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Digital Twin-enabled Synchronization Mechanism for Pick-and-Sort Ecommerce Order Fulfillment

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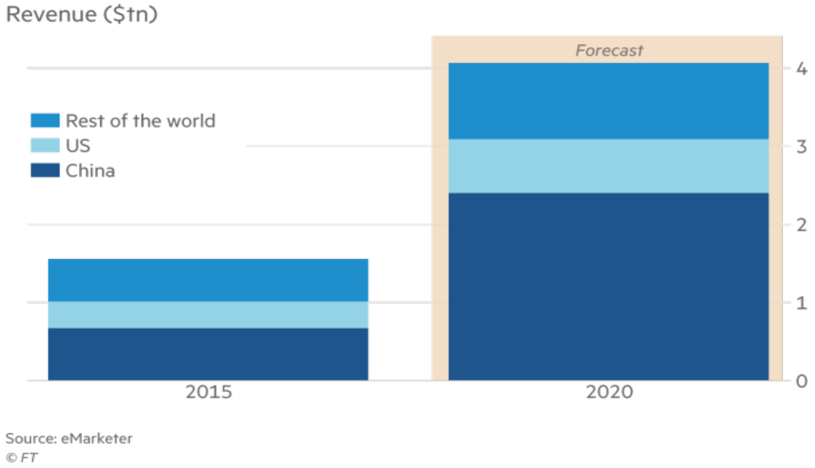
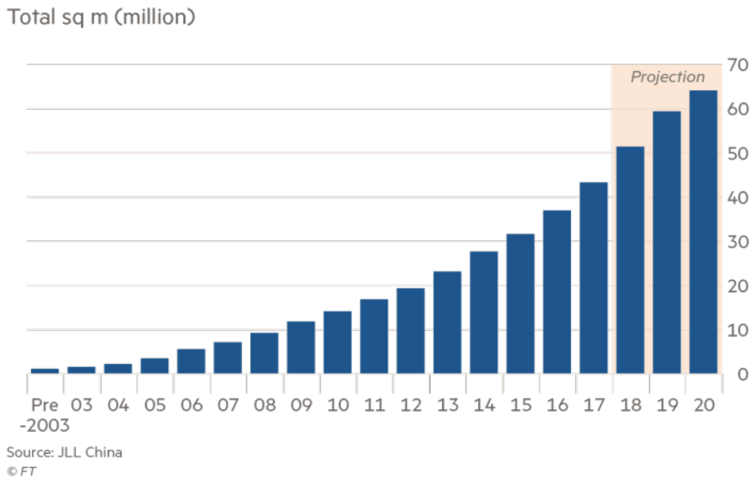
Motivations

China ecommerce boom fires up logistics warehousing sector

From 100 million parcels per day to 1 billion parcels per day



Chinese market in global ecommerce >50%



Ecommerce fuels China warehouse boom >>65m sq

Motivations

Why is Ecommerce Logistics Important to Hong Kong?

- **Hong Kong:** leading logistics hub in Asia and world
- **Logistics & Trading:** largest pillar industry in Hong Kong
- **Hong Kong:** free trading, suitable for ecommerce
- **Double Singles Day (11/11):** more than US$10B online orders
- **Ecommerce:** big business, big opportunity
- **Ecommerce logistics:** big challenges

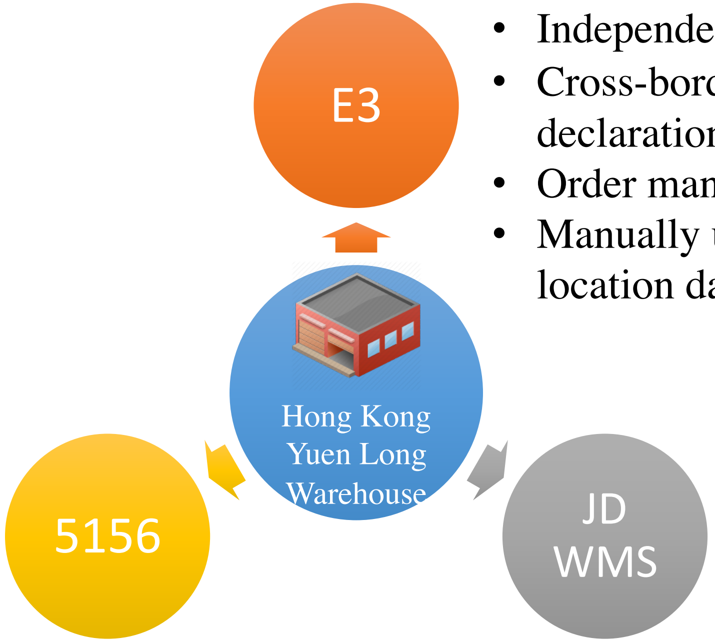
Disparities in size, shape, weight, color, mechanical properties

Large volume, Large variety, Fast moving, Small items, Large space

Labor-Intensive + Land-Intensive

Rental contracts of 2-3 years: not viable for full automation

A typical cross-boarder ecommerce logistics warehouse in Hong Kong



E3
- Independent system
- Cross-border e-commerce declaration management
- Order management
- Manually update inventory location data

5156
- Independent system
- Daily warehouse operation management
- Manually enter/update order and warehousing data

JD WMS
- Customer specified WMS system
- JD goods management
- JD order management
- Perform warehousing operations using mobile devices

*E3,5156,JD WMS are different warehouse management system

Difficulties in information sharing across multiple warehousing systems

- System independence generates information islands
- Lag and inconsistent information
- Increase management complexity and increase operating costs

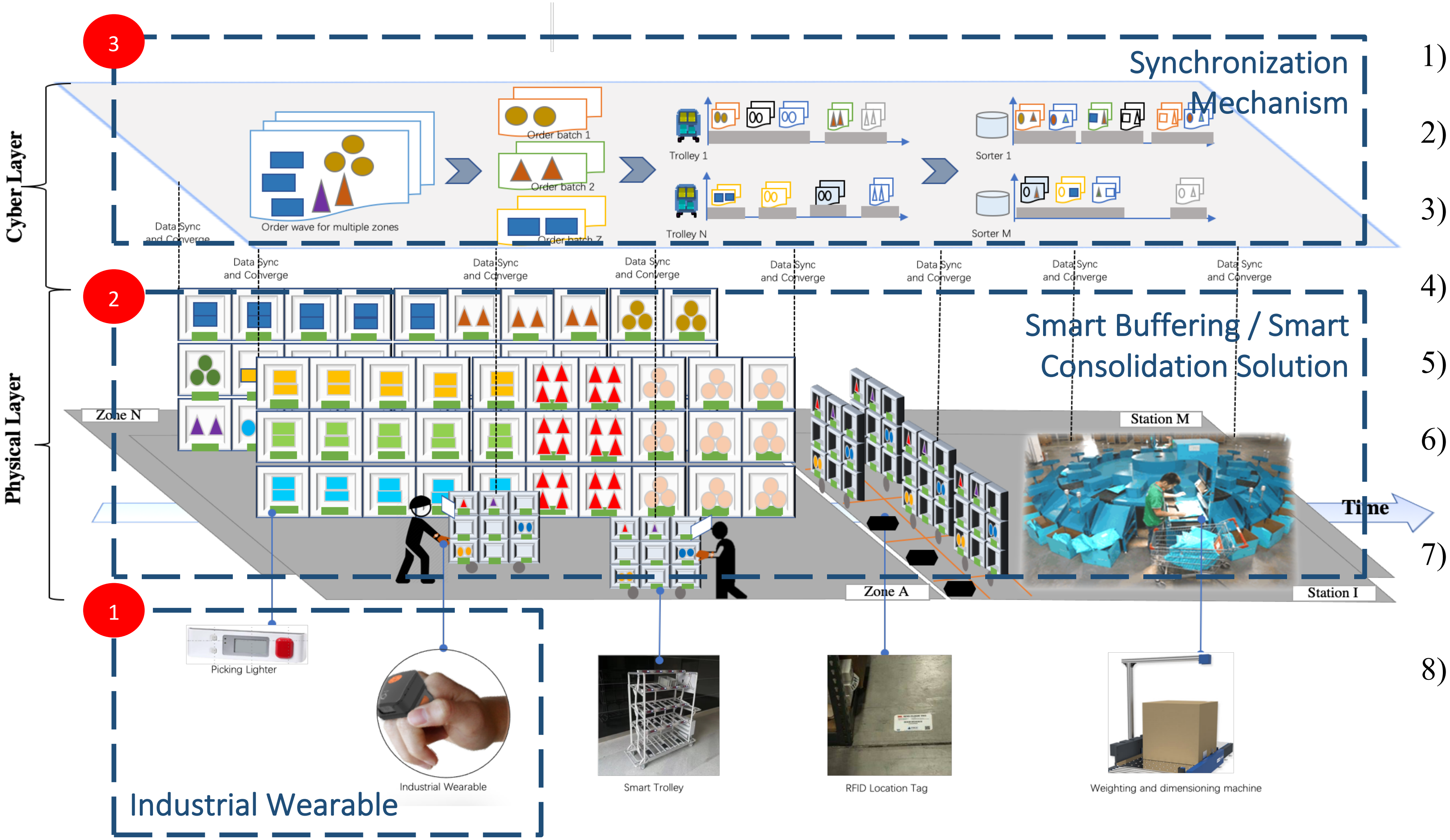
Lack of global optimal resource planning and synchronization management

- Non-unified information management platform
- No real-time data collection method
- Reduce the efficiency of warehouse use

Hard to achieve the transformation of digitalization and data-driven decision optimization

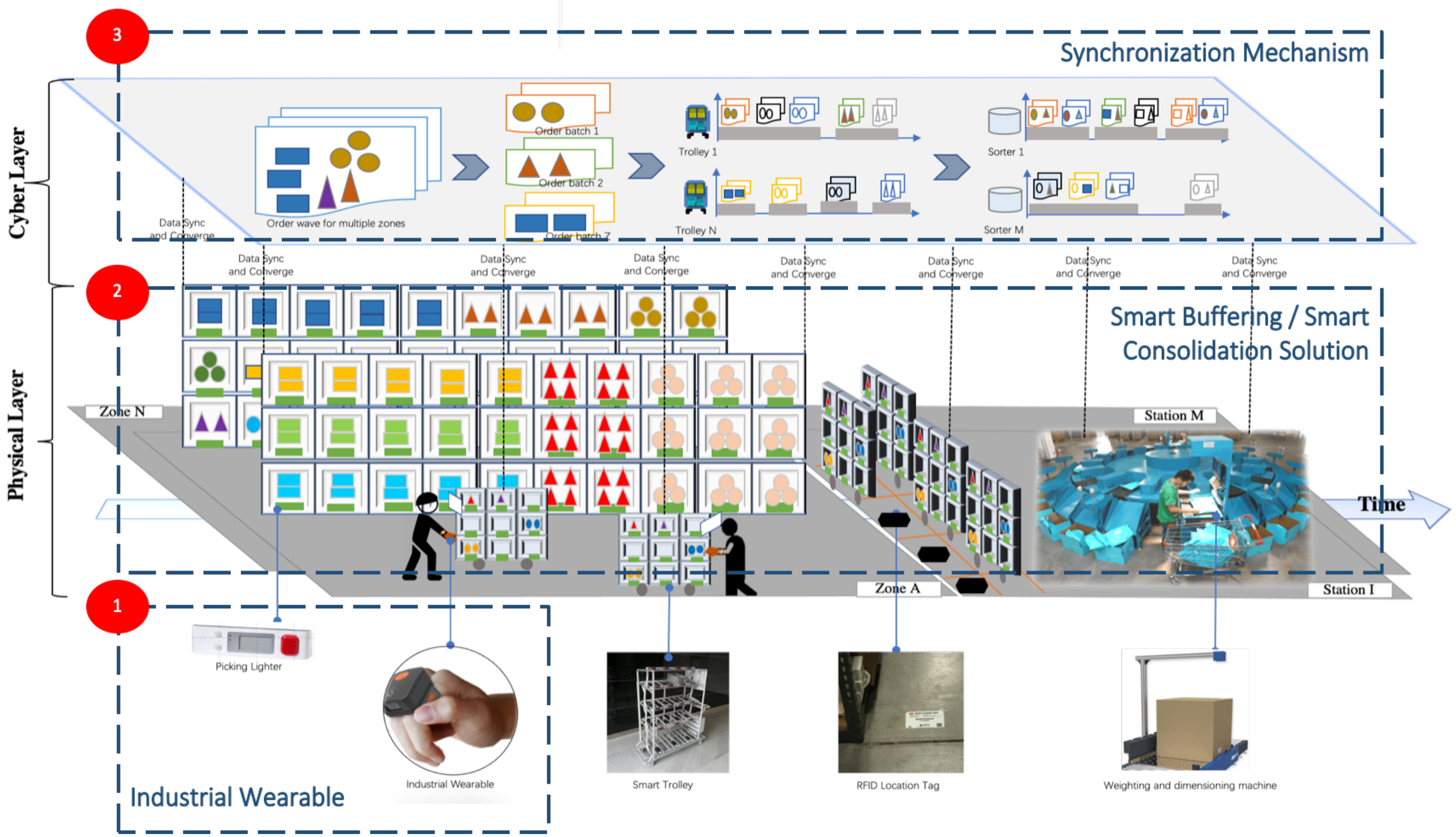
- The management decision-making behavior based on the information lagging and the experience of the management, which affects the smooth progress of the business of each department.

Digital Twin-enabled Synchronization Solution for Pick-and-Sort Ecommerce Logistics



1) Customer orders will be released in a wave;
2) The orders with similar storage locations are almost processed together as a batch;
3) Each customer order is composed of many SKUs;
4) Each SKU is placed on the specific and known storage location;
5) The customer orders must be completed by the certain due dates;
6) All order and SKU location information will be digitalized, analyzed and shared by DT system in cyber layer;
7) Dynamic batching, sequencing and allocation decisions are made in cyber layer considering synchronization;
8) Based on the integrated cyber decisions, real-time executions will be carried out in physical layer of ecommerce warehouse.

Challenges



From operational perspectives: Non-stop sortation automation, Queueing picking-cart with multi-order lines

From performance measure perspectives: Simultaneous-and-punctual Synchronization or Due-date First?

From market demands perspectives: Ecommerce logistics volatility and variability (e.g., order, resource, …)

Research Questions

1) How to design a synchronization mechanism of DT-enabled pick-and-sort ecommerce order fulfillment system, considering integrated policies and rules such as batching, sequencing, assignment and buffering?
2) What are the trade-offs between picking simultaneous and sorting punctuality?
3) Which key factors will impact the performance of pick-and-sort ecommerce order fulfillment system and what levels? Key factors might include different shape of picking area, storage assignment schemes, demand patterns, picking-cart capacity.

30+ classical and recent literature are review from three dimensions: (1) order picking planning; (2) synchronization mechanism; and (3) digital twin technologies, several research gaps are summarized as follows:

- This study focuses on examining synchronized zone picking with new type of automation facilities;
- Few studies examine synchronization's beneficial effect on pick-and-sort order picking system performance;
- Most of studies focus on single optimization problem individually;
- This study considers the impact of combined polices on total pick-and-sort system performance;

Two-stage Pick-and-sort Order Fulfillment Optimization Problem

The objective is to balance the process of two stages. The objective of the first stage is to minimize the waiting duration (WT) of total batch picking. The objective of the second stage is to minimize the mean earliness (E_o) and tardiness (T_o) of each customer order.

- *A picking system is consisting of a set of parallel aisles(A) with storage racks on the both sides.*
- *These aisles and racks are divided into several consecutive zones(Z).*
- *Assuming that the total types of SKU(I) are already known, and each SKU might have a different demand pattern.*
- *A particular SKU is allocated to only one storage position in one rack. Each SKU cannot be retrieved in another zone.*
- *A picker would only travel and retrieve items in one particular zone. We adopt the S-shape routing strategy.*
- *A set of parallel circular automated sorting systems are used. When the picking of a batch orders in each picking zone is finished, all the items required are entering the buffering area and waiting for sorting.*

Objective function:

$$Min(wpFp + wsFs)$$

Subject to:

$$\sum_{b\in B} X_{ob} = 1, \forall o \in O; \quad (1)$$

$$\sum_{b\in B} S_{bl} = 1, \forall l \in L; \quad (2)$$

$$\sum_{l\in L} S_{bl} = 1, \forall b \in B; \quad (3)$$

$$\sum_{z\in Z} Y_{iz} = 1, \forall i \in I; \quad (4)$$

$$\sum_{o\in O}\sum_{b\in B} X_{ob} N_{oi} \le C_{unit}; \quad (5)$$

$$R_b = \{o \mid X_{ob} = 1\}, \forall b \in B; \quad (6)$$

$$N_{bz} = \sum_{o\in O, Y_{iz}=1} N_{oi}, \forall b \in B, z \in Z; \quad (7)$$

$$TT = [(A-1)W + AD]/V_t; \quad (8)$$

$$PT_{bz} = N_{bz}/V_p, \forall b \in B, z \in Z; \quad (9)$$

$$TPT_{bz} = TT + PT_{bz}, \forall b \in B, z \in Z; \quad (10)$$

$$TST_b = \underset{b\in B, z\in Z}{Max}(TPT_{bz}),; \quad (11)$$

$$SPT_{b+1} = TST_b, \forall b \in B; \quad (12)$$

$$FPT_b = SPT_b + TST_b, \forall b \in B; \quad (13)$$

$$WD_b = Max(TST_b) - Min(TPT_b), b \in B; \quad (14)$$

$$F_p = \sum_{b\in B} (WD_b)/N_B; \quad (15)$$

$$N_b = \sum_{o\in R_b} N_{oi}, \forall b \in B; \quad (16)$$

$$ST_b = N_b/V_s, \forall b \in B; \quad (17)$$

$$SST_{b+1} = \underset{b\in B}{Max}(FPT_{b+1}, FST_b); \quad (18)$$

$$FST_b = SST_b + ST_b, \forall b \in B; \quad (19)$$

$$E_o = \underset{o\in R_b, b\in B}{Max}(o, D_o - FST_b); \quad (20)$$

$$T_o = \underset{o\in R_b, b\in B}{Max}(o, FST_b - D_o); \quad (21)$$

$$F_s = \sum_{o\in R_b} (Eo + To)/|R_b|; \quad (22)$$

$$N_O, N_B, N_L, N_I, N_Z, D, A, W, V_t, V_p, V_s \geqslant 0; \quad (23)$$

$$SPT_1 = 0, SST_1 = FPT_1; \quad (24)$$

Results & Insights

Model Verification and Evaluation

In this experiment, the computational results will be compared with 'due-date first' algorithm. Given that the 'due-date first' algorithm is quite straightforward and simple in most warehousing operations (Tzu-Li Chen et al,. 2014).

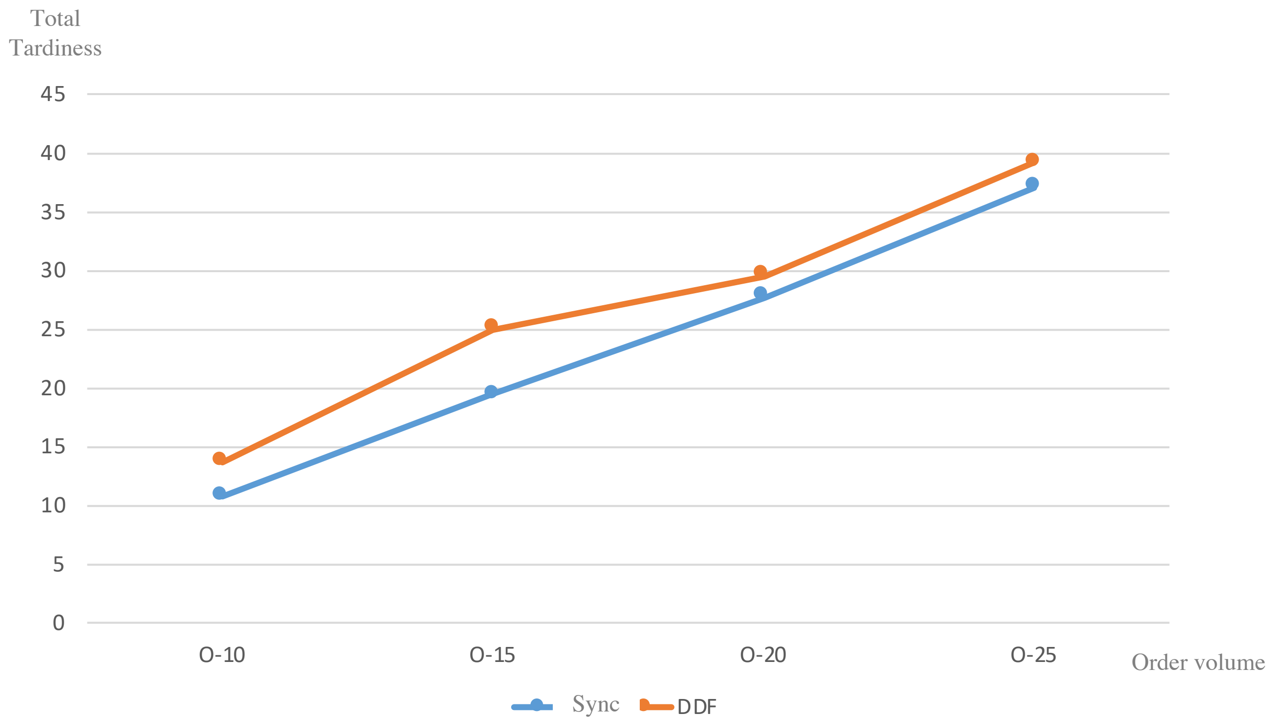


Figure 1. Total tardiness on different order quantities

- The proposed Sync mechanism has better performance than 'Due-date First', which verifies the facts that sync-based batching and sequencing policies are beneficial to ecommerce order fulfillment operations.

Results & Insights

Trade-off Analysis under Peak and Off-peak Season

- *To investigate the criteria trade-off between the two stages under different order-quantity scenarios (e.g. double eleven, 618, etc.), 11 sets of weight combination and 8 order-quantity levels representing peak and off-peak seasons are considered.*
- *A combination could be described as (w_p, w_s) where w_p is the weight of minimizing waiting in picking process, and w_s is the weight of minimizing order tardiness in sorting process.*
- *We use the picking simultaneity (F_p), sorting punctuality (F_s) and their sum (SUM) as the criteria to measure the performance.*
- *The objective is to figure out the best weight combination which contributes to the minimized sum of F_p and F_s.*

Table 1. Results of trade off computation

			Off-season				Peak season			
NO.	(wp, ws)	criteria	0-10	0-15	0-20	0-25	0-30	0-35	0-40	0-45
1	(1-0)	fp	6.5	5.6	4.5	6.5	7.444	8.5556	7.5556	7
		fs	16.2	40.3	59.275	56.52	58.5	63.2286	83.3875	120.922
		sum	22.7	45.9	63.775	63.02	65.944	71.7842	90.9431	127.922
2	(0.9-0.1)	fp	5.7	4.5	4.75	7.0556	8	8.2222	8.9444	9.1111
		fs	14.55	37.9	57.975	42.18	44.5167	50.9714	64.625	78.4889
		sum	20.25	42.4	62.725	49.2356	52.5167	59.1936	73.5694	87.6
3	(0.8-0.2)	fp	6.2	7.2	8.8	8.333	8.5	10.111	9.5	11.8333
		fs	11.9	22.3	29.2	34.54	40.1167	45.2857	57.4375	68.4556
		sum	18.1	29.5	38	42.873	48.6167	55.3967	66.9375	80.2889
4	(0.7-0.3)	fp	6.6	7	8.5	8.5625	8.5556	9.4444	10.5	12.125
		fs	12.5	21.5	29.175	37	35.95	43.6571	55.525	62.1222
		sum	19.1	28.5	37.675	45.5625	44.5056	53.1015	66.025	74.2472
5	(0.6-0.4)	fp	6.5	8.1	9.3	8.0625	8.8889	9.5	10.9444	11.2222
		fs	12.05	19	27.9	36.98	38.2333	42.2429	52.975	64.5778
		sum	18.55	27.1	37.2	45.0425	47.1222	51.7429	63.9194	75.8
6	(0.5-0.5)	fp	6.3	8.3	9.9	8.2778	8.5	10.111	10.8333	12.125
		fs	10.3	18.2667	29.8	35.28	35.6667	46.0429	54.0625	60.6889
		sum	16.6	26.5667	39.7	43.5578	44.1667	56.1539	64.8958	72.8139
7	(0.4-0.6)	fp	7	7.8	9.4	8.1667	8.444	9.7222	11.1667	11.8889
		fs	10	20.733	28.5	35.32	34.95	45.3571	51.2375	61.9556
		sum	17	28.533	37.9	43.4867	43.394	55.0793	62.4042	73.8445
8	(0.3-0.7)	fp	6.7	8.1	9.6	8.2778	8.6667	9.6111	10.7222	11.8333
		fs	11.2	16.0667	31.7	33.68	36.6	42.2	51.85	64.066
		sum	17.9	24.1667	41.3	41.9578	45.2667	51.8111	62.5722	75.8993
9	(0.2-0.8)	fp	6.4	7.7	9	7.6111	9.0625	9.5556	10.7222	11.75
		fs	9.8	20	30.625	36.06	33.5333	43.4143	50.6875	61.3333
		sum	16.2	27.7	39.625	43.6711	42.5958	52.9699	61.4097	73.0833
10	(0.1-0.9)	fp	6.3	8	8.6	8.375	8.7778	9.3889	12.0625	11.9444
		fs	11.25	19.4333	30.4	33.9	33.3	41.2429	52.05	66.5889
		sum	17.55	27.4333	39	42.275	42.0778	50.6318	64.1125	78.5333
11	(0-1)	fp	6.625	7.8	9.4	8.0556	9.25	9.2778	11	11.4444
		fs	9.35	18.2	29.325	38.5	39.2667	45.5857	53.3	56.8778
		sum	15.975	26	38.725	46.5556	48.5167	54.8635	64.3	68.3222

Results & Insights

Trade-off Analysis under Peak and Off-peak Season

Figure 2-4 demonstrate the results of F_p, F_s and SUM respectively. In each of the figure, four representative order quantities are selected for illustration, the X-coordinate stands for the related weight combination from (1-0) to (0-1), and the Y-coordinate means the normalized value of F_p, F_s, and SUM.

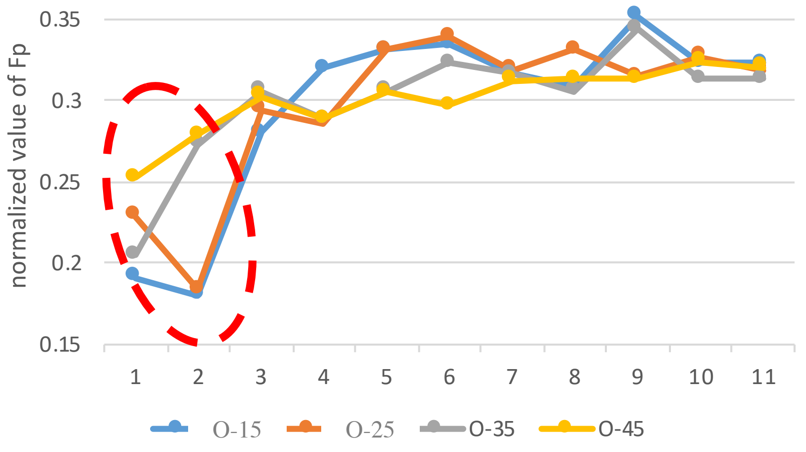


Figure 2. Normalized F_p on different weight combination

- Fp goes up as the picking weight wp goes down. This means the waiting duration in picking process deteriorates as the weight of picking simultaneity decreases.
- There is first a jump in off-season at combination (0.9, 0.1), reaching to a minimum point. However, the peak season shows a steady increase throughout the combination.

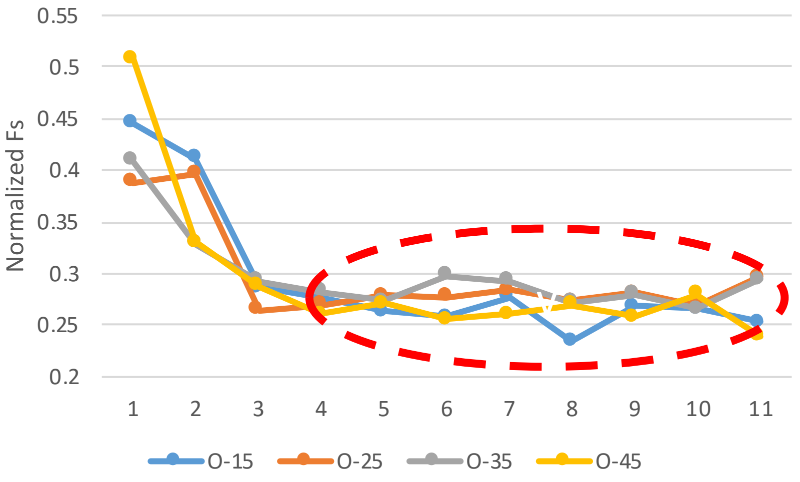


Figure 3. Normalized F_s on different weight combination

- Fs goes down as ws goes up.
- The value of normalized Fs stays stable when weight combination ranging from (0.7, 0.3) to (0, 1).

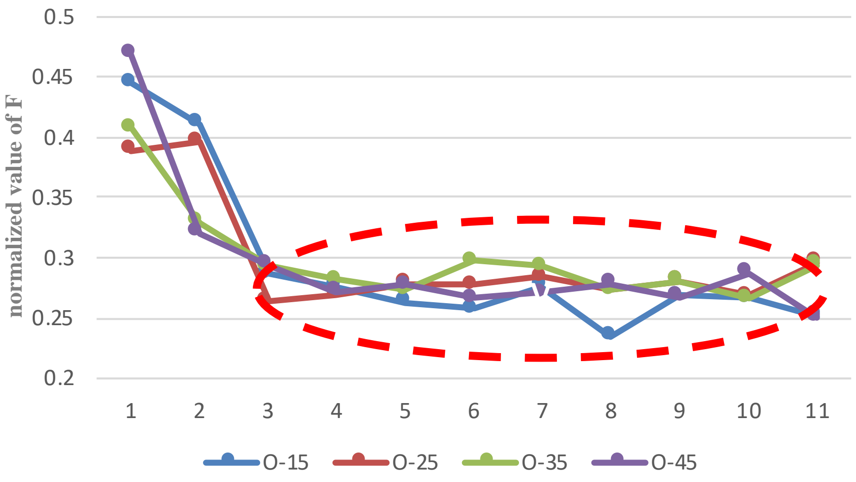


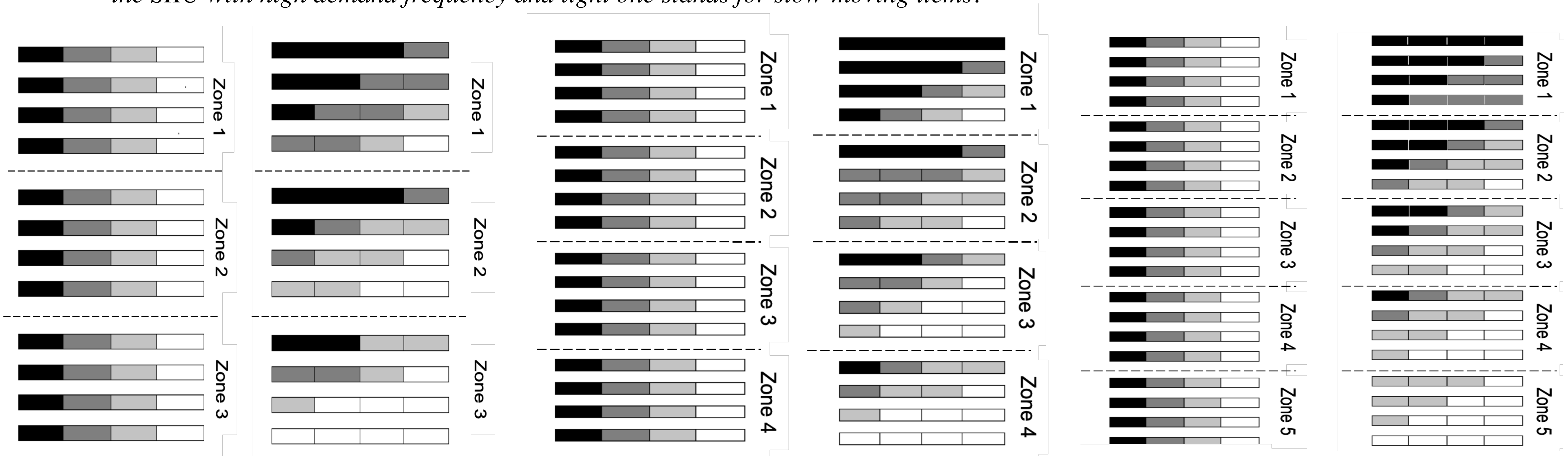
Figure 4. Normalized SUM on different weight combination

- The changing slope decreases slower after (0.8, 0.2). Since the gap between (0.8, 0.2) to (0, 1) is very small, the managers is suggested to choose a reasonable combination from this interval.

Results & Insights

The impact of Zoning on Synchronization Performance

This part of experiment focuses on the impact of imbalanced workload raised from zoning and SKU assignment. Generally, different storage keeping unit (SKU) in a warehouse has different demand frequency, thus the SKUs with high demand frequency is called fast-moving items and low demand frequency slow-moving items. In the figure, the dark color represents the SKU with high demand frequency and light one stands for slow-moving items.



a. SKU assignment in 3 zones

b. SKU assignment in 4 zones

c. SKU assignment in 5 zones

Figure 5. SKU assignment across varied zoning

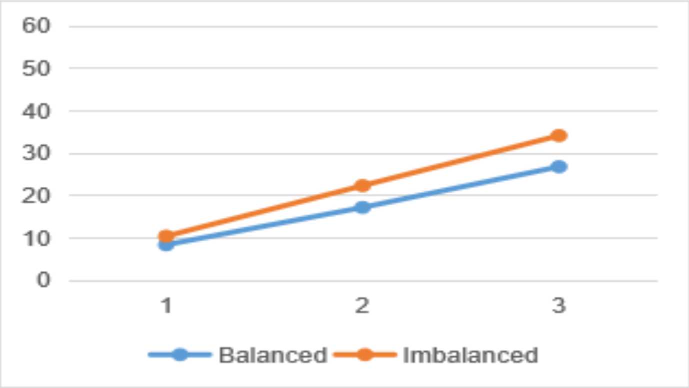
Results & Insights

The impact of Zoning on Synchronization Performance

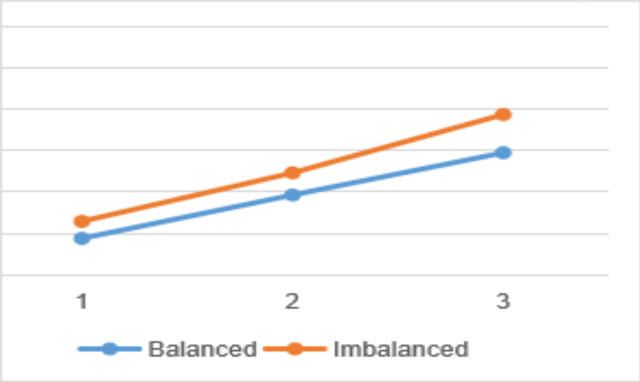
Table 2. Results under different zoning and SKU assignment

Number of zones	Criteria	Order quantity=10		Order quantity=20		Order quantity=30	
		Balanced	Imbalanced	Balanced	Imbalanced	Balanced	Imbalanced
5	F	8.4125	10.45	17.2179	22.3607	26.8306	34.1639
	F_p	6.375	7.5	7.7857	10.5714	8.7778	11.9444
	F_s	10.45	13.4	26.65	34.15	44.8833	56.3833
4	F	8.8	12.9	19.2643	24.6036	29.4556	38.6528
	F_p	6.8	9.2	8.9286	11.8571	10.2778	14.2222
	F_s	10.8	16.6	29.6	37.35	48.6333	63.0833
3	F	11.025	20.2	22.8589	32.7232	34.2806	55.9889
	F_p	7.2	13.5	10.6429	15.5714	12.1111	19.6111
	F_s	14.85	26.9	35.075	49.875	56.45	92.3667

- **When decreasing the number of zones, the value of SUM will slightly increase as we expected.** Because the less the zones, the more SKUs assigned to one zone, hence increasing the workload of picker.
- **As the order quantity becomes larger, the objective value deteriorates faster in imbalanced case** as the changing slope turns larger, while the slope of the balanced environment stays steady.



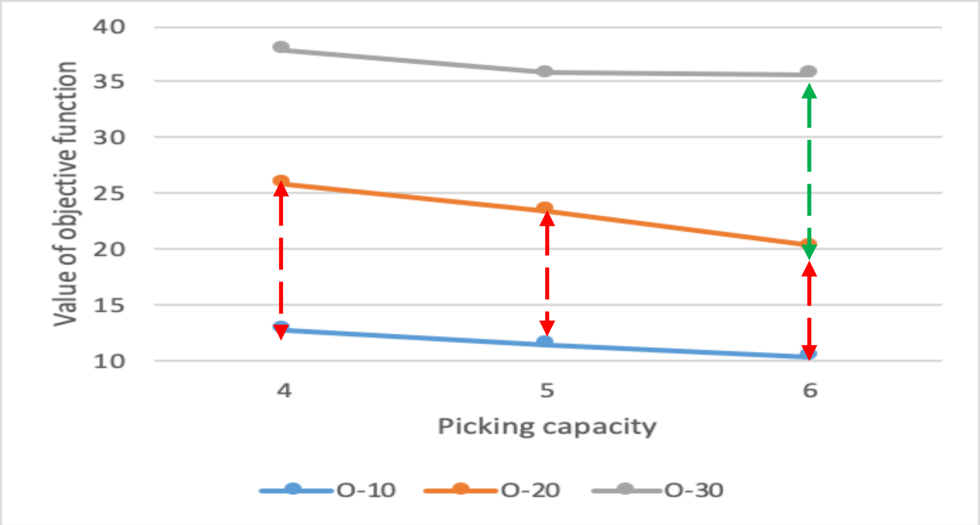
Zone 5



Zone 4

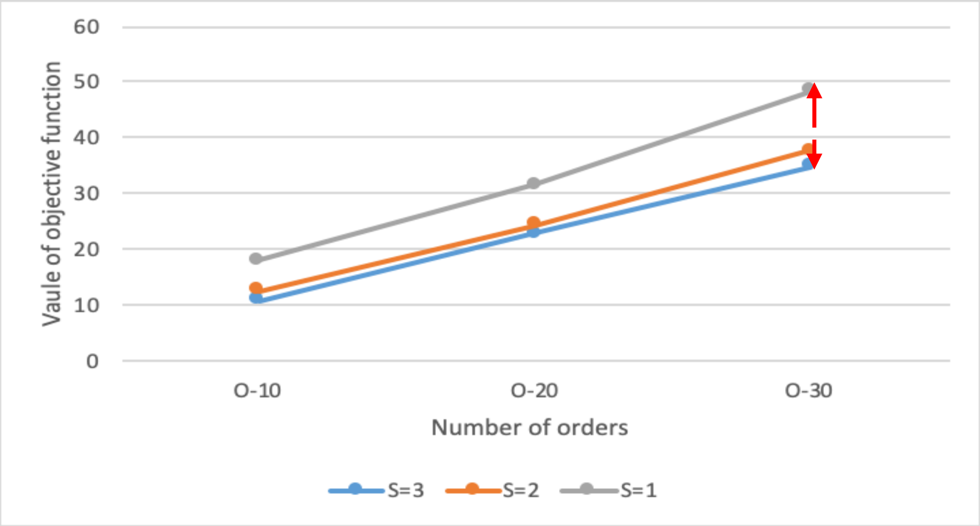
Zone 3

The Impact of System Configuration and Capacity on Synchronization



Picking capacity	4			5			6		
Order quantity	O-10	O-20	O-30	O-10	O-20	O-30	O-10	O-20	O-30
F	12.83	25.86	37.85	11.51	23.48	35.75	10.45	20.3	35.67
F_p	5.36	7.92	7.15	6.42	7.91	8.41	6.6	7.4	9.73
F_s	20.3	43.8	68.55	16.6	39.05	63.1	14.3	33.2	61.62

- **The value of objective function decreases as the picking cart capacity increases.** When enlarging the picking capacity, F_p has a trend of rising while F_s goes inversely. The larger the picking capacity, the less the batches would be grouped from all demand orders.



Number of sorting station	Criteria	Order quantity		
		O-10	O-20	O-30
3	F	10.975	22.8318	34.90595
	Fp	6.25	7.3636	8.9286
	Fs	15.7	38.3	60.8833
2	F	12.56665	24.4125	37.69805
	Fp	6.5833	8.85	8.5294
	Fs	18.55	39.975	66.8667
1	F	18.025	31.55	48.4417
	Fp	8.5	9	10.0667
	Fs	27.55	54.1	86.8167

- **Without the consideration of picking capacity, the more sorting stations, the better the sync performance.** Managers should consider the optimized (re)configuration of operational resources to bring about maximized benefits.

Future Research Opportunities

Short-term Work

- Interaction & full-factor analysis for picking and sortation stages;
- Taking the real-world dynamic uncertainties into account, such as the warehousing congestion. Re-synchronization scheme might be designed and incorporated in the existing mechanism;
- Different storage policy should be examined, in addition to the current dedicated storage;

Long-term Work

- It would be necessary to conduct a series of sensitivity analysis to study the impacts of macro and micro time periods (T and t) and impacts of parameters of jobs and orders;
- The concepts and models proposed could be realized in a decision support system (DSS) which is useful for helping the decision makers such as planners or schedulers for DT-enabled collective intelligence.

Thanks!

Q&A

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