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AN INTEGRATED MODEL OF STORAGE AND ORDER-PICKING AREA LAYOUT DESIGN

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Abstract:

In many warehouses both storage and order-picking process take place in same physical area. Designing layout of such area using either model for optimal storage area layout or model for optimal picking area layout leads to sub optimization. This paper presents an idea and initial attempt to combine those models into one integrated model, aimed to design optimal physical layout minimizing expected total travel distances of all operations. Presented analysis for different cases provides useful guidelines for designing layout of storage and low-level order picking area.

Keywords:

storage area layout, order-picking area layout, integrated model, warehouse design

1. INTRODUCTION

It is well known that logistics costs have an important influence on the business success of any company. Representing on average around 10% of sales in western companies, costs of logistics operations in industrial systems can play a vital role in determining the competitiveness of a company. The efficiency and effectiveness of logistics of a company are largely determined by design of logistics systems and operations performed in such systems. Warehousing systems are one of them. Since warehouses are in most cases non-avoidable places within the production site of industrial companies, and are also nodes in the distribution network towards final customers, proper warehouse planning and control have drawn full attention in literature [1,2,3]. Warehouse design is unfortunately highly complex task with many trade-offs between conflicting objectives and a large number of feasible designs. In [2] was proposed a structured approach to warehouse decision making, with the strategic, tactical and operational levels. In [3] was proposed a framework of warehouse design and operation, classifying the warehouse design problems as overall structure, sizing and dimensioning, department layout, selection of equipment and operation strategy. Both contributions have a common conclusion that multiple decisions are interrelated and have to be solved simultaneously, while, unfortunately, the majority of papers listed in their literature reviews are focused on the analysis of an isolated problem rather than on the synthesis. This is also concluded in [4]. According to [3], a researcher addressing one decision would require a research infrastructure which would integrate all other decisions, and to properly evaluate the impact of changing one of the design decisions requires estimating changes in the operation of the warehouse.

Those mentioned conclusions were drivers for writing this paper that aims to combine two, in literature addressed isolated problems, into one integrated problem and solution. Namely, those problems are optimal storage area layout problem and optimal order-picking area layout problem (in warehouse design also usually named as aisle configuration problems). Those two most important areas in warehouses already got a lot of attention of researchers regarding solutions (models) of optimal layout design. However, all so far developed models are analyzing storage or order-picking areas isolated one from another, trying to design an optimal layout either regarding expected travel distance for storage/retrieval operations or expected distance of routes in picking operations.

Although there are warehouses with separate storage and order-picking areas (and this approach is valid), in many warehouses there is only one physical area where both storage/retrieval of pallets and order-picking of cases/items take place. One clear example, which is in focus of this paper, is warehouse system of selective pallet racks where higher level rack locations serve as storage (reserve) locations, while lower level locations are picking locations. Such racking system is in the same time a (reserve) storage system and low-level manual order-picking system. Since pallet storage, full pallet picking, replenishment of picking locations and case- (and even item-) picking occur in such systems, the problem stated for this research is: can we find and design an optimal area layout, such that will minimize expected total travel distance (or travel time, or cost of travelling) of all mentioned operations.

In the remainder of this paper Section 2 briefly explains layout design problems that are in focus of this paper, as well as selected models for storage and order-picking area layout design identified as applicable sub-models (parts) of proposed integrated model. Developed integrated model of storage and order-picking area layout is presented in Section 3. Analysis of proposed model's results, applicability and usefulness on several instances is presented in Section 4. Comments on limitations and deficiencies of proposed model and possible ways of further research are given at the end of the paper in Conclusion.

2. STORAGE AND ORDER-PICKING AREA LAYOUT PROBLEM AND MODELS

The layout problem of storage area of conventional warehouses has quite a long history ever since 1960s. In 1980s and 1990s, a lot of attention was given to the layout problems of automated storage/retrieval systems. The layout of conventional warehousing systems with manual order-picking from multiple aisles has been the topic of several papers only in the last 15 years. Recently, some radically new, innovative warehouse layouts, which do not include traditional assumptions, have been proposed in [5]. Despite those new innovative layouts as well as various automated systems available, most warehouses today are still designed as conventional warehouses with traditional storage and order-picking layout. The basic form of such layout is rectangular, with parallel straight aisles. There are two possibilities for changing aisles, at the front and at the rear of the warehouse. These aisles are also straight and meet the main aisles at right angles. One such layout is given in Figure 1 (with symbols explained in section 3).

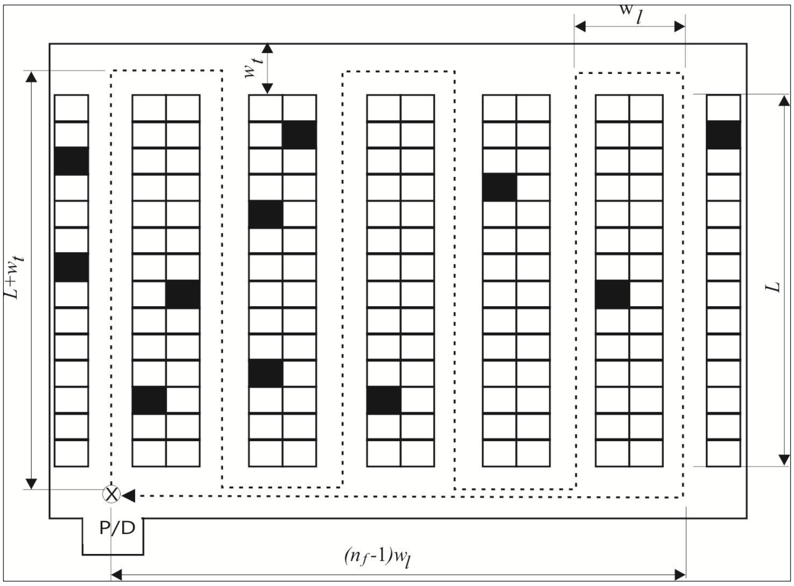

Figure 1 – Basic storage and order-picking area layout

Therefore, the term "a conventional storage area layout" in this paper refers to the layout with unit-load operations (storage and retrieval) in above described layout, while the term "conventional order-picking area layout" refers to the one with manual order-picking operations (case- or item-picking) from pick locations in above described layout. One example, where both storage and order-picking operations occur in the same physical area is the system of selective pallet racks, illustrated in Figure 2. Storage or/and retrieval of unit-loads (full pallets) in presented system would be done either with single commands (one storage or one retrieval per trip) or dual commands (combining one storage and one retrieval per trip). Since for a given required capacity of storage area (number of storage locations) one could design various layouts (altering the number of aisles and the length of aisles), the problem is which layout is optimal regarding the design objective. Design objective could be minimization of cost (investment cost and operational cost), time (operations of storage and retrieval), or simply only expected travel distance (minimizing travel time as most dominant component of total operation time). Most models in literature optimize the layout minimizing the expected travel distance to store/retrieve an item. The theoretical background to warehouse layout can be found in [6] with derived expressions for optimal warehouse designs represented as continuous storage areas both for non-rectangular and rectangular designs. A simple model for optimal storage layout that minimizes the expected travel in the rectangular storage area with parallel aisles assuming random storage and single location of pickup and delivery point (P/D), which might be located in any place along the front aisle or in the corner, was presented in [7]. That model is used as a part of our proposed integrated model in Section 3. Similar idea for optimal storage layout, although in case of dual commands, was used in [8].

Figure 2 – Storage and order-picking system with selective pallet racks

Designing the layout of order-picking area could have even greater influence on the efficiency of warehouse operations. The order-picking process, defined as the process of retrieving items from storage locations in response to a specific customer request, is the most laborious and the most costly activity in a typical warehouse, making up to 55% of the total operating costs of a warehouse [9]. The order-picking operation in illustrated system with Figure 1 consists of visiting several picking locations (marked as black locations) and retrieving cases (or items) in picking route. Efficient order-picking process could be achieved using various operating policies. The fact that about 50% of total order-picking time in conventional warehouses is spent on travelling [9] is the reason that most methods aimed for operational efficiency of order-picking focus on reducing travel times (distances). For a most comprehensive overview of literature regarding the methods in order-picking systems we refer to [10]. The most important for this research are routing methods that determine the picking sequences and routes of travelling, trying to minimize total travel distances. The analysis of routing methods presented in literature has shown a non-negligible influence of the layout on their performances. Therefore, minimized expected travel of picking routes for selected methods could be achieved with optimal layout of order-picking area. Order-picking area layouts that can be found today in the majority of warehouses are the same as for the storage area. A non-linear programming model for optimal order-picking layout is presented in [11]. The model aims at finding the minimum average travel distance expressed as a function of a number of layout variables and parameters (number of aisles, length of aisles, depot location, width of aisles including storage racks, width of a cross-aisle), under defined conditions. The mathematical expressions for the expected route distance for probably most popular routing policy, named S-shape policy, was presented in [12]. This model is also used as a part of our proposed integrated model in Section 3.

3. INTEGRATED STORAGE AND ORDER-PICKING AREA LAYOUT MODEL

As mentioned in introduction, developed storage layout models and order-picking layout models consider two problems independently and minimizing either expected storage/retrieval cycles or picking routes. In presented conventional system with pallet racks both storage/retrieval and order-picking operations occur in the same layout. Additionally, picking locations should be replenished from time to time with goods stored in upper locations (reserve locations). Replenishment was not considered in any of previously mentioned models. Idea of finding such

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layout that could minimize all relevant travels motivated us toward development of integrated storage and order-picking layout model. However, there is a certain complexity of that problem considering all possible influencing variations and control policies: There are alternatives of possible conventional layouts; Storage and full pallet retrieval operations could be done by single and dual commands; Replenishment operations might be also carried out with single commands or combined with storage and/or retrieval in more complex commands; Various picking policies also have influence on expected routes and therefore resulting optimal layout; Storage policies (slotting) would have impact both on storage/retrieval and picking operations; etc. To explore the proposed idea, most simple model is developed, with aim to investigate applicability and possible usefulness. It considers layout illustrated in Figure 1, with parallel aisles (racks), front and rear aisle, and one P/D location in the corner. Storage, retrieval, replenishment and order-picking operations start and end at P/D location. Storage, retrieval (full pallet picking) and replenishment operations are assumed as single commands regarding travel. Although replenishment cycle of course has 2 operations (retrieval of full pallet from reserve storage location and put away of that full pallet into picking location), it is assumed that reserve location is above picking location so travel for replenishment is equal to a single command. Storage assignment method is assumed random therefore any location is equally likely to be visited for storing, retrieval or replenishment (meaning no using popularity to determine locations for items in front, however storage locations should be above picking locations).

Notation used in models and Figure 1:
L^* – total storage capacity per layer in meters (total length of pallet racks, $L^*=2NL$),
L – length of one pallet rack = length of an aisle [m],
B – width of storage/order-picking area [m],
w_t – width of front and rear aisle [m],
w_l – width of racking segment per one aisle [m],
N – number of aisles,
x – order size (equals the number of visited locations in picking tour),
E_S – expected travel of storage or retrieval cycle [m],
E_R – expected travel of replenishment cycle [m],
E_P – expected travel per picking cycle [m],
n – expected number of visited aisles in picking tour,
n_f – expected furthest aisle in picking tour,
X – expected number of pallets stored in the system in observed time T,
X_1 – expected number of pallets picked (retrieved) as full pallets in observed time T,
X_2 – expected number of pallets used for replenishment of picking locations in observed time T,
p_1 – fraction of stored pallets picked as full pallets,
p_2 – fraction of stored pallets used to replenish picking locations,
Y – expected number of picking cycles in observed time T,
k – factor defining number of replenishment cycles in relation with number of picking cycles (equals the size of the order picked in one tour in relation to the full size of the stored pallet),
E_T – expected total travelled distance by forklifts and picking trucks in observed time T [m],
$E_{T/X}$ – expected total travelled distance per one stored pallet [m].

Using storage layout models presented in literature, expected travel to storage location (and back from storage location to P/D point) for storage/retrieval in single command can be expressed as (1).

$$E_S = \frac{L^*}{4 \cdot N} + \frac{w_t}{2} + \frac{(N-1) \cdot w_l}{2} \tag{1}$$

As already explained, for the sake of simplicity expected travel to and from location in replenishment cycle could be represented in the same way as single command, with the same equation as expected storage/retrieval travel (2).

$$E_R = \frac{L^*}{4 \cdot N} + \frac{w_t}{2} + \frac{(N-1) \cdot w_l}{2} \tag{2}$$

For order-picking we assume most used in practice routing heuristics, S-shape policy. With the S-shape routing policy, any aisle containing at least one item is traversed through the entire length. Aisles where nothing has to be picked are skipped. Aisles are visited in sequential manner. Figure 1 illustrates one example of a picking route using S-shape policy. In [12] authors recognized this problem similar to occupancy problem, and derived expressions for expected number of visited aisles and expected furthest visited aisle, as (3), (4):

$$n = N \cdot \left[1 - \left(1 - \frac{1}{N} \right)^x \right] \tag{3}$$

$$n_f = N - \sum_{i=1}^{N-1} \left(\frac{i}{N} \right)^x \tag{4}$$

where x is the size of the order that equals the number of visited picking locations. Expected picking travel per route can be then expressed as (5):

$$E_P = n \cdot \left(\frac{L^*}{2N} + w_t \right) + 2 \cdot \left(n_f - 1 \right) \cdot w_l \tag{5}$$

In one particular system there might be different number of storage, full pallet picking (retrieval), replenishment and picking cycles per observed time T. Let's assume X number of pallets stored in the system. Some number of pallets might be retrieved as full pallets (X_1) while the rest (X_2) will be used for replenishment of picking locations. The number of picked (retrieved) full pallets in relation with stored pallets is represented by ratio p_1 as $p_1 = X_1/X$. Number of pallets used for replenishment of picking locations in relation with stored pallets is accordingly represented by ratio p_2 as $p_2 = X_2/X$. The cases or items (requested by customers) will be retrieved from pallets used for replenishment by order-picker in picking cycles. In case of many small orders, number of picking trips might be significantly larger than number of replenishments. In case of larger order sizes picker might pick approximately full mixed pallet per route and number of trips could be similar to the number of replenishments. In cases where picker is using picking truck with double sized forks (carrying two pallets) number of picking cycles could be even smaller than number of replenishments. To address all those possible situations factor k is introduced in proposed model, in order to relate number of picking cycles Y to a number of replenishments X_2 as $k = Y/X_2$. Factor k therefore could be considered also as the fraction of the full pallet picked in one picking tour. In observed time T with X number of full pallets entering the system for storage, X_1 number of retrieved pallets as full pallet picking, X_2 number of replenishments of picking locations and Y number of picking cycles, expected total travel distance by forklifts and picking trucks could be expressed as (6):

$$E_T = 2 \cdot X \cdot E_S + 2 \cdot X_1 \cdot E_S + 2 \cdot X_{2\cdot} \cdot E_R + Y \cdot E_P \tag{6}$$

Using equations from (1) to (5), for p_1, p_2 and Y, and then dividing total travel distance with X, expected total travel distance per stored pallet could be finally expressed as

$$E_{T/X} = 4\cdot\left(\frac{L^*}{4\cdot N}+\frac{w_t}{2}+\frac{(N-1)\cdot w_t}{2}\right)+ \\ +\frac{(1-p_1)}{k}\cdot\left\{N\cdot\left[1-\left(1-\frac{1}{N}\right)^x\right]\cdot\left(\frac{L^*}{2N}+w_t\right)+2\cdot\left[N-\sum_{i=1}^{N-1}\left(\frac{i}{N}\right)^x-1\right]\cdot w_t\right\} \tag{7}$$

Being a function of number of aisles N for a given set of parameters L^*, w_t, w_l, x, k and p_1, minimal expected total travel distance per stored pallet will be achieved with optimal number of aisles N_{opt}.

4. ANALYSIS

Model was analyzed on three different storage size instances (namely small, medium and large layout, with $L^* = 300$, 600, and 900 meters respectively), for different order sizes for picking routes ($x = 5$, 10, 20, and 40) and structure of operations (numbers of different types of cycles represented by values of k and p_1). Varying the number of aisles, sub-models and integrated model were used to calculate expected travel distances for storage/replenishment operations, expected travel distance of picking routes and expected total travelled distance per stored pallet. Values for w_t and w_l were constant, 3 and 5.2 meters respectively. Due to the limited size of the paper, results for only one layout size ($L^* = 600$) are presented for 3 typical scenarios.

4.1. Structure of operations with equal number of order-picking cycles and storage cycles

Table 1 presents resulting values (minimal travel distances are highlighted) assuming all stored pallets are used for replenishment (in other words no full-pallet picking, $p_1 = 0$) and same number of order-picking cycles as storage/replenishment cycles (picking results in full size mix pallets, $k = 1$).

It is obvious from results that optimal layout for storage/replenishment with single command travels do not correspond with optimal layout for order-picking with multiple commands (using S-shape routing policy). Optimal order-picking area layout tends to be with just 2 aisles for “higher density of locations” (lower average distance between locations), which are situations in smaller warehouses and larger orders (higher number of locations to be visited), while in opposite situations optimal order-picking area layouts are often with higher number of aisles compared to the optimal storage area. Obtained results show that obtained minimum value with integrated models is different than minimums for separate optimization of storage and picking layouts. However the differences measured are less than 5% (calculated using values for $E_{T/X}$ in columns with marked minimums).

Table 1 – Expected values of traveling distances for storage/replenishment cycle, picking cycle and total travel per stored pallet (scenario one)

N	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
E_S	81.7	59.3	49.4	44.5	42.1	41.1	41.05	41.6	42.5	43.7	45.2	46.8	48.6	50.5
x=5														
E_P	306.5	287.7	266.4	249.0	236.3	227.3	221.4	217.9	216.2	215.0	217.0	218.9	221.7	225.2
$E_{T/X}$	633.3	524.9	464.0	427.1	404.7	391.8	385.6	384.1	386.2	390.9	397.8	406.3	416.2	427.2
x=10														
E_P	316.1	324.3	325.0	321.6	316.8	312.1	308.1	305.2	303.4	302.6	302.8	303.8	305.6	308.0
$E_{T/X}$	642.9	561.5	522.6	499.6	485.2	476.6	472.3	471.5	473.4	477.6	483.6	491.1	500.0	510.0
x=20														
E_P	316.4	329.7	342.2	352.8	361.4	368.2	373.6	378.1	382.1	385.7	389.3	392.9	396.6	400.4
$E_{T/X}$	643.2	566.9	539.8	530.8	529.8	532.7	537.8	544.4	552.1	560.7	570.1	580.2	591.0	602.4
x=40														
E_P	316.4	329.8	343.2	356.6	369.8	382.7	395.2	407.2	418.6	429.4	439.7	449.6	459.0	468.1
$E_{T/X}$	643.2	567.0	540.8	534.6	538.2	547.2	559.4	573.4	588.6	604.4	620.5	636.9	653.5	670.1

4.2. Structure of operations with greater number of storage cycles than order-picking cycles

Situation where there are less order-picking cycles than storage cycles might happen where substantial number of stored pallets is picked as full pallets (pallet picking), which is modelled in analyzed situations with p_I=0.5 (therefore half of the stored pallets is picked as full pallets, half is used to replenish picking locations). Less order-picking cycles than storage cycles might also happen when forklift with double size forks is used for picking, resulting in 2 mixed pallets per picking cycle. This is modelled in analyzed situations with $k = 2$. In this case both scenarios explained above are assumed to take place (therefore there are four times more storage cycles than order-picking cycles). Results are presented in Table 2. Being unlikely that smaller order sizes could result in 2 formed full size mix pallets, only larger orders ($x = 20$ and $x = 40$) were considered.

Table 2 – Expected values of traveling distances for storage/replenishment cycle, picking cycle and total travel per stored pallet (scenario two)

N	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
E_S	81.7	59.3	49.4	44.5	42.1	41.1	41.05	41.6	42.5	43.7	45.2	46.8	48.6	50.5
x=20														
E_P	316.4	329.7	342.2	352.8	361.4	368.2	373.6	378.1	382.1	385.7	389.3	392.9	396.6	400.4
$E_{T/X}$	405.9	319.6	283.1	266.2	258.8	256.6	257.6	260.8	265.5	271.4	278.1	285.6	293.6	302.1
x=40														
E_P	316.4	329.8	343.2	356.6	369.8	382.7	395.2	407.2	418.6	429.4	439.7	449.6	459.0	468.1
$E_{T/X}$	405.9	319.7	283.4	267.1	260.8	260.2	263.0	268.1	274.6	282.3	290.7	299.7	309.2	319.0

Less number of picking cycles reduces influence of optimal order-picking area layout on total result. Optimal layout obtained with integrated model is similar to the optimal layout for just storage/replenishment operations, with differences in total travel under 1%. However, please note that optimizing layout using integrated model instead of optimizing it just for order-picking operations results in almost 30% reduction of total travel.

4.3. Structure of operations with greater number of order-picking cycles than storage cycles

There is also possible to have many smaller orders in warehouse, with very intense order-picking. In this case number of order-picking cycles would be much greater compared to the number of storage and replenishment cycles. This situation is modelled with assumptions that there is no full pallet picking ($p_1 = 0$) and that amount of goods on replenished pallet will be picked in 5 order-picking cycles (therefore $k = 0.2$). Results are presented in Table 3, while this time larger orders are skipped being more likely that smaller order sizes ($x = 5$ and $x = 10$) correspond to this situation.

Table 3 – Expected values of traveling distances for storage/replenishment cycle, picking cycle and total travel per stored pallet (scenario three)

N	2	3	4	5	6	7	8	9	10	11	12	13	14	15
E_S	81.7	59.3	49.4	44.5	42.1	41.1	41.05	41.6	42.5	43.7	45.2	46.8	48.6	50.5
x=5														
E_P	306.5	287.7	266.4	249.0	236.3	227.3	221.4	217.9	216.2	215.0	217.0	218.9	221.7	225.2
$E_{T/X}$	1859.4	1675.7	1529.4	1423.3	1349.8	1301.2	1271.3	1255.6	1250.9	1254.8	1265.7	1282.1	1303.1	1327.8
x=10														
E_P	316.1	324.3	325.0	321.6	316.8	312.1	308.1	305.2	303.4	302.6	302.8	303.8	305.6	308.0
$E_{T/X}$	1907.3	1858.5	1822.8	1786.0	1752.3	1724.8	1704.9	1692.5	1687.1	1688.1	1694.7	1706.3	1727.2	1741.9

In this case optimal layout resulting from integrated model is closer to the layout optimized for just picking operations, which is expected. Due to the fact that there are small order sizes (greater distance between picking locations), optimal number of aisles tends to be higher compared to the optimal number of aisles from storage layout model. However, in this case optimizing layout using integrated model instead of picking area layout model would result again in very small reduction of total travel. Even in comparison with design based on optimal storage layout, reductions obtained using integrated model are only about 2.5%.

5. CONCLUSION

From theoretical point of view, analysis of proposed integrated model of optimal storage and order-picking area layout confirms correctness of the idea that it is possible to find optimal layout of storage and order-picking area where storage, replenishment and order-picking operations are taking place. Such layout will result in minimized expected total travel, although reductions that could be achieved are not high. From the practical point of view, based on presented results designers are able to think about “adjusting” solution according to the expected composition of the processes. With domination of full pallet picking operations and/or larger picking orders, layout could be designed closer to the optimal storage layout. With more intense order-picking process expected, layout could be designed closer to the optimal picking area layout.

Of course presented integrated model has several limitations and deficiencies. First of all, only single commands for storage and full pallet picking are assumed. Those two operations might be combined in one dual command cycle, reducing average travel per operation and having influence on optimal storage layout. Location of reserve pallet for replenishment was assumed above picking location, which does not have to be a case in real warehouses and it is then hard to follow random storage policy. Proposed model also assumed S-shape routing method for generating picking routes. For other heuristics or optimal routing one would need different models of expected picking travel. Another limitation is assumed random storage, while in practice dedicated or class-based storage could be applied. Those assignment strategies would affect both average travel distances for storage and order-picking, however they are very difficult to model analytically. Possible congestion also might affect final decision. Congestion increases total time (not distance) and layouts with more aisles are expected to result in less congestion than layouts with smaller number of aisles.

Some limitations of proposed integrated model are also inherited from previously developed sub-models. In practice we will have orders with different size. Averaging order size not necessarily results in the same average travel. Both storage and order-picking model assume start/end location (P/D point) in the corner of the layout. This point might be located anywhere along front aisle or on different locations, changing analytical expressions in the proposed model. Even further, warehouses using WMS with wireless communication might issue tasks to available forklift drivers without the need to travel to the assumed starting position. Another assumption inherited from used sub-models is basic layout with rectangular shape and only two possibilities for changing aisles, at the front and at the rear of the warehouse. Adding additional cross-aisles might reduce both dual command travel in storage/retrieval operations and total route distances of order-picking cycles. However modelling these situations analytically is again very difficult. Assumed one fixed start/end point also doesn’t have to be a case for plenty warehouses. Storage area might be connected with receiving area (and many docks) in a way that it is possible to enter it on different places, while start/end point for order-picking operations could be on completely different place (for instance near sorting/accumulation/packing area or shipping area).

Nevertheless listed limitations and deficiencies, results from presented model might serve to warehouse designers as a guidelines how to design storage and order-picking layout trying to minimize expected total travel distance, leading to the more productive and efficient solutions of storage and order-picking area layouts.

Further research might go into several directions. Limitations and deficiencies of proposed model might be reduced with developing analytical expressions for more complex model. To analyze influence of different parameters (different initial assumptions) that cannot be expressed analytically, simulation could be used. Simulation experiments could be also used to verify proposed formula, taking into account stochastic nature of some parameters as well.

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