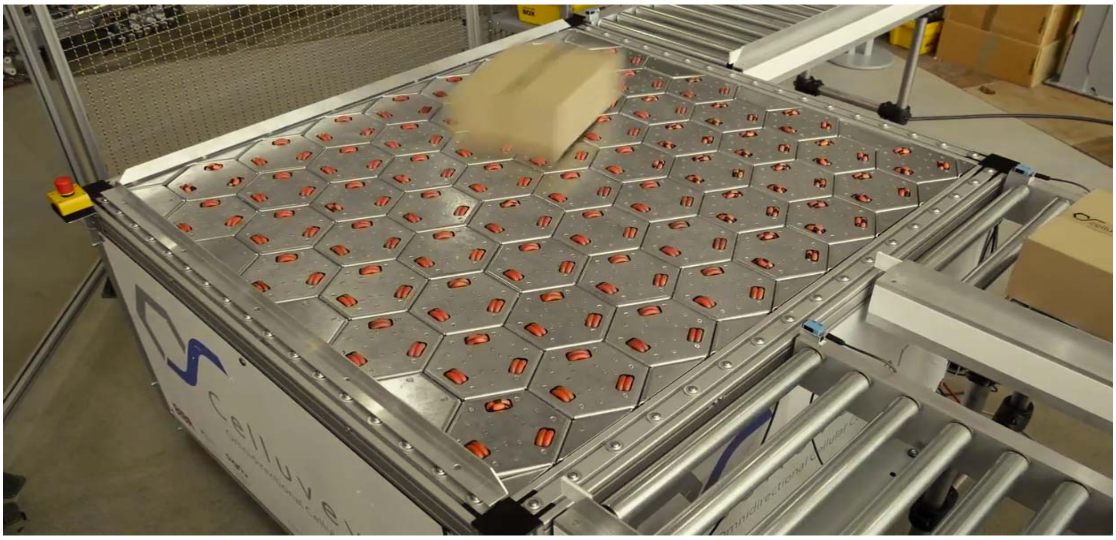

Figure 5: The Celluveyor system (Celluveyor, 2018)

As can be seen, many major logistics companies and labs all over the world are designing new warehousing systems to chasing for higher efficiency, accuracy, flexibility and space utilization rate as well as lower costs and risks, especially when the orders usually come in small batches and items vary from one to another. Some innovative technologies are now available to handle some types of items, such as Sure Sort or t-Sort. However, one sorting system or warehousing system is usually designed for one category or several categories of goods, but they are not able to handle all types of items. Therefore, these systems should be allocated to different cells in the cellular warehouses, and one cell will handle a portion of all orders. There is a need of establishing a framework for formatting the cells and assigning the items to various cells, i.e. the cell formation methods.

(4) Dispatching bay: the loading robots will help handle the loading jobs to save the manpower to a great extent based on smart truck loading schedule. The items ordered by the customers in the adjacent customer cells will be assigned to a departing truck or trailer. The truck will not stay in the dispatching bay for a long time, because a high turnover rate should be guaranteed. Given there are no containers ready, the trucks should not queue in line in the dispatching station to avoid a deadlock. Though in the picture, the dispatching bay and the receiving station are on the opposite side of the warehouse. In reality, they might be located near each other, depending on the design of the warehouse.

3.2 The cloud cyber decision layer

The cloud cyber decision layer mainly focus on the design, planning and optimization-related issues, including cell formation, cell loading with staff/machine assignment, inter-cell or intra-cell synchronization and cell control tactics.

(1) Cell formation: cell formation is the first stage in cellular warehousing design. There have been many mature cell formation methods in the field of cellular manufacturing, including mathematical programming, the visual inspection based method, similarity coefficient technology, the array based method, the graph theory, classification and coding techniques, the neural network, knowledge based system, fuzzy clustering, and simulation of the heuristics system. They are designed to increase the efficiency, throughput, machine utilization rate or reduce the cost subject to the constrains of the machine capacity, technology limitations, cell numbers, and machine availabilities. They might be taken as references when designing the cell formation models in cellular warehousing. For example, Tsai et al. (2006) came up with a multi-functional mathematical programming model to optimize the cell formation in cellular manufacturing, which is induced from conventional classic models (Adil et al., 1996; Dahel et al., 1993; Vakharia et al., 1993). The model can help achieve different objectives such as minimizing the number of intercellular transfers or minimizing the total number of EEs and voids, while constrained by corresponding relationship between the parts and the machines, the number of a certain type of machine in a cell and the processing sequence. This model can be taken as reference when desiging the cell formation in cellular warehousing. In CW, there are also the intercellular transfers of items, which should be reduced as many as possible to save the cost. The objective will be constrained by similar conditions as well. Such model can be referred to when establishing cell formation model in the field of cellular warehousing, because they share similar objectives and constrains. However, several differences exist as well. For example, along with the emergence of smart AGVs which can plan their routes and move freely without strictly restricted paths, the distance from one location to another location is not determined and there will be many more pairs of locations. This will lead to the difficult to compute the distance between two points. For another example, the matching relationship between the part and machines are known in the mathematical model of manufacturing cellular formation problem, while in omni-channel retailing warehouses,large volumes and variarites of ecommerce goods complicate the model formulation. Therefore, the matching relationship has to be found with great efforts.

(2) Cell loading with staff/machine (re)assignment: Cell loading refers to determining which cell among all feasible cells the items should be assigned to and in what kind of order (Suer et al., 1999), which is especially crucial when there are multiple cells within a warehouse. By designing appropriate cell loading process, the work-in-process and lateness can be minimized while the utilization rate of the cells can be maximized. It will also lead to a better balance of the load among the cells. Several tasks will be required, which are product selection, cell selection and order confirmation for assigning the items to cells. In the cellular warehousing, product priority will be considered in the most cases, i.e. the item will be chosen first and then the search shifts to find the cells for the item. There are classic rules for cell loading in cellular manufacturing giving priorities to products or cells which might be referred, including earliest due date, number of feasible cells, number of cells required and cell loading rules.

(3) Inter-cell or intra-cell synchronization: Synchronization of the inter-cell and intra-cell operations can help increase the efficiency and reduce the cost. With appropriate synchronization mechanism, the items finished in one cell do not need to stay a long time in the consolidation state for the other items belonging to the same order. Given they can arrive within the same time window, they can be packed quickly for dispatching. To achieve the synchronization, different cells should have the identical operation time on the items of the same order and the machines should be synchronized with the operators. This can be achieved with the full use of the cyber optimal decisions in cloud. The operation data will be uploaded to the cloud in real time, so that the pace of the set up or operation of one machine/robot can be adjusted according to the status of another one in the same cell or another cell.

(4) Cell control: The overall cell control includes the control of the stock, indoor transport, operation, inspection and packing within the cells. Especially, the control over the workstation includes the control of machine setup, the material handling and the buffers. Cell control is vital since it can facilitate minimizing the exposure risk to single point failure, improving the total warehousing performance, providing responsive decision support tools and saving operation costs (Huang et al., 1992). To offer the potential for improved cell control, both software and hardware supports are needed. The software should be used to facilitate the system (re)configuration and easy–to-customize for specific warehousing scenarios. The hardware should facilitate expansion and modification for a higher degree of flexibility.

4 Case Study

Through some visits to the major ecommerce logistics companies and the collaboration work with them, our research team has observed that some companies have set about upgrading their warehouses, which might be considered as an early version of PI-enabled cellular warehousing system. The Figure 6 is the warehouse plan of Alibaba Group (left) and COSCO (right)

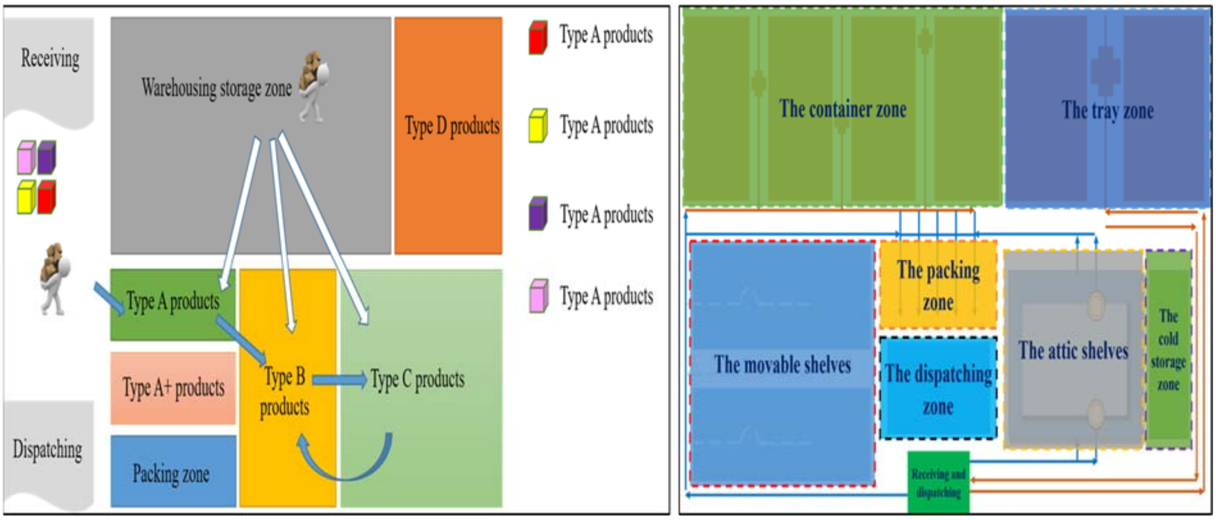

Figure 6: The linked storage and picking mode of the warehouse of Alibaba Group (Huanqiu tech, 2017) (left) and the warehousing plan of COSCO (HKU-Ziri Lab, 2018) (right)

4.1 Alibaba

Alibaba has upgraded their warehouses with automation as well and is attempting to divide its warehouse into different zones for keeping different products (see Figure 6 left).It is planning to roughly partition its warehousing system to three major cells this year.

Currently, Alibaba already has relatively the mature ordering management system (OMS), warehousing management system (WMS) and transportation management system (TMS). In the OMS, one single tag attached on the item contain all the necessary data, including its name, category and locations. Billions of data can be well handled with the powerful computation system and the item location will be identified automatically. In the WMS, the items ordered will be replenished within the required time window automatically. The intelligent robots adopted by Alibaba can lift heavy items, queue, and move away from the obstacles. The TMS is able to track and trace the logistics through the entire process in real time.

However, with the booming development of omni-channel retailing and ecommerce, the varieties and quantities of items will increase dramatically. It is still difficult to cater to the market demand with only automatic warehouses. Therefore, Alibaba Group is considering establishing a preliminary cellular warehouse this year. It is to build a completely automatic warehousing cell with cutting-edge technologies such as Kiva robots, a semi-automatic warehousing cell and another manual warehousing cell with more manpower. Different items will be assigned to different warehousing cell according to the physical characteristics of the items, the popularity or sales condition of the items, as well as the advantages and the capacities of the warehousing cell. Whereas, this is just a relatively rough design now. Because it is urgent for Alibaba to set about building this warehousing system to catch up with the development of the market, Alibaba has not found a method to compute the quantity and confirm the design of the cells with the information of items.

4.2 JD.com

JD is another successful group, of which the warehouse is the rudiment of PI-enabled cellular warehouse. The warehousing center of JD.com is composed of four operating systems: receiving, storage, picking and packing system.

Each operational stage of its warehouse is supported by innovative systems, advanced data processing technologies and algorithms. For example, the receiving station of JD.com is equipped with intelligent robots for unpacking the packages and identifying the items. Then, all inbound and inspected items are put-away in storage area. AGVs are used in internal movements that make full advantage of the QR code on the ground to locate and navigate itself. They can even avoid the obstacles automatically and optimize their paths from the departure point to the destination to save time and distance. In the sorting system, intelligent robots are responsible for the moving items of different sizes or shapes. Advanced visual technologies are applied to act as “eyes” of the machines to achieve the interaction and connection of the robots or machines with the surrounding environment.

The data processing technologies developed by JD.com play an important role in the warehousing process. By making use of the real-time monitoring and simulation technologies, the system can collect the data reflecting the performance of every machine in real time. Given any unusual data is detected, the system can diagnose the error and find the counter-measures from the system to facilitate self-configuration, self-maintenance and self-control.

Deliciated algorithms are adopted by JD.com to improve the warehousing operation efficiency. With these algorithms, the system can automatically suggest the most appropriate storage locations with regard with the sales volume and the physical characteristics of these items. In the dispatching process, the inherent algorithms will compute the locations of the items which is the most appropriate to be picked from many identical items. The scheduling algorithm will suggest the corresponding AGV to move the items, which will incur the lease moving cost in terms of time and distance.

It can be seen JD.com has established different systems targeting at handling products of different shapes, sizes and sales volume, although it has not started to take the further step to locate them into different cells. What is more, the basic algorithms and automatic machines to facilitate the implementation of cellular warehousing system.

4.3 COSCO

COSCO aims at designing a highly flexible ecommerce warehousing s ystem (see Figure 6 right), which has a stable performance in terms of inventory and turnover rate under the fluctuated demands.

To achieve this objective, COSCO has come up with several innovative designs. For example, there are two major types of conveyors in their warehouse. The conveyors of the first type is responsible for transmitting items only and they are equipped with many idler wheels so that they are movable and can be freely spliced. The second type can help in sorting while transporting the items, so they are fixed in the most cases.

Similarly, their shelves are movable as well so that they can be configured as needed. Different movable shelves are selected for keeping goods of different characteristics in terms of size, categories, weights and special requirements on the environment. In other words, products of different characteristics will be sorted by their light sorting system first and then go to different shelves.

Then, their operating tables are extensible so that more working stations can be added in the peak season and vice versa. On the operating tables, most of the machines including computers, weighting machines, packaging machines and monitors are customized according to their needs. These operating tables can be moved freely to combine with other operating tables according to the planned operation process.

In addition, their thermostatic chambers are designed referring to the container concept so that they can be moved with ease. Last but not least, they adopt the mixed-flow turnaround system to integrate the merits of different systems leading to a much higher efficiency

With these innovative designs, COSCO increases their flexibility to a great extent. In the slack season, they will reduce the scale of storage zone and operation zone. The number of conveyors and operators will be cut down. The automation zone is closed to save cost. On the contrast, in the peak season, the storage zone and operation zone will be enlarged to cater to the increasing needs. Both number of conveyors and operators will be increased. The automation zone will be activated so as to improve the operation efficiency and accuracy.

As can be seen, they have partition their warehouse into several zones and the flexibility is high. However, there is still room for improvement. For example, the adjustment from peak season to the slack season may leave some machines idling. It seems that they do not have a mature plan to deal with the excel capacities to reduce the opportunity cost. Therefore, a wiser plan of establishing cell warehousing systems is needed to further enhance efficiency and flexibility while reducing the waste of resources.

5 Discussion and conclusion

The era of omni-channel retailing is just around the corner, which will bring valuable opportunities and critical challenges to the logistics, especially the warehousing area. Considering the orders will come from various ordering channels any time in small batches and large varieties, the traditional manual warehouses or automatic warehouses are not capable enough to cater to these complicated order fulfillment scenarios, not to mention the increasing tight delivery due date. By referring to the cellular manufacturing concept which improves the operation efficiency greatly, this paper comes up with the paradigm of cellular warehousing. With the emerging and innovative technologies, it is possible to apply this concept in the near future. This paper suggests the general process and basic elements to support the operation of a typical cellular warehouse. The practices of three leading Chinese ecommerce logistics companies are briefly discussed, which verify the necessity of establishing a new paradigm of warehousing system and can be considered as a very early form of PI-enabled cellular warehouses. The avenues of the future research on the implementation of cellular warehousing concepts are open, because there are still many specific research, technical and development questions with regard to cellular warehousing.

Our future work on cellular warehousing will mainly consists of three areas, which are the framework of cellular warehousing, the cellular formation models and the impact of uncertainties on cellular warehousing.

First, the framework of cellular warehousing will include some major problems, such as the competition and collaboration game theoretical relationship among the cells, the dynamic equilibrium of workers/machines/items, the impact of advanced technologies such as the big data, the exact constrains or conditions to apply the cell concepts into a warehouse for major logistics companies and small or medium sized logistics players, and the technologies required to support CW implementation.

Second, the cell formation method will be suggested, which is the first stage in cellular warehousing design. There are some research questions with regard to cell formation.

- What is the objective of cellular formation?
- Which method among many mature manufacturing cellular formation methods is more applicable to CF problems in cellular warehousing?
- What is the impact of key parameters on cellular warehousing formation?
- What is the impact on the stakeholders of improved cellular formation?

Third, the uncertainties from many sources will be discussed, such as the fluctuating demands and the composition of an order structure, leading to a changing requirements on the capacity and efficiency of the warehouses. The priority of customers is another source of uncertainty, requiring a reasonable and practical algorithm to sequence the various orders to optimize its service level. To further explore the impacts of these uncertainties on the performance of cellular warehousing, some classic methods for cellular manufacturing such as modelng and simulation might be applied to CW to simulate the real cases.

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