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Design and application of Internet of things-based warehouse management system for smart logistics

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Warehouse operations need to change due to the increasing complexity and variety of customer orders. The demand for real-time data and contextual information is requried because of the highly customised orders, which tend to be of small batch size but with high variety. Since the orders frequently change according to customer requirements, the synchronisation of purchase orders to support production to ensure on-time order fulfilment is of high importance. However, the inefficient and inaccurate order picking process has adverse effects on the order fulfilment. The objective of this paper is to propose an Internet of things (IoT)-based warehouse management system with an advanced data analytical approach using computational intelligence techniques to enable smart logistics for Industry 4.0. Based on the data collected from a case company, the proposed IoT-based WMS shows that the warehouse productivity, picking accuracy and efficiency can be improved and it is robust to order variability.

Keywords: Internet of things; warehouse management system; low–volume, high-mix; Industry 4.0; smart logistics

1. Introduction

To enhance productivity and cope with the changing needs of customers, product design, production, packaging and distribution accordingly. In 2011, a new concept, Industry 4.0, was introduced in Germany. In the context of Industry 4.0, the future logistics on how physical objects are transported, handled, stored, supplied, realised and used across the world can be reshaped by Physical Internet so as for improvements in logistics efficiency and sustainability (Montreuil 2011) and cyber-physical systems and Internet of things (IoT) make it possible that industry-relevant items like materials, sensors, machines and products or in terms of Physical Internet containers are all connected and communicate with one another. All the connected items can be tracked and monitored so as to allow manufacturers to know the patterns and performance. With the decentralised intelligent decision-making, Industry 4.0 can be described as the increasing digitisation and automation of the manufacturing environment as well as the creation of a digital value chain that enables communication between products, the environment and business partners (Lasi et al. 2014). Industry 4.0 represents the coming fourth industrial revolution by adopting IoT, information and services for the next production paradigm. Decentralised intelligence helps create intelligent networks and optimise independent processes, with the interaction of the real and virtual worlds representing a crucial new milestone in industry development. Industry 4.0 represents a paradigm shift from ‘centralised’ to ‘decentralised’ production – made possible by technological advances, which constitute a reversal of conventional production process logic. Industrial production machinery no longer simply ‘process’ product, but the product communicates with the machinery to tell it exactly what to do (Wang et al. 2016). Industry 4.0 introduces an embedded system with latest production technologies. Smart production processes pave the way to a new technological age, which will radically transform industry and production value chains and business models.

Apart from production, inbound logistics and outbound logistics pay an important role in fulfilling customer orders. The role of the warehouse has changed dramatically due to the complexity and variety of customer orders, the demand for real-time information and data accuracy. Therefore, it raises the problem that the traditional manual operation leads to low warehouse operation efficiency and is no longer responsive to the customer requirements. Among all the operations in the warehouse, research studies found that the order picking process can account for 50–55% of total operating expense (Frazelle and Frazelle 2002; de Koster, Le-Duc, and Roodbergen 2007).

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The contemporary warehouse management system (WMS) used by manufacturers is required to support the changes in production orders and to enhance the efficiency of the warehouse operation (Lee, Cao, and Ng 2017). Generally, WMS is always associated with auto-ID data capture technology in order to improve the inventory control and minimise the manual operation. The purpose of this research is to design and evaluate the effectiveness of the IoT-based Warehouse Inventory Management System for the low-volume, high-product mix situations faced by manufacturers, so as to achieve better performance of the receiving, storage and picking activities in the warehouse.

Furthermore, the order picking process is the major bottleneck of the warehouse operation. Therefore, we propose WMS integrated with the fuzzy clustering technique in order to suggest the most suitable order picking method and to enhance the efficiency of the order picking process. Through the proposed WMS system, the warehouse activities, including the receiving, storage and order picking, can be managed and improved.

In view of difficulties described above, the manual operation should be replaced by an advanced WMS. The functionality of the WMS, such as the order picking method, is proposed. An IoT device can provide the pickers' work location information on the items, such that the efficiency of the order picking process can be enhanced. On the other hand, the high workload of the workers is the core problem. In the manual operation, it is very common that the worker places the product randomly and the picking process relies on worker's memory and experience. Therefore, the operation is very time-consuming, and the workload of the worker is relatively a higher compared with a highly automated warehouse. As a result, the morale of the worker will be reduced, leading to a high turnover rate.

Because of the above problems, an IoT-based WMS is proposed in order to minimise the warehouse operation process. The reduction of unnecessary processes can reduce the workload of the picker by applying the IoT-based technology in the receiving process instead of a manual paper record of the inventory. Therefore, it can help to improve the efficiency of the warehouse operation and increase the job satisfaction of the workers.

In this paper, Section 2 lists a current research review for warehouse management in coping with low-volume, high-product mix with IoT technology. Section 3 outlines the whole framework of the proposed system and a case study is presented in Section 4 to validate our proposed system. The last section gives the conclusions and lists the limitations and future work.

2. Literature review

2.1 *Challenge of warehouse operation in the era of industry 4.0*

Inventory accuracy, space utilisation, process management and picking optimisation are the major challenge in modern warehouse management (Richards 2014). An agile supply chain strategy becomes a necessity in a supply chain network. In order to maintain smooth inbound and outbound logistics, there is a need to enhance the flexibility in the changing environment and reduce the total cycle time of a supply chain system. The cyber-physical systems (CPS) network becomes a mediator to connect people, objects and physical processes in a warehouse operation over the IoT, a wireless network (Culler and Long 2016). The emergence of the CPS network fosters responsiveness and flexibility in WMS (Leitão, Colombo, and Karnouskos 2016). Evolution from the traditional WMS to CPS-WMS requires the integration of technological and administrative innovations, and this becomes the major challenge for the design of WMS. These include proper selection of CPS technologies, ambient intelligence, timely information flow and agility (Reaidy, Gunasekaran, and Spalanzani 2015).

2.1.1 *CPS technology in WMS*

The implementation of the CPS-WMS assists in the establishment of cooperation between human, intelligent machines and robots, transparent in the performance of a smart WMS (Posada et al. 2015). Reviewing the nine pillars of technology in supporting the development of CPS-WMS, the common technologies includes radio frequency identification/near-field communication (RFID/NFC), wireless sensor and actuator networks (WSANs), IoT and Cloud computing (Qiu et al. 2015; Wan et al. 2016). CPS network synergises the growth of big data analytics with these separated key-enabling technologies to provide insight towards greater value proposition, analytical powers and decision-making process (Waller and Fawcett 2013).

2.1.2 *Ambient intelligence*

The availability of CPS technology in WMS helps to facilitate the traceability and transparency in warehouse operations via the use of ambient intelligence (Olaru and Gratie 2011). The heterogeneity and composability of the ambient intelligence system allow the system to detect the activities and interactions of operation within the warehouse (Atmojo et al. 2015). In addition, the system contains multiple synchronous decisions. If an improper software framework is developed, a deadlock condition may arise during the running of the system (Atmojo et al. 2015).

2.1.3 *Real-time information sharing*

With the purpose of remaining a high level of agility in CPS-WMS, the CPS network requires real-time information monitoring and visibility of the CPS system among all the operations and activities within the WMS (Reaidy, Gunasekaran, and Spalanzani 2015). The advanced connectivity of data acquisition between the physical operations and visual system is of the essence (Lee, Bagheri, and Kao 2015). Real-time information sharing enables right decision support and coping with the changing requirement from customers.

2.2 *Latest research development of IoT for WMS*

WSANs create transparency and value in WMS with more vigorous and sophisticated support decision-making. IoT becomes the essential element in CPS-WMS, which enhances the visibility and real-time taking in management through WSANs. Deploying automated data acquirement enables communication between warehouse operations in the cloud platform or big data infrastructure (Tracey and Sreenan 2013). Intelligent WMS enhances the tally process, simplifies the operations and increases the degree of automated WMS (Ding 2013).

Application of IoT-based WMS has become popular. RFID technology is widely adopted in warehouse management, as the technology allows trace and track and identification of specified objects. Chow et al. (2006) proposed a RFID-based WMS for the retrieval and matching process of customer orders to enhance the throughput of the warehouse and provide an accurate inventory monitoring system. Poon et al. (2009) utilised RFID-based order-picking operations to reduce the likelihood of operational errors. Besides, the integration of RFID-based WMS and Enterprise Resource Planning encourage the development of Event-driven Process Chains (EPC) in business process management (Liu, Jeng, and Chang 2008). Furthermore, WSNs is another complementary research approach in assisting information extraction on the conditions of objects. However, it is challenging in data acquisition, distribution and mining (Wang et al. 2014). In order to obtain complete logistics order tracking in the tobacco supply chain, the tracking and delivery in in-bound and out-bound logistics was reviewed by Jiang and Su (2013) employing Global Positioning System (GPS), Geographic Information System (GIS) and General Packet Radio Service (GPRS). Yang (2012) proposed a location-based system for forklifts in order to monitor the logistics activities in an intelligent warehouse.

The deployment of IoT facilitates the development of the automated warehouse. Kim and Sohn (2009) introduced a control system for managing industrial machines, resources and products via IoT in an information technology infrastructure. Alyahya, Wang, and Bennett (2016) further studied the feasibility of an RFID-enabled automated storage and retrieval system without manual intervention. Bajic (2009) presented a platform with IoT and the ambient network between the product, process, environment and users for agent warehousing management. The proposed agent-based WMS, which allows remote action invocation, becomes the service-based control point in providing a high level of manageable capability and the enhancement of operational efficiency. Finally, process control in WMS comes in to the CPS network era, which further enhances the control level from automated WMS to virtual synchrony of physical objects. This perspective allows WSANs-based communication in an autonomous CPS-WMS.

Although there are more findings of applying the IoT concept in WMS to enable autonomous characteristics for CPS, there has been sparse research illustrating the practical and operational level of WMS, such as order picking using computational intelligence with IoT to enable smart logistics.

3. Framework of proposed WMS

The purpose of this research is to design and evaluate the effectiveness of an IoT-based WMS for a low-volume, high-product mix scenario. Due to the complexity of IoT data synchronisation in this WMS, the status tracking and connection of the cyber-physical system is extremely important so as to maintain data consistency. This is why the proposed IoT-based WMS system is highly desirable. In this section, the workflow of the low-volume, high-product mix WMS is proposed, and the whole framework is provided and embedded with appropriate techniques to handle different problems at each stage.

3.1 *Workflow of low-volume, high-mix scenario WMS*

Warehouse activities include the inbound area activities and outbound areas activities, like receiving, storage, quality inspection, picking and shipping. However, in the low-volume, high-mix industrial environment, other than the inbound and outbound areas, the internal processing is another very crucial part in warehouse management as this particular warehouse configuration allows a higher flexibility of purchase order (PO) change.

Figure 1 illustrates the warehouse activities with the typical workflow of a low-volume, high-mix scenario. When a new order comes in, the Bill of Material is generated based on the required quantity of different raw materials such that the production process can start on time, without any delay. If the required materials are available, the picking activities proceed from like inbound store or sub-store. After checking the current inventory, if the quantity of the required materials is inadequate, a PO for the shortage is generated. It triggers the inbound logistics activities so that the outstanding amount of material is received afterwards. In between, the internal engine is responsible for changing the orders. If the customers call for pull-in, push-out or cancel of a certain order, the PO adjust to the different situations to update the corresponding information. The updated PO leads to inbound warehouse activities, which correspond to the new PO.

3.2 *IoT-based WMS*

In the highly customised and flexible low-volume, high-product mix industry, the involved raw parts and semi-finished goods are in small amounts with high variety. The information exchange and updating is a crucial problem in handling the new orders, while order changes always occur. The proposed IoT-based WMS fully utilises RFID technology and wireless sensors to track and trace the raw parts, semi-finished goods and finished goods. The embedded system helps collect all the information changes and updates of the warehouse activities. With IoT technology, the incoming parts and activities are all controlled, and the inconsistency due to order change or updating can be automatically handled and solved by the proposed system.

Figure 2 shows the framework of the proposed IoT-based WMS: raw material, semi-finished goods and finished goods are stored in the warehouse, sub-store, or are pending for delivery in the distribution centre. In the IoT environment, all the parts are labelled with an RFID tag. The parts or products are identified from the RF reader antenna and then information is transmitted to the radio identification reader and subsequently through the RFID middleware to the EPC information server. The host application then integrates applications according to different needs (Lv et al. 2012,

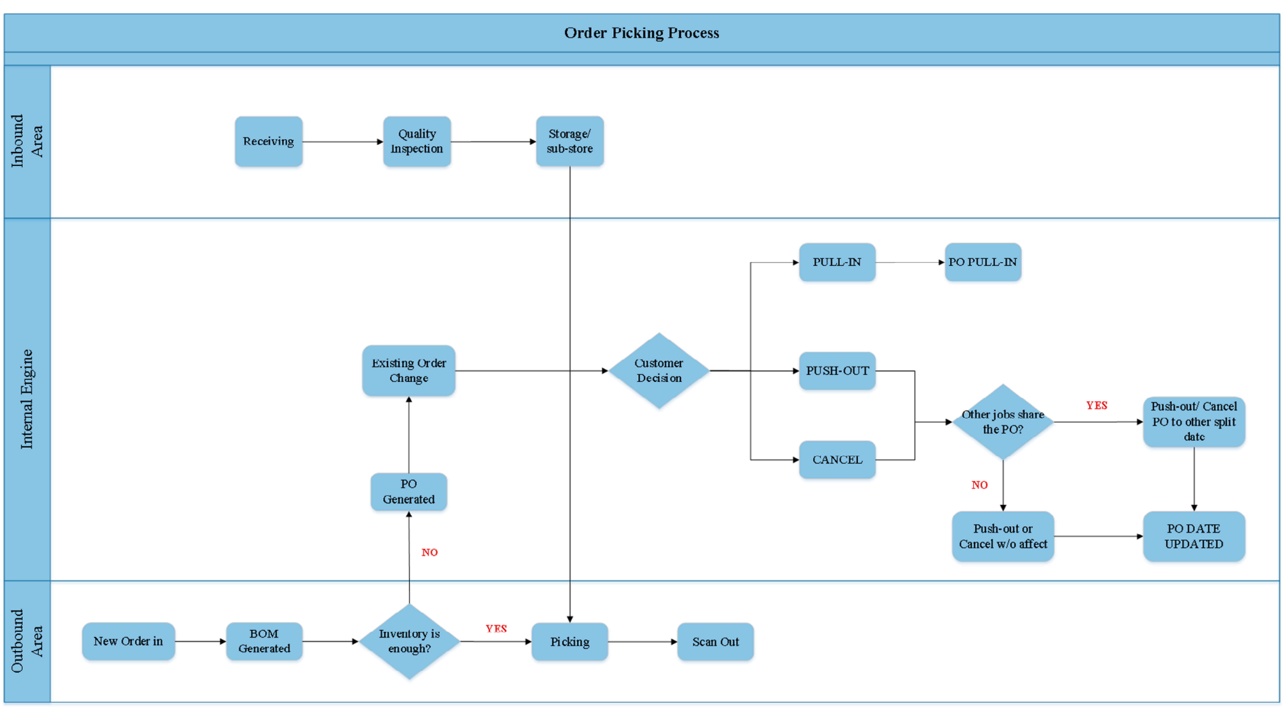


Figure 1. Workflow of low-volume high-mix manufacturing inventory management system.

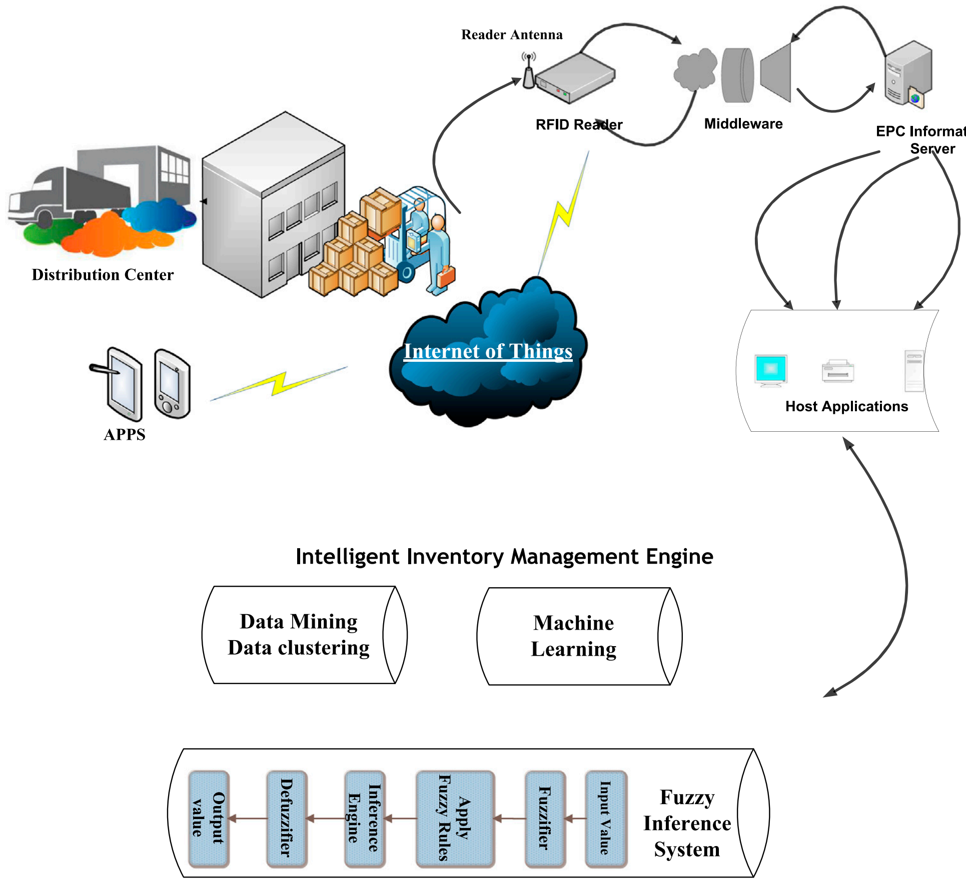


Figure 2. The framework of proposed IoT-based warehouse management system.

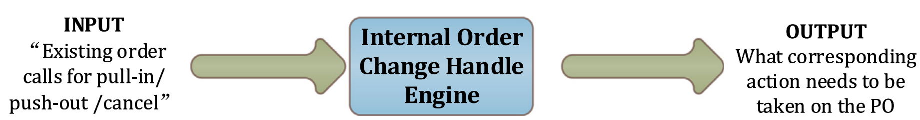


Figure 3. The function of internal order-change handle engine.

2013). Since this proposed system is designed for a low-volume high-mix scenario, which is the typical situation faced by the manufacturers in the Industry 4.0 era, the customisation of orders requires high flexibility of information updating. That is why the collected information by RFID can be mortified or deleted by authorised staff via mobile apps any place at any time. To synchronise and optimise the inventory, the data and information are inputted to an intelligent inventory management engine to handle order change and picking problems, among which data clustering and some machine learning methods as well as fuzzy inference system are applied for information processing in decision-support. The output is transmitted back to the host application and shares the results with the mobile apps. Hence, the staff involved in this IoT-based WMS can receive the corresponding action information.

As specified in Section 3.1, the inbound logistics for receiving goods can be easily settled by IoT technology. The internal engine focuses on handling order change, as shown in Figure 3. The input is the change requested from customers on existing orders, inclusive of pull-in, push-out and cancellation. In the low-volume, high-mix scenario, most of the parts under a certain PO include common parts, and because of the Minimal Order Quantity one PO may serve for several job orders. Therefore, the internal engine will build up an efficient and effective logical, rule-based engine to provide the correct action, which avoids affecting other job schedules.

After all, if all the POs are confirmed with sufficient inventory, another significant operation of the warehouse management is order picking. Picking is more complex and difficult than the receiving processes, and the proposed system integrated with the fuzzy logic technique suggests the most suitable order picking method to enhance the efficiency of operation. One of the advantages of the fuzzy logic model over other approaches is that it is easier for the end-user to understand through its linguistic fuzzy terms, fuzzy values and logical reasoning process. For the qualitative attributes like configurability, the outstanding easy-to-understand feature of our model makes it useful for non-numerical or insufficient input-data assessment feasible to meet real-life needs. Its second advantage is the ability to adopt end-user's domain knowledge or business logic into the measurement process through refining or customising its fuzzy systems. Figure 4 shows the picking process with fuzzy logic technique.

When the warehouse operators receive the goods from the production department, information on the goods such as SKU number, PO number, customer details, quantity and the location is captured by IoT technology in the data collection module. Such information is taken into account to generate the best order picking method. In this order picking module, the fuzzy logic engine is involved. In this module, the fuzzy logic theory is applied in order to assess the most appropriate method of order picking to improve the efficiency of the order picking process. Fuzzification is the first step in the fuzzy logic engine. After the data are collected by the RFID, the input data are converted into the fuzzy set and the characteristic is mainly determined by the membership function using the formulation:

$$M_{fc} = \left(U|\mu_{ik} \in [0,1]; \quad \sum_{i=1}^{c} \mu_{ik} = 1; \quad 0 < \sum_{k=1}^{n} \mu_{ik} < n \right)$$

where $i = 1, 2, \ldots, c$ and $k = 1, 2, \ldots, n$.

In the engine, the working principle of the inference process is to transfer the input fuzzy set into the fuzzy inference engine, where the process involves rule block formation and rule composition. The final step of the fuzzy logic is defuzzification. In defuzzification, Graded Mean Integration Representation is adopted in order to calculate the results. The GMIR can be described as follows:

suppose L^{-1} and R^{-1} are inverse functions of functions L and R, respectively, and the graded mean h-level value of generalised fuzzy number $A = (c, a, b, d; w)_{LR}$ is $h[L^{-1}(h) + R^{-1}(h)]/2$, then the graded mean integration representation of generalised fuzzy number based on the integral value of graded mean h-levels is:

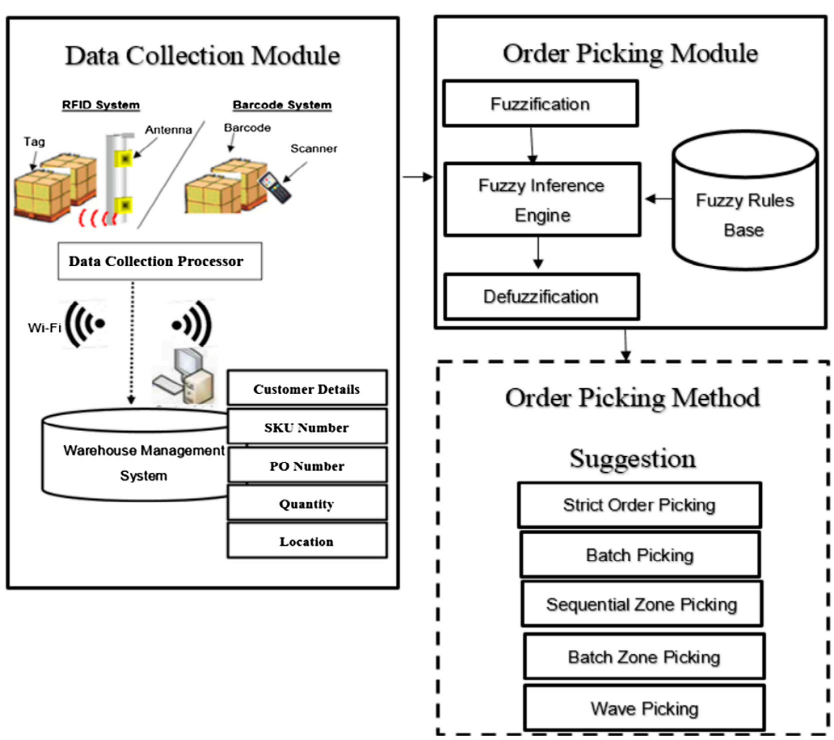


Figure 4. Picking processes with fuzzy logic technique.

$$P(A)=\frac{\int_0^w h\left(\frac{L^{-1}(h)+R^{-1}(h)}{2}\right)\mathrm{d}h}{\int_0^w h\mathrm{d}h}$$

where h is between 0 and w, $0 < w \leq 1$.

Through this process, the crisp values can be generated so as to assess the order picking method for the picker's operation in the picking activity, with respective actions such as strict order picking, batch picking, sequential zone picking, batch zone picking, wave picking. Table 1 summarises the order picking a policy and analyses the advantages and disadvantages of each policy (Ii 2000).

Table 1. Comparison of order picking policy.

Order picking policy	Description	Advantage	Disadvantage
Strict order picking	Each worker handles one order at one time. In other words, a worker will go to one picking station and finish one order	Simple and clear order picking approach for the worker Allows direct error checking by the worker Does not require re-handling of the goods such as sorting	Lower efficiency for an order with a lot of single items
Batch picking	Batch Order picking means that each worker will pick more than one order at one time. In other words, the worker will go to one picking station and finish several orders	Higher efficiency Less travel time per item	More complicated than the strict order picking. Sorting for each batch order is required, and space for sorting is required More potential error
Sequential zone picking	The worker will pick one order at a time, and the picking sequence is from zone to zone. The worker will pick the goods from their zone and then pass the picking list to another worker. The next worker also will pick the goods from their own zone and then pass it again until the picking list is finished and then go through all the zones	Suitable for a large distribution centre No sorting is required Increase responsibility of picker and house keeping	Difficult to define the zone and zone capacity Imbalanced workload in picking zone
Batch zone picking	Orders are picked and put on the conveyor belt and sent to other zones. Sorting is conducted in the final area	Volume picking of single or several items is allowed	Loss of order integrity Error of picking and sorting increases the chance of errors Imbalanced workload in picking zone
Wave picking	Wave picking occurs when the worker picks a batch items requiring long completion times. In this situation, the worker will finish the first wave and then start to pick the second wave. The wave picking is not finished until all the waves are picked	Maybe higher efficiency compared with batch picking in a large distribution warehouse	Loss of order integrity Error of picking and sorting increases the chance of error Imbalance workload in picking zone More time for order consolidation

This above depicts how the inbound area, internal engine and outbound area work is used to handle the whole order picking problems with the proposed IoT-based inventory management system. This system connects and communicates all the parts/goods, locations and workers together in real-time with the embedded intelligent warehouse management engine, which provides suggestions for corresponding actions in different scenarios.

4. Case study

In this section, a manufacturing company (with an alias name CCI) is discussed and studied. CCI is a reputable manufacturer of Box Build and Equipment Manufacturing, who focuses on High-Mix, Low-Volume Contract Manufacturing Services and Equipment Integration. Due to CCI's high-mix low-volume mode, the manufacturing material components accumulate enormously in the warehouse. With the high complexity of raw materials and semi-finished goods, CCI encounters difficulties in maintaining the inventory at a reasonable level.

CCI's low-volume, high-mix manufacturing mode determines its order-driven material inventory management process. With IoT technology, the material flow is controlled, and at the same time, the information flow is transparent in the company, which allows the planners to respond quickly to any new situation. Compared with traditional forecasting and planning, IoT allows users to obtain more relevant contextual information on the environment through sensors, actuators and computation tools to ensure smart behaviour. Accurate forecasting methods can calculate the material requirement for mass production. However, CCI faces typical low-volume, high-mix situations and forecasting are not easy, with wrong forecasting always leading to high inventory. That is why CCI operates on an order-driven mode, which requires material real-time monitoring capability and prompt order-change handling capability. Under such circumstances, the proposed IoT-based WMS is introduced to CCI for monitoring a wide variety of materials and in handling different scenarios automatically. This section discusses how the proposed IoT-based WMS works for CCI.

4.1 *Processing engine for PO synchronisation*

Figure 5 presents the workflow of CCI's inbound logistics activities. Firstly, the goods are received and temporarily stored in the inbound area of the warehouse. Then, the workers do inspections such as checking the quality and counting the amount of the incoming goods. If there are defects or non-conformance of the purchase requirement, the goods

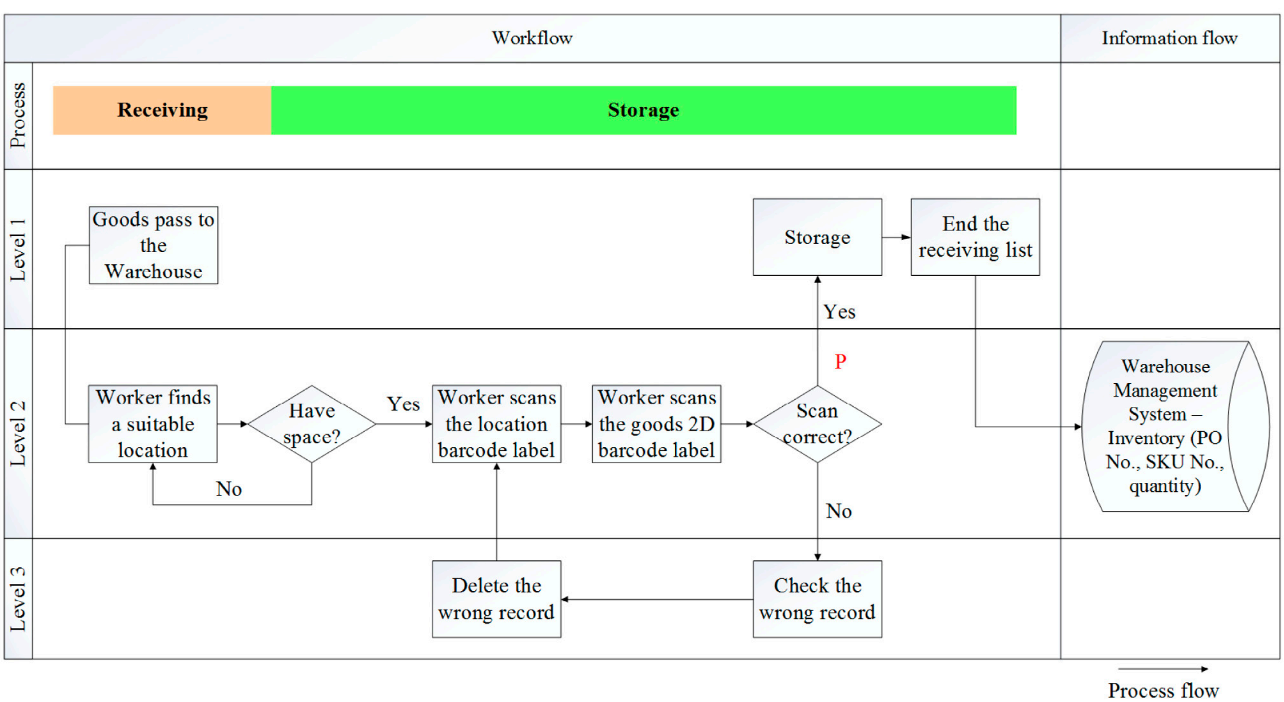


Figure 5. Workflow of CCI's inbound inventory processes.

will be returned to the manufacturer. If the goods meet the requirement and meet the conformance level, the storage process will proceed.

In the storage process, the workers make use of RFID technology to record the information. In this process, there is a potential error such as recording the inventory higher or less than the actual inventory received. After the worker records the goods information, a check is needed as to whether the record is correct or not. If the record is correct, the storage process is complete. If the record is incorrect, the worker checks out the wrong record and deletes it. After the deletion process, the worker re-records the goods.

Meanwhile, information flow is involved. Once the worker uses the technology record the goods information such as the storage location and goods quantity, all information passes through the wireless update in the WMS. Once the data are recorded in the data collection module, the data passes to the order-picking module as the input variable and the best order picking method is then generated.

As mentioned in Section 3, work at this stage is quite straightforward with the incoming goods record. Figure 6 is the interface of the mobile apps, which is proposed for CCI to record and update the information of the various items.

4.2 *Internal processing engine for PO synchronisation*

When CCI's customers request certain projects are having a low-volume, high-mix requirement, CCI builds up many jobs under the project in the ERP system with corresponding information like item number, scheduled start date, required quantity, etc. Through CCI's ERP system, the required items such as quantity on hand, order lead time and costs. as shown in Figure 7, can be checked.

Normally for a particular project, jobs will be generated at the same time to get a holistic understanding on any shortages. Once there is a shortage of a certain item, a PO will be generated. But in the low-volume, high-mix situation, items are always used across different jobs/projects. Due to different scheduled start dates, the need date for same item will be different for different jobs. That means one PO will serve multi-jobs. However due to the various lead time of items, the PO promised by the vendors cannot be confirmed at the specific times. CCI faces the problem that for a particular job, not all the PO, can arrive on time to meet the scheduled start date. If items on one PO arrive later than other PO, it will definitely lead to waiting. This is a crucial issue to bring up high inventory for CCI. Therefore, CCI wants to have an intelligent engine to help them solve such problems. If some PO is confirmed as late, is it possible to push out some existing POs without affecting other jobs? This engine is designed to point out possible push-out items to reduce inventory. Here, a simple example is depicted to explain what the engine does is shown in Figure 8.

An online report in JavaScript is designed for CCI's request, providing the report as shown in Figure 9.

This excel report displays a job 'WA6246-GY10' with a list of needed items of shortage. For example, the job was scheduled on 18 September 2015 but different PO with promised date for different items. Some POs are confirmed to be late, so this job has to be push-out. To avoid high inventory, the proposed system will suggest some existing POs for push-out. For CCI's case, one PO will serve more than one job. Therefore, before pushing out a PO, a check as to whether it will affect other jobs must be done. After full synchronisation, the results are shown in Figure 8.

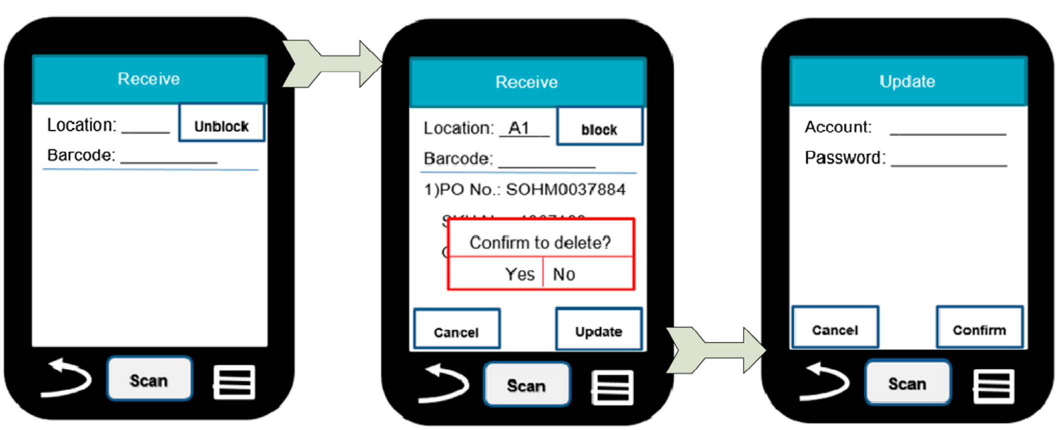
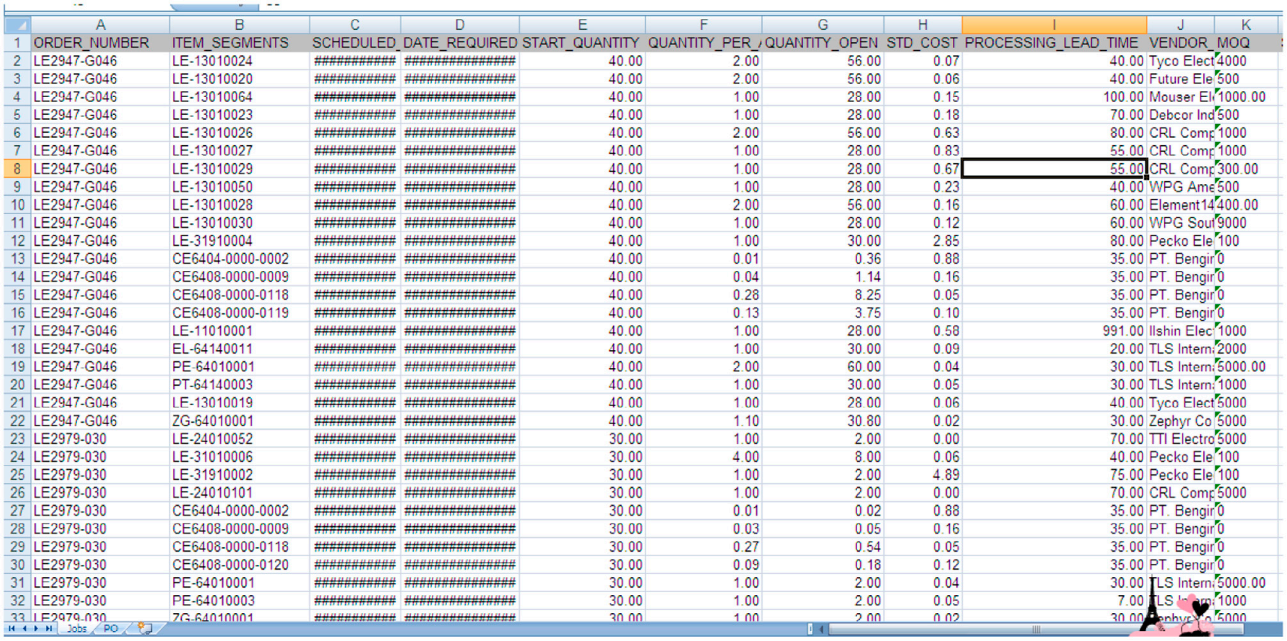


Figure 6. Interface of mobile apps for receiving process.



	A	B	C	D	E	F	G	H	I	J	K
1	ORDER_NUMBER	ITEM_SEGMENTS	SCHEDULED_	DATE_REQUIRED	START_QUANTITY	QUANTITY_PER_/	QUANTITY_OPEN	STD_COST	PROCESSING_LEAD_TIME	VENDOR_	MOQ
2	LE2947-G046	LE-13010024	###########	###############	40.00	2.00	56.00	0.07	40.00	Tyco Elect	4000
3	LE2947-G046	LE-13010020	###########	###############	40.00	2.00	56.00	0.06	40.00	Future Ele	500
4	LE2947-G046	LE-13010064	###########	###############	40.00	1.00	28.00	0.15	100.00	Mouser El	1000.00
5	LE2947-G046	LE-13010023	###########	###############	40.00	1.00	28.00	0.18	70.00	Debcor Ind	500
6	LE2947-G046	LE-13010026	###########	###############	40.00	2.00	56.00	0.63	80.00	CRL Comp	1000
7	LE2947-G046	LE-13010027	###########	###############	40.00	1.00	28.00	0.83	55.00	CRL Comp	1000
8	LE2947-G046	LE-13010029	###########	###############	40.00	1.00	28.00	0.67	55.00	CRL Comp	300.00
9	LE2947-G046	LE-13010050	###########	###############	40.00	1.00	28.00	0.23	40.00	WPG Ame	500
10	LE2947-G046	LE-13010028	###########	###############	40.00	2.00	56.00	0.16	60.00	Element14	400.00
11	LE2947-G046	LE-13010030	###########	###############	40.00	1.00	28.00	0.12	60.00	WPG Sout	9000
12	LE2947-G046	LE-31910004	###########	###############	40.00	1.00	30.00	2.85	80.00	Pecko Ele	100
13	LE2947-G046	CE6404-0000-0002	###########	###############	40.00	0.01	0.36	0.88	35.00	PT. Bengir	0
14	LE2947-G046	CE6408-0000-0009	###########	###############	40.00	0.04	1.14	0.16	35.00	PT. Bengir	0
15	LE2947-G046	CE6408-0000-0118	###########	###############	40.00	0.28	8.25	0.05	35.00	PT. Bengir	0
16	LE2947-G046	CE6408-0000-0119	###########	###############	40.00	0.13	3.75	0.10	35.00	PT. Bengir	0
17	LE2947-G046	LE-11010001	###########	###############	40.00	1.00	28.00	0.58	991.00	Ilshin Elec	1000
18	LE2947-G046	EL-64140011	###########	###############	40.00	1.00	30.00	0.09	20.00	TLS Intern	2000
19	LE2947-G046	PE-64010001	###########	###############	40.00	2.00	60.00	0.04	30.00	TLS Intern	5000.00
20	LE2947-G046	PT-64140003	###########	###############	40.00	1.00	30.00	0.05	30.00	TLS Intern	1000
21	LE2947-G046	LE-13010019	###########	###############	40.00	1.00	28.00	0.06	40.00	Tyco Elect	5000
22	LE2947-G046	ZG-64010001	###########	###############	40.00	1.10	30.80	0.02	30.00	Zephyr Co	5000
23	LE2979-030	LE-24010052	###########	###############	30.00	1.00	2.00	0.00	70.00	TTI Electro	5000
24	LE2979-030	LE-31010006	###########	###############	30.00	4.00	8.00	0.06	40.00	Pecko Ele	100
25	LE2979-030	LE-31910002	###########	###############	30.00	1.00	2.00	4.89	75.00	Pecko Ele	100
26	LE2979-030	LE-24010101	###########	###############	30.00	1.00	2.00	0.00	70.00	CRL Comp	5000
27	LE2979-030	CE6404-0000-0002	###########	###############	30.00	0.01	0.02	0.88	35.00	PT. Bengir	0
28	LE2979-030	CE6408-0000-0009	###########	###############	30.00	0.03	0.05	0.16	35.00	PT. Bengir	0
29	LE2979-030	CE6408-0000-0118	###########	###############	30.00	0.27	0.54	0.05	35.00	PT. Bengir	0
30	LE2979-030	CE6408-0000-0120	###########	###############	30.00	0.09	0.18	0.12	35.00	PT. Bengir	0
31	LE2979-030	PE-64010001	###########	###############	30.00	1.00	2.00	0.04	30.00	TLS Intern	5000.00
32	LE2979-030	PE-64010003	###########	###############	30.00	1.00	2.00	0.05	7.00	TLS [illegible]	1000
33	LE2979-030	ZG-64010001	###########	###############	30.00	1.00	2.00	0.02	30.00	[illegible]	5000

Figure 7. CCI Jobs' information collected.

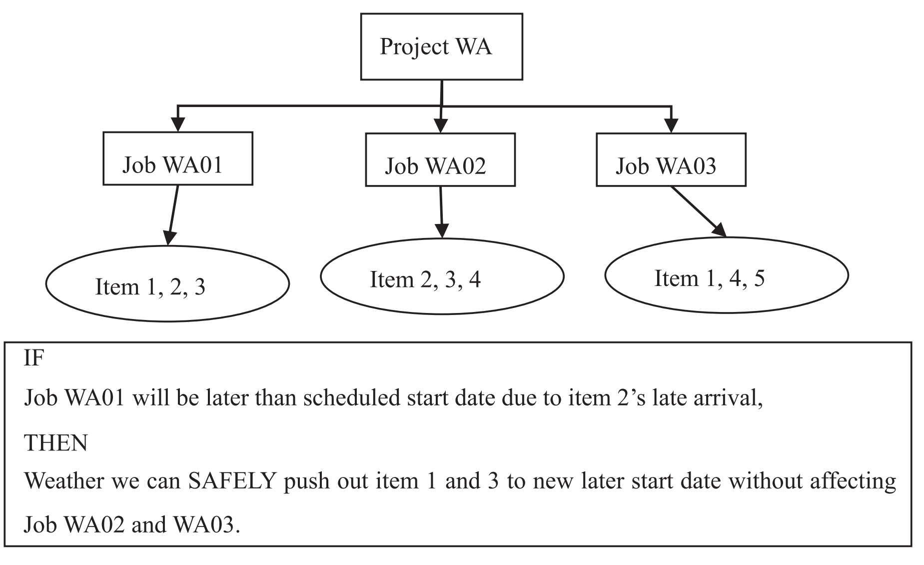
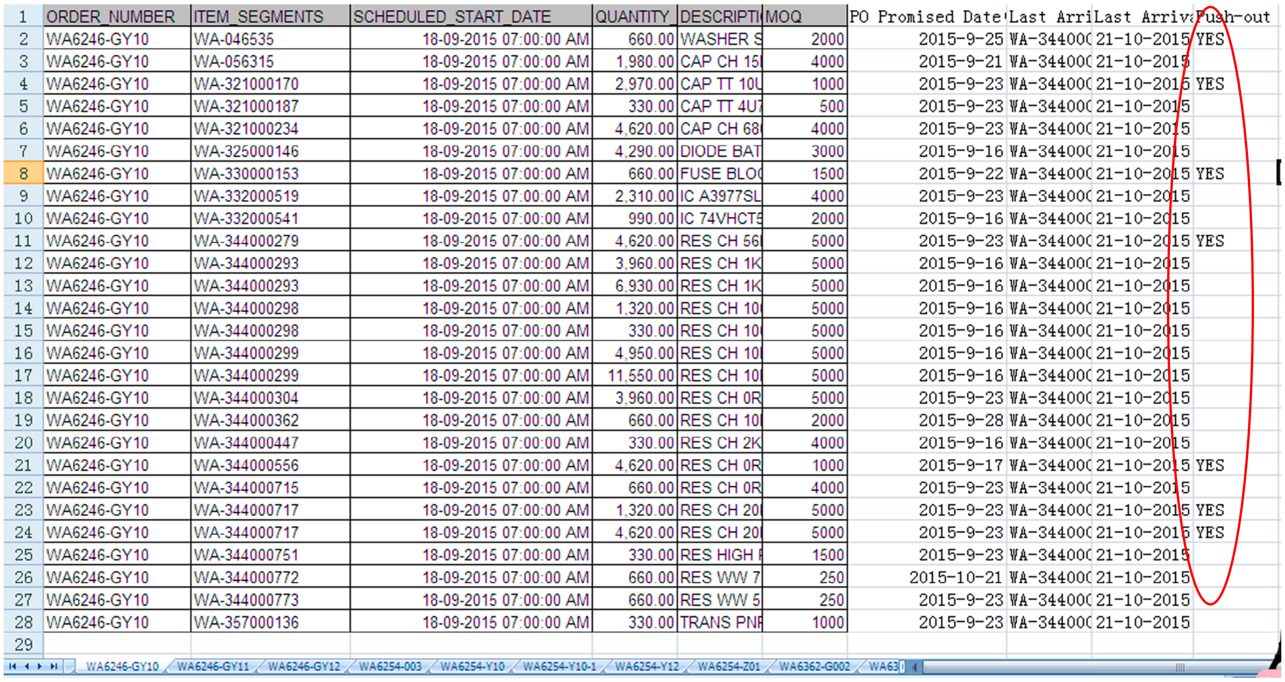


Figure 8. Push-out suggesting engine.

4.3 *Fuzzy inference engine applied for picking process of CCI*

In this case study, to find out which type of order picking policy is most suitable for CCI, contextual information is used and analysed. Table 3 shows the input and output variables. The number of orders and the SKU are retrieved from WMS. A timer is used to record the staff picking operation, and the IoT device can sense the number of workers in the warehouse. Integrating the information from the IoT-based WMS, the system can help to analyse which order picking is more appropriate by comparing the priority of strict order picking and batch picking. Table 2 shows the rule of strict order picking and Table 3 shows the rule of batch picking.

The fuzzy logic engine was constructed after obtaining the input variable. Using MATLAB, Figures 10 and 11 shows the output variable membership function of the strict order picking and the batch picking respectively.



1	ORDER_NUMBER	ITEM_SEGMENTS	SCHEDULED_START_DATE	QUANTITY	DESCRIPTI	MOQ	PO Promised Date	Last Arri	Last Arriv	Push-out
2	WA6246-GY10	WA-046535	18-09-2015 07:00:00 AM	660.00	WASHER S	2000	2015-9-25	WA-34400(	21-10-2015	YES
3	WA6246-GY10	WA-056315	18-09-2015 07:00:00 AM	1,980.00	CAP CH 15	4000	2015-9-21	WA-34400(	21-10-2015	
4	WA6246-GY10	WA-321000170	18-09-2015 07:00:00 AM	2,970.00	CAP TT 10U	1000	2015-9-23	WA-34400(	21-10-2015	YES
5	WA6246-GY10	WA-321000187	18-09-2015 07:00:00 AM	330.00	CAP TT 4U7	500	2015-9-23	WA-34400(	21-10-2015	
6	WA6246-GY10	WA-321000234	18-09-2015 07:00:00 AM	4,620.00	CAP CH 68	4000	2015-9-23	WA-34400(	21-10-2015	
7	WA6246-GY10	WA-325000146	18-09-2015 07:00:00 AM	4,290.00	DIODE BAT	3000	2015-9-16	WA-34400(	21-10-2015	
8	WA6246-GY10	WA-330000153	18-09-2015 07:00:00 AM	660.00	FUSE BLO(	1500	2015-9-22	WA-34400(	21-10-2015	YES
9	WA6246-GY10	WA-332000519	18-09-2015 07:00:00 AM	2,310.00	IC A3977SL	4000	2015-9-23	WA-34400(	21-10-2015	
10	WA6246-GY10	WA-332000541	18-09-2015 07:00:00 AM	990.00	IC 74VHCT5	2000	2015-9-16	WA-34400(	21-10-2015	
11	WA6246-GY10	WA-344000279	18-09-2015 07:00:00 AM	4,620.00	RES CH 56	5000	2015-9-23	WA-34400(	21-10-2015	YES
12	WA6246-GY10	WA-344000293	18-09-2015 07:00:00 AM	3,960.00	RES CH 1K	5000	2015-9-16	WA-34400(	21-10-2015	
13	WA6246-GY10	WA-344000293	18-09-2015 07:00:00 AM	6,930.00	RES CH 1K	5000	2015-9-16	WA-34400(	21-10-2015	
14	WA6246-GY10	WA-344000298	18-09-2015 07:00:00 AM	1,320.00	RES CH 10	5000	2015-9-16	WA-34400(	21-10-2015	
15	WA6246-GY10	WA-344000298	18-09-2015 07:00:00 AM	330.00	RES CH 10	5000	2015-9-16	WA-34400(	21-10-2015	
16	WA6246-GY10	WA-344000299	18-09-2015 07:00:00 AM	4,950.00	RES CH 10	5000	2015-9-16	WA-34400(	21-10-2015	
17	WA6246-GY10	WA-344000299	18-09-2015 07:00:00 AM	11,550.00	RES CH 10	5000	2015-9-16	WA-34400(	21-10-2015	
18	WA6246-GY10	WA-344000304	18-09-2015 07:00:00 AM	3,960.00	RES CH 0R	5000	2015-9-23	WA-34400(	21-10-2015	
19	WA6246-GY10	WA-344000362	18-09-2015 07:00:00 AM	660.00	RES CH 10	2000	2015-9-28	WA-34400(	21-10-2015	
20	WA6246-GY10	WA-344000447	18-09-2015 07:00:00 AM	330.00	RES CH 2K	4000	2015-9-16	WA-34400(	21-10-2015	
21	WA6246-GY10	WA-344000556	18-09-2015 07:00:00 AM	4,620.00	RES CH 0R	1000	2015-9-17	WA-34400(	21-10-2015	YES
22	WA6246-GY10	WA-344000715	18-09-2015 07:00:00 AM	660.00	RES CH 0R	4000	2015-9-23	WA-34400(	21-10-2015	
23	WA6246-GY10	WA-344000717	18-09-2015 07:00:00 AM	1,320.00	RES CH 20	5000	2015-9-23	WA-34400(	21-10-2015	YES
24	WA6246-GY10	WA-344000717	18-09-2015 07:00:00 AM	4,620.00	RES CH 20	5000	2015-9-23	WA-34400(	21-10-2015	YES
25	WA6246-GY10	WA-344000751	18-09-2015 07:00:00 AM	330.00	RES HIGH	1500	2015-9-23	WA-34400(	21-10-2015	
26	WA6246-GY10	WA-344000772	18-09-2015 07:00:00 AM	660.00	RES WW 7	250	2015-10-21	WA-34400(	21-10-2015	
27	WA6246-GY10	WA-344000773	18-09-2015 07:00:00 AM	660.00	RES WW 5	250	2015-9-23	WA-34400(	21-10-2015	
28	WA6246-GY10	WA-357000136	18-09-2015 07:00:00 AM	330.00	TRANS PNI	1000	2015-9-23	WA-34400(	21-10-2015	
29										

Figure 9. Push out suggestions for inventory deduction.

Table 2. Rule of the strict order picking.

Rule 1	IF	Number of orders is relative high AND Number of SKU is relative large AND Possible time for picking is limited AND Number of staff is small	Then	Priority is relatively low
Rule 2	IF	Number of orders is high AND Number of SKU is large AND Possible time for picking is limited AND Number of staff is small	Then	Priority is relatively low
Rule 3	IF	Number of orders is relative high AND Number of SKU is relative large AND Possible time for picking is medium AND Number of staff is medium	Then	Priority is low
Rule 4	IF	Number of orders is medium AND Number of SKU is large AND Possible time for picking is medium AND Number of staff is small	Then	Priority is medium
Rule 5	IF	Number of orders is high AND Number of SKU is relatively large AND Possible time for picking is limited AND Number of staff is small	Then	Priority is low
Rule 6	IF	Number of orders is relatively high AND Number of SKU number is large AND Possible time for picking is limited AND Number of staff is small	Then	Priority is relatively low

The priority results of the strict order picking and the batch picking are shown in Table 4. From the results, it is found that batch picking has a higher value of 0.714 than the strict order picking value of 0.286. Therefore, the finished goods warehouse of CCI Company should adopt batch picking in the warehouse management in order to increase the efficiency of order picking activities.

Table 3. Rule of the batch picking.

Rule 1	IF	Number of Orders is relative high AND Number of SKU is relative large AND Possible Time for picking is limited AND Number of Staff is small	Then	Priority is relative high
Rule 2	IF	Number of Orders is high AND Number of SKU is large AND Possible Time for picking is limited AND Number of Staff is small	Then	Priority is relative high
Rule 3	IF	Number of Orders is relative high AND Number of SKU is relative large AND Possible Time for picking is medium AND Number of Staff is medium	Then	Priority is high
Rule 4	IF	Number of Orders is medium AND Number of SKU is large AND Possible Time for picking is medium AND Number of Staff is small	Then	Priority is medium
Rule 5	IF	Number of Orders is high AND Number of SKU is relatively large AND Possible Time for picking is limited AND Number of Staff is small	Then	Priority is high
Rule 6	IF	Number of Orders is relatively high AND Number of SKU number is large AND Possible Time for picking is limited AND Number of Staff is small	Then	Priority is relatively high

Figure 10. Strict order picking.

4.4 *System evaluation*

To evaluate the performance of the IoT-based WMS, a case study is conducted in the manufacturing company. The following data are collected to illustrate the performance of IoT-based WMS in the case company.

Before IoT-based WMS	
Average number of order/month	93
Average number of order finished per month	85
After IoT-based WMS	
Number of the wrong shipment	1 within 3 months
Time for picking one carton	1.86 min
Number of carton per order	130
Manpower required	4
After adoption of IoT-based WMS	
Average number of order/month during the pilot run	84
Average number of order finished per month during the pilot run	83
Number of the wrong shipment during the pilot run	0
Time for picking one carton	54 s
Number of carton per order	140
Manpower required	3

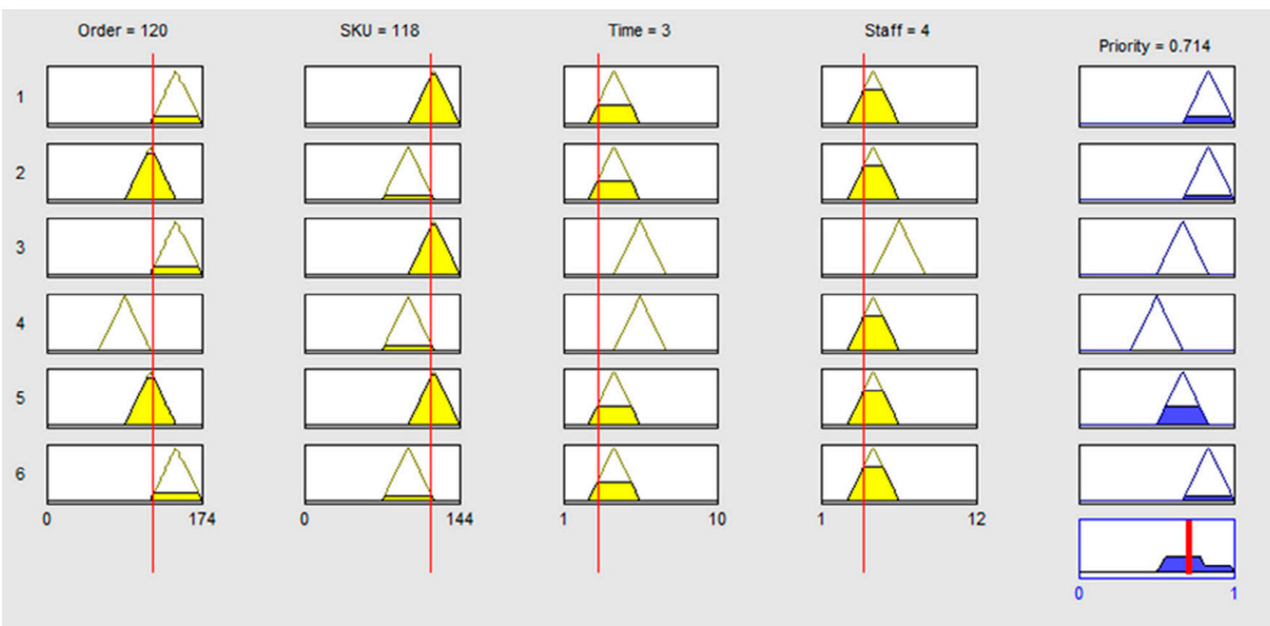


Figure 11. Batch picking.

Table 4. Results of order picking and priority.

	Priority results	Ranking
Strict order picking	0.286	2
Batch picking	0.714	1

In the case company, through implement the pilot study, the proposed WMS helps to improve the efficiency of receiving process; enhance the order fulfil performance in the warehouse; enhance the accuracy of the inventory management and improve the warehouse productivity; especially in the picking process. Table 5 illustrates the performance of the warehouse operation.

Table 5. The result of the warehouse operation improvement.

Category	Measurement	Before WMS	After WMS	Equation
Inbound process	Receiving	2.54 min	0.96 min	$\frac{t_1+t_2+t_3+\cdots+t_3}{n}$ where t: time receive the goods per pallet n: number of pallets
Order fulfilment	Order fill rate	96%	99%	*Order complete*: Total order
	Order accuracy	99%	100%	*Order ship to right customer*: Total order
Inventory management	Inventory accuracy	92%	100%	*Inventory qty in actual*: Inventory qty in system
Warehouse productivity	Picking order per hour	4.03 h	2.015 h	Total SKU in an order * time per pick one SKU

4.4.1 *Improve the efficiency of receiving process*

Using the IoT-based WMS, it can minimise the time of receiving the goods. As traditionally the finished goods warehouse are using the manual record, therefore there will be time-consuming and the average receiving time is 2.54 min. Using the IoT-based WMS, the receiving process can be streamline as the data can be automatically captured and inputted to the WMS and the average receiving time can be largely reduced to 0.96 min.

4.4.2 *Enhance the order fulfil performance*

4.4.2.1 *Order fill rate.* Order fill rate can be highly improved by applying the IoT-based WMS. Using the WMS, the location of the inventories are clearly shown in the system. Therefore, the worker can save the time to complete the order rather than spend an hour to find the inventory locations. From the results, it can show that before implementing the WMS, the order fill rate is 96% (average 89.5 order finish out of 93 order per month) and after the implement the WMS, the order fill rate is improved to the 99% (average 83 order finished out of 84 order per month).

4.4.2.2 *Order accuracy.* The product misidentification can be minimised using the IoT-based WMS in the finished goods warehouse. As there are lots of SKU number and those SKU number is very similar, it may lead to the worker mistake the item and deliver the wrong goods to the customer. If the goods do not have a shipment, the system promotes up the message to let the worker know that they have picked the wrong items. Eventually, it can reduce the probability of picking the wrong goods due to misidentification. From the results, the order accuracy from 99% (average three month will have one wrong order) can be improved to 100%.

4.4.3 *Inventory accuracy can be improved*

Using the IoT-based WMS, it can reduce the chance of record inaccuracy because of poor handwriting or poor data integrity. The IoT-based technology can help the worker record the information of inventory automatically as the worker just require use the handheld device to scan the goods. As the whole process is not requiring data enter and consequently, the mistake of record manually can be decreased. Before implementing the WMS, the inventory accuracy only 92%, using the WMS, the inventory accuracy improved to 100%. Also, though out the Wi-Fi connection, the record of the goods can be updated in a real-time manner. In results, it can help the worker monitor the warehouse in more effective ways.

4.4.4 *Improve the efficiency of order picking*

With implementing the fuzzy logic engine of the order picking process, the process time of the order picking process can be reducing. Using the fuzzy logic engine, the software can generate the most suitable method of the order picking policy and batch order policy was applied in the case study. In the case study, the batch picking can help the worker picking the order in less travel time and hence can improve the efficiency of order picking. Moreover, the redesign floorplan also can help to the same type of group storage in the same area, and the concentrate can reduce the travel distance to the worker.

In the results, it shows that the time of original one order picking required 4.03 h (130 cartons per order multiply by average 0.031 h pick one carton) and after implementing the WMS, it can minimise to 2.015 h (140 cartons per order multiply by average 0.015 h pick one carton). It shows that the warehouse productivity can enhance nearly 50% using the proposed WMS.

5. Conclusions

The operations of a warehouse are required to change accordingly, due to the complex and high variety of customer orders as well as the demand for real-time information. Therefore, the traditional manual warehouse operation is no longer suitable for manufacturers in the era of Industry 4.0. Thus, an innovative WMS is very important to improve the efficiency and allow customised order fulfilment.

In this paper, the proposed WMS is integrated with the fuzzy logic technique to select the most suitable order picking method, thereby enhancing the efficiency of the order picking process. Through the case study results in this research, it was implied that the WMS could help to provide a better warehouse operation performance regarding both tangible and intangible benefits. For the tangible benefits, it can improve order fulfilment such as order fill rate and order accuracy. Moreover, it can enhance the time of receiving, the inventory accuracy and the warehouse productivity in order picking. For the intangible benefits, it can enhance the packing method, and the inventory can be traceable with RFID. In addition, the morale of the staff can be improved. As this study mainly focuses on practical applications and the order picking operation, the routing and storage policies have not been discussed in detail. However, the space allocation and the reduction of travel distance are very important in enhancing the warehouse performance. Therefore, future work in the fuzzy logic application for batch the zone, sequential zone and wave picking approaches can be further studied. Incorporating artificial intelligence will be one of the future direction to enable smart logistics and information can be further automated so as to streamline the warehouse operation with higher efficiency, performance and less costly in long term and further research on smart robotics should be conducted as it changes the warehouse pick and pack operations from picker-to-goods to goods-to-picker using robots. In general, the adoption of IoT and robotics is the main future research direction to further improve warehouse efficiency.

Disclosure statement

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