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Multi-Criteria Simulation Evaluation for Manual-Order-Picking Warehouse Design

Safwan Altarazi[1],* and Maysa Ammouri[1]

[1]Department of Industrial Engineering, German Jordanian University, 35247Amman, 11180, Jordan

*Corresponding author. Email address: safwan.altarazi@gju.edu.jo

Abstract

Simulation has been widely adopted by researchers in assessing warehouse design and deciding its suitability. Using simulation, the current study presents a multi-criteria evaluation approach for manual-order-picking warehouse design. Three evaluation dimensions are considered: cycle time, space utilization, and resource productivity. The results showed that design's selection decisions are criterion-dependent. Nevertheless, the following design attributes indicated a comparatively better performance in the cycle time and space utilization criteria: traditional or fishbone layouts, low flow, standard operational policies, large manpower, and small warehouse size. For better resource utilization, traditional or fishbone layout, high flow, standard operational policies, low manpower, and large size are recommended.

Keywords: Warehousing; Manual-order-picking; Simulation; Multi-criteria performance evaluation.

1. Introduction

Despite initiatives to integrate supply chains and synchronize direct supply to customers, warehouses approve to be vital in supply chain structure and will continue to play a key role in coordinating the products flow between supply and demand. Warehouses may be manually operated, as current major warehouses (Shammas et al. 2019, Klodawski et al. 2018, Tompkins 2010), partially automated, or fully automated. In all types, evaluating the warehouse performance is essential in deciding the suitability of its design (Salhieh et al. 2018, Chen et al. 2010). Frazelle (2002) listed five dimensions for evaluating the performance of a warehouse. These dimensions are financial, productivity, utilization, quality, and cycle time. The financial dimension is mainly related to the cost of fulfilling an order, the quality to the percentage of perfect orders, the productivity to the total shipped items per total man-hour, the utilization to the percentage of utilized storage capacity, and the cycle time to the elapsed time between placing and shipping an order to/from the warehouse. Other performance measures could be found in literature. For example, Calzavara et al. (2017) developed a more complicated performance measure considering financial and ergonomic aspects. Warehouses are complex systems. The interrelated stochastic nature of manual-order-picking adds to the complexity of these systems. Thus, simulation is typically used to model and analyze such systems. Simulation techniques, mainly discrete event, agent-based and dynamic, have found various research adaptations in this regard. Such applications include warehouses operations analysis and optimization (Urzúa et al. 2019, Elbert et al. 2016, Shqair et al. 2014, Ducik et al 2010, Altarazi and Ammouri 2010), warehouses layout design and comparisons (Shqair and Altarazi 2014, Dukic et al. 2010), warehouses equipment requirements and efficiency assessment (Macro and Salmi 2002, Kosfeld 1998), and manpower identification in warehouses (Kosfeld 1998). For example, Wasusri and Theerawongsathon (2016) utilized discrete event simulation to compare different picking types, Hug et al. (2006) studied replenishment systems in warehouses using discrete event simulation, and Elbert et al. (2015) used agent-based modeling to compare the effect of routing policies on cycle time. Simulation has been also used to analyze picker blocking in order picking process (Elbert et al. 2015, Bahrami et al. 2017) and manual workload in hybrid warehouses (Zhang et al. 2021). In addition, simulation was integrated in a simulation-optimization framework to optimize these complex systems (Amorim-Lopes et al 2021).

Researchers have analyzed the effect of different factors on the performance of the warehouse, such analysis can be found in the work of Petersen and Aase (2004). However, most related studies have considered single design element (factor) and analyzed its impact on the warehouse performance. Few studies simultaneously studied more than one warehouse design element (Altarazi and Ammouri 2018, Roodbergen et al. 2015). Thus, these studies cnsidered the interelation between different elements and their impact on the performance. Simulation has played a vital role in these analyses. Simulation was also widely used in assessing warehouse design choices. In a review of the techniques used by companies for warehouse design, Baker and Canessa (2009) found that simulation ranked first among the tools used for the "evaluation and assessment" of possible designs. Most such simulation-assessment models adopted the criterion of the travelled distance, or its coin face, the elapsed time for the order picking (Chen et al. 2010).

In 2018, the authors of the current study proposed a concurrent comprehensive discrete event simulation methodology for designing manual order-picking warehouses (Altarazi and Ammouri 2018). The study considered five key warehouse design components and all warehouse key functions with their stochastic nature. The study adopted the average cycle time (ACT) per a stock-keeping unit (SKU) criterion to evaluate the proposed designs. In the current study, the work of Altarazi and Ammouri (2018) is extended by proposing a comprehensive simulation-based evaluation for manual-order-picking warehouses design considering three metrics: ACT (cycle time dimension), space utilization (utilization dimension), and average handled SKUs per manpower working unit time (productivity dimension).

The rest of the paper is arranged as follow: In Section 2, the general flow of the simulation modeling is presented; Section 3 presents the results and their deployments; and finally, the work is concluded in Section 4.

2. Scope of current study and its link to Altarazi and Ammouri (Altarazi and Ammouri 2018)

2.1. Background from Altarazi and Ammouri (Altarazi and Ammouri 2018)

Covering its probabilistic nature, the methodology of Altarazi and Ammouri (Altarazi and Ammouri 2018) simulated the key warehouse functions of receiving, unloading, put away, storage, preparation and picking, as well as shipping. Furthermore, the methodology considered five key design components, namely: throughput (also called flow), size, layout, operational policies (Op. policies), and the number of utilized manpower/carts. A full factorial design was adopted where each design factor has several levels as summarized in Table 1. As a result, 216 (4 x 3 x 3 x 2 x3) combinations have emerged, and a simulation experiment for each combination was conducted.

Table 1. Factors and levels of the full factorial design

Factor	Factor's levels
Layout	1. the traditional one-block layout 2. traditional with one cross-aisle layout 3. the horizontal layout 4. the fishbone layout
Operational policies	1. no policies (random storage policy with no routing policy) 2. standard policies (volume-based storage policy with traversal routing policy)
Flow type	1. low 2. medium 3. high
Size	1. small 2. medium 3. big
Manpower	1. small 2. medium 3. large

The simulation model integrated several modules and was arranged in two main parts. The first part handled the inbound warehouse operations (receiving, unloading, put away, and storage functions), and the second part handled order preparation and picking, loading, and shipping functions. Figure 1 is quoted to present the flowchart of the first part. Finally, the model was appropriately verified and validated.

The simulated warehouse designs were evaluated based on the ACT an SKU spent in a warehouse as shown in Equation (1). The ACT is used to evaluate the overall performance of a warehouse (Revillot-Narváez et al. 2019) with low ACT values indicate better performance and service.

$$ACT = \frac{\sum_{i=1}^{i=SKUs} CT_i}{n} \tag{1}$$

and:

$$CT_i = ST_i - ET_i$$

Where:

CT_i: is the cycle time of an SKU_i

ST_i: is the time once an SKU_i is ready for shipment

ET_i: is the time when an SKU_i enters the warehouse

n: is the total number of SKUs picked during a simulation run

The simulation model was realized in Arena rockwell software, and process analyzer was used to run the experiments and record the results.

2.2. The current study scope and methodology structure

In the current work, the authors extended the previous work in Altarazi and Ammouri (2018). In addition to the ACT, the authors considered additional performance criteria. These criteria are the warehouse space utilization (WHSU) and the average handled SKUs (AHS) per hour of available resources in the warehouse. The WHSU assesses the total utilization of the warehouse storage with “the larger the better” values, while the AHS indicator evaluates the productivity of a warehouse (Frazelle 2002). Equations (2) and (3), was calculated over a 100 hr simulation experiment length, expressing how the simulation model computes WHSU and AHS criteria. Logic entities, assigned attributes, and different model variables were used to calculate these criteria.

$$WHSU = \frac{\text{Occupied storage locations}}{\text{Available storage locations}} \tag{2}$$

$$\text{AHS} = \frac{\text{Total handeled (stored or picked) SKUs}}{\text{Total available resources hours}} \tag{3}$$

where:

Equation (2) is calculated as the average ratio of occupied storage locations to available storage locations for every 10 minutes of a simulation experiment.

In order to calculate these additional performance criteria, the previously developed simulation model by Altarazi and Ammouri (2018) was updated. Extra variables were defined. These variables are updated every ten minutes or at an SKU storage or picking during a simulation run. Then, the performance criteria are calculated and used as a simulation output at the end of a simulation run. Finally, the full factorial experiment, consisting of 216 combinations as explained in Section 2.1, was run, and the values for the additional performance criteria were calculated. As a summary, Figure 2 demonstrates the structure of the methodology used in the current study.

It is important to note that the presented performance criteria may be correlated for some combinations of the design components’ levels. Hence, the intention is not to present multi-independent performance criteria. Instead, the decision-maker can choose from different performance criteria to evaluate a warehouse design scenario. Finally, the financial, such as receiving cost and storage cost, and quality, such as the percentage of receipts processed accurately and the percentage of perfect warehouse orders, performance evaluation criteria are not included since they do not fit under the current research scope.

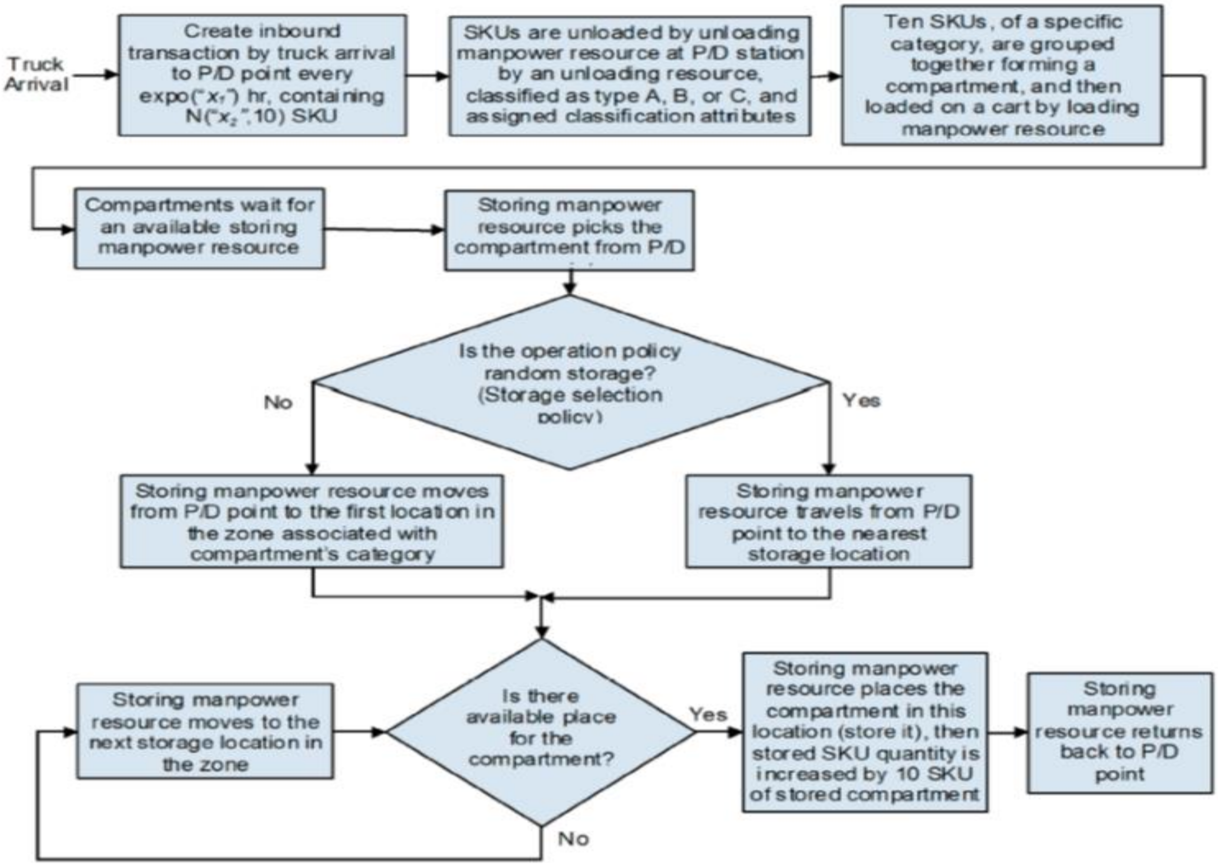

Figure 1. The simulation flow chart of inbound warehouse operations (receiving, unloading, putting way, and storing), based on Altarazi and Ammouri (2018)

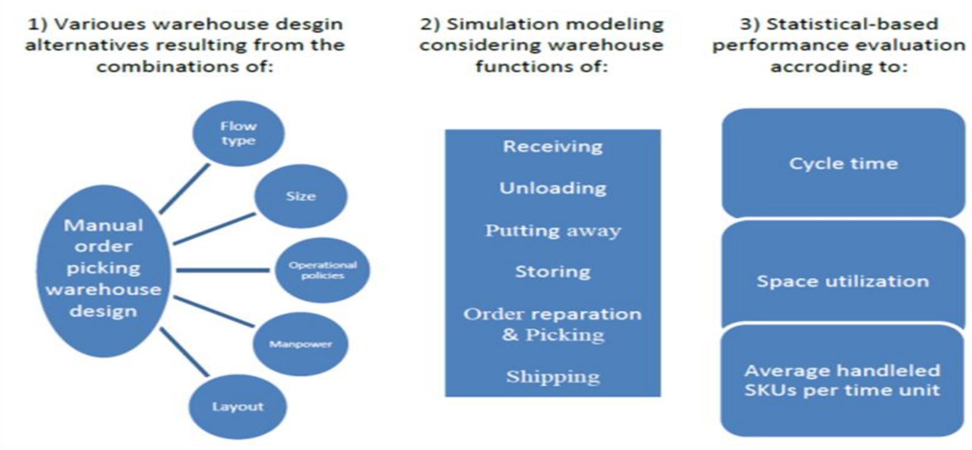

Figure 2. The presented methodology

3. Simulation Results Analysis

Table 2 presents a sample of the simulation model results for the three performance criteria. Each simulation result in Table 2 is the average of twenty simulation experiments, and each simulation experiment replication is 100 hr long. The subsections below provide the performed analyses for the results.

Table 2. Sample of simulation results for the three performance criteria

Simulation experiment notation*	ACT (hr)	WHSU (%)	AHS (SKUs/hr)
11111	5.08	60.8	4.46
11211	4.92	71.2	3.66
21111	5.10	56.6	3.92
………	…	……	………
22122	5.74	50.0	5.30
22222	5.22	60.3	4.68
……	……	……	……
32333	5.45	56.1	4.40
42133	6.12	41.4	5.49
42233	5.70	49.3	4.92

*The five-digit notation represents the five factors associated with their levels

3.1. Full factorial design analysis

This section introduces the Analysis of Variance (ANOVA) of the three performance criteria using a single replicate (average of twenty replicate) for each simulation experiment. The main and two interaction effects plots were generated and studied. Also, model adequacy was verified through appropriate residual analyses. Table 3 summarizes the results by presenting the design components with the most significant effect on the performance measures. These components are divided into single component (second column), interaction of two components (third column), and interaction of three components (third column). For instance, all the five warehouse design components (single factor's effects) significantly affect the three performance criteria and exemplifies, as given between brackets, which components' levels are best for each performance criterion. For example, for best AHS performance, the design components should be selected as "high" for flow rate, "traditional" for layout, "low" for manpower, "big" for size, and "standard policies" for the operational policies.

3.2. Results' Deployment

The results of Section 3.1 can be utilized for warehouse design selections. That is, given a warehouse design component level, Table 4 can be used to select other warehouse design components' levels based on the required performance criterion. The first column in Table 4 tabulates the components along with their levels. The rest of the columns present the effect of the single components and the combinations of other components to meet that effect. Table 4 was generated from main effect plots, two-way interaction plots, and confidence intervals on differences in means of the effect of the various components' levels. Furthermore, Table 4 assesses how the main effect of an input design component's level influences the required performance criterion. This assessment is expressed comparatively between the various design component levels in a three ranks scale: preferable (+), neutral (n), and not preferable (-). In addition, Table 4 recommends levels of other design components to improve the intended performance criterion. For example, to build a new warehouse that is expected to face a high flow (input design component), standard operational policies, large manpower, small size, and any layout are recommended to excel in the WHSU criteria (Table 4). Note that Table 4 indicates that high flow is preferable for the WHSU. Even if the actual situation is not preferable or neutrally preferable, such as low flow in the above example, Table 4 still provides specific design recommendations for each of the three performance criteria.

Table 3. Summary of significant effects (and their best levels) on the three performance criteria

Performance criterion	Significant Effect Main component	Two-way interaction	Three-way interaction
ACT	Flow type (low), Size (small), Layout (traditional or fish), Op. policies (standard), Manpower (large)	Layout*Op. policies (trad.,*stand.), Layout*size (fish*small), Op. policies*Manpower (stand.*large), Op. policies*Flow type (stand*low), Op. policies*Size (stand.*small), Manpower*Flow type (large*low), Manpower*Size (large*small), Flow type*Size (low*small)	Layout*Op. pol.*Manpower (trad.*stand.*large), Layout*Op. pol.*Size (trad. or horiz.*stand.*small), Layout*Manpower*Size (trad. or horiz.*large*small), Op. pol.*Manpower*Flow type (stand*large*low), Op. pol.*Manpower*Size (stand.*large*small) Op. pol.*Flow type*Size (stand.*low*small) Manpower*Flow type*Size (large*low*small)
WHSU	Flow type (low), Size (small), Layout (traditional. or fishbone), Op. policies (standard), Manpower (large)	Layout*Op. policies (fish*stand.), Layout*Manpower (trad. or fish*large), Layout*Flow type (trad. or fish*low), Layout*size(trad. or fish*small), Op. policies*Manpower (stand.*large), Op. policies*Flow type (stand*low), Op. policies*Size (stand.*small), Manpower*Size (large*small), Flow type*Size (low*small)	Layout*Op. pol.*Manpower (trad.*stand.*large), Layout*Op. pol.*Flow type (fish*stand.*low), Layout*Op. pol.*Size (fish*stand.*small), Layout*Flow type*Size, (fish*low*small), Op. pol.*Manpower*Size, (stand.*large*small) Op. pol.*Flow type*Size (stand.*low*small)
AHS	Flow type (high), Size (Big), Layout (traditional), Op. policies (standard), Manpower (low)	Layout*Op. policies (trad.*stand.), Layout*size(trad. or fish*medium), Op. policies*Manpower (stand.*low), Op. policies*Flow type (stand*high), Op. policies*Size (stand.*medium or big), Manpower*Flow type (low*high), Manpower*Size (low*medium or big), Flow type*Size (high*big)	Layout*Op. pol.*Size (trad. or fish*stand.*medium or big), Layout*Manpower*Flow type (trad. or fish*low*high), Layout*Manpower*Size (trad. or fish*low*medium), Layout*Flow type*Size (trad. or fish*high*medium), Op. pol.*Manpower*Size (stand.*low*medium)

Table 4. Results deployment for the five warehouse design components *(+: favourable effect, -: undesirable effect, n: neutral effect)

		Required performance Criterion					
Warehouse design component and its levels		**ACT Main effect***	**Other warehouse design components' selections**	**WHSU Main effect**	**Other warehouse design components' selections**	**AHS Main effect**	**Other warehouse design components' selections**
Warehouse flow type	Low	+	Any layout, standard policies, large manpower, and small size	+	Any layout, standard policies, large manpower, and small size	-	Fishbone layout, standard policies, low manpower, and big size
	Medium	n		n		n	
	High	-		-		+	
Layout	Traditional	n	Standard policies, large manpower, high flow, and large size	+	Standard policies, large manpower, low flow, and large size	+	Standard policies, low manpower, high flow, and medium or big size
	Traditional with one cross aisle	n		-		-	
	Fishbone	n		+		+	
	Horizontal	n		n		-	Standard policies, low manpower, high flow, and big size
Operational Policies	No policies	-	Any layout, large manpower, high or medium flow, and large size	-	Fishbone layout, large manpower, low flow, and small size	-	Fishbone layout, low manpower, high flow and big size
	Standard Policies	+	Any layout, standard policies, manpower, low flow, and small size	+	Any layout, large manpower, low flow, and small size	+	Fishbone layout, low manpower, high flow and medium or big size
Available manpower	Low	-	Any layout, standard policies, low flow, and small size	-	Any layout, standard policies, low flow, and small size	+	Any layout, standard policies, high flow, and big size
	Intermediate	n		n		n	
	Large	+		+		-	
Warehouse size	Small	-	Any layout, standard policies, large manpower, and low flow	+	Horizontal layout, standard policies, large manpower, and any flow	-	Any layout, low manpower, standard policies, and high flow
	Medium	n	Any layout, standard policies, large manpower, and any flow	n	Traditional or fishbone layout, standard policies, large manpower, and any flow	+	Horizontal layout, low manpower, standard policies, and high flow
	Big	+		-	Any layout, standard policies, large manpower, and any flow	+	Any layout, low manpower, standard policies, and high flow

3.3. Results' Discussion

Further insights from the above results are as follows:

• As a general rule, for best performance with respect to both ACT and WHSU, the recommended design selections are traditional or fishbone layout, low flow, standard operational policies, large manpower, and small size. In contrast, the selections for AHS are traditional or fishbone layout, high flow, standard operational policies, low manpower, and big size. On the one hand, The ACT, or the logistics customer service criterion, and utilization criterion, the WHSU, can be achieved by the same warehouse design selections. On the other hand, the productivity criterion, the AHS, which can be described as the cost efficiency criterion, required different design selections in the flow type, manpower, and size components. These results are rational since the cost and service are typically in conflict. Low flow (throughput) is preferable for both the ACT and WHSU. For the ACT, the low flow contributes to the less time required for putting away, storing, and picking activities; hence, enhancing the ACT. For the WHSU, the low flow had the highest numerator value of Equation (2) and, accordingly, the best WHSU. Finally, with high flow, more SKUs can be handled per unit time; hence, higher AHS can be achieved. • Small size warehouse was found superior for the ACT and WHSU criteria. The reasons behind this result can be attributed to: a) shorter total routing distance for "putting away and picking up" SKUs, and b) less available storage locations (dominator of Equation (2) compared with medium and big warehouses.

• Generally, traditional and fishbone warehouses outperformed the horizontal and "traditional with one cross-aisle" layouts for the entire three performance criteria (exceptions were found for particular design components combinations as shown in Table 4. This result explicates and partially contradicts Dukic et al. (2010) founding. It agrees that the fishbone layout is appropriate for pallet picking; yet, the current results show that traditional layouts are not always preferable with multiple picking routes. The choice depends on other design components of the warehouse and the performance criterion under consideration. As can be seen from Table 4, for a warehouse with any flow type, the fishbone warehouse performed as good as other layouts for the ACT and WHSU criteria. However, it topped all other layouts in optimizing the AHS criterion. Other illustrations can be found in Table 4.

• Regarding the "Operational policies", it was found that "volume-based storage policy with traversal routing policy" is better for the entire performance criteria than "random storage policy with no routing policy." This result was expected for the high flow/large size warehouses (Petersen & Aase 2004), yet, it was also proved valid for low flow/mall size warehouses. The reason is that the implementation of both "volume-based" storage policy and "traversal" routing policy will always overcome the drawbacks of, for instance, requiring more space for low flow-large size warehouse. Hence, resulting in enhanced WHSU and ACT. For the AHS criterion, it was expected that "random storage" and "routing without a policy" would result in transmitting lower items than what standard policies would transmit; hence standard policies provided better AHS at all levels of available resources.

• For the "manpower" component, since a large number of operators is expected to reduce the average time difference between receiving the SKU and shipping it, ACT was improved with large manpower. On the contrary, a large number of operators means more idle available resources; therefore, the low number of operators was the best selection for the AHS performance.

4. Conclusions

The current study presented a simulation-evaluation approach for manual-order-picking warehouses design considering three dimensions criteria of cycle time, space utilization, and resources productivity. The study results can support the question of "what design components should be selected to excel in a particular performance criterion?" It was found that design's selection decisions vary based on the criterion/criteria to be attained. On the one hand, the following selections revealed a comparatively better performance in optimizing both the ACT and WHSU: traditional or fishbone layouts, low flow, standard operational policies, large manpower, and small size. On the other hand, the selections for the AHS are traditional or fishbone layout, high flow, standard operational policies, low manpower, and large size.

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