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ANALYTICAL MODEL FOR OPTIMUM WAREHOUSE DIMENSIONS

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Abstract Warehouses are essential components of any supply chain in terms of customer service and cost levels. Warehouses are one of the important players in the success or failure of businesses from not only the customer service levels perspective but also the cost perspective. Warehouses, as one of the important components of supply networks, should be continually improved from design and operation perspectives to increase the performance. All efforts and solutions regarding the performance improvement are important and complex. In other words, warehouses should operate effectively in terms of the costs and technical performance that are determined during the design phase of warehouses. There are a few studies in the literature regarding the calculations of the optimum dimensions of a warehouse along the x, y, and z directions. In this paper, an analytical model is proposed to achieve the optimum warehouse dimensions in terms of the number of stocking zones along each of three dimensional axes directions: the x-, y-, and z-axes as non-linear mathematical modelling is developed to ensure the optimality. The warehouse dimensions (length, width, and height under the rafter of the building) are then calculated according to the results obtained from the model to minimise the average travel time.

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1. INTRODUCTION

Warehouses are essential components of supply chains (Gu, Goetschalckx, & McGinnis, 2007). Warehouses are one of the important players in the success or failure of businesses from not only the customer service levels perspective but also the cost perspective (Baker & Canessa, 2009; Ashayeri & Gelders, 1985). Warehouses have several major roles: enabling a buffer for the material flow along the supply chain due to the variability caused by seasonality, batching, and transportation, as well as a location to provide value-added service such as knitting, labelling, and stamping. When market competition is added to this situation, warehouses, which play an important role in supply networks, must have a continuous improvement in the design and operations to achieve higher performance from the warehouses (Gu, Goetschalckx, & McGinnis 2010). Because of the increase in labour costs, allocating more people for any warehouse performance problem is not a viable solution (Gray, Karmakar, & Seidmann, 1992). Therefore, these improvement efforts result in the adoption of new management philosophies: tighter inventory control, shorter response times, as well as new technology implementations, such as bar coding, radio frequency communications (RF), warehouse management systems (WMS), and automatic storage and retrieval systems (AS/RS) (Gu, Goetschalckx, & McGinnis, 2007; Gray, Karmakar, & Seidmann, 1992). All of these solutions have a very significant cost impact. As a result, such logistical costs related to warehouses should be very well managed, in other words, warehouses should function cost effectively (Baker & Canessa, 2009). These cost drivers are in fact determined during the design phase (Rouwenhorst, Reuter, Stockrahm, van Houtum, Mantel, & Zijm, 2000).

Warehouse Design involves making decisions regarding different design parameters to satisfy the objectives in terms of the costs and/or performance of the warehouse. In the literature, a structured design approach of decision making at a strategic, tactical, and operational level can be found in which there are multiple interrelated decisions. For each level, the problems are defined using three axes: processes (receiving, storage, picking, shipping, etc.), resources (storage unit, storage system, pick equipment, WMS, etc.), and organisation (process flow, storage policy, order picking policy, etc.) (Rouwenhorst, Reuter, Stockrahm, van Houtum, Mantel, & Zijm, 2000). For example, a decision regarding conventional or automatic selection of the warehouse storage strategy is a strategic decision that affects the warehouse design (Gu, Goetschalckx, & McGinnis, 2007; de Koster, van der Poort, & Wolters, 1999, 2007; Karakış, Baskak, & Tanyaş, 2011, 2012, 2013a).

A total of 243 studies that contain problems, solution methods and/or approaches related to warehouse design in the literature were reviewed, and 170 of these are classified according to solution methods and/or approaches. The studies in the literature are first classified into three levels, namely strategic, tactical, and operational, according to the problem types from the warehouse design perspective. Based on the review, a general finding is that one study may focus on more than one topic under the same or different hierarchical levels. This characteristic is observed because warehouse design problems are strongly coupled (Gu, Goetschalckx, & McGinnis, 2010). In other words, warehouse design should consider a large number of interrelated decisions (Rouwenhorst, Reuter, Stockrahm, van Houtum, Mantel, & Zijm, 2000).

Within the literature review, "sizing", one of the strategic level tasks, is defined as the storage capacity of the warehouse. The decision regarding warehouse sizing affects the dimensions and layout of the warehouse. Warehouse dimensioning, another strategic level task, is the translation of the sizing into floor space to assess the construction and operating costs (Gu, Goetschalckx, & McGinnis, 2010). With regard to warehouse sizing and problems, most of the existing studies propose analytical models, such as normative models, a greedy network flow algorithm, linear programming, dynamic programming, etc., to determine the storage capacity within a planning time horizon based on the stochastic demand for the storage location of a product (White & Francis, 1971; Lowe, Francis, & Reinhardt, 1979; Hung & Fisk, 1984; Rao & Rao, 1988). In addition, there are a few studies that propose analytical models to determine the storage capacity using inventory cost models that consider warehouse construction, inventory holding and replenishment costs analytically (Levy, 1974; Cormier & Gunn, 1996; Goh, Jihong, & Chung-Piaw, 1999). In another paper, an optimisation model is presented that determines the optimal storage capacity under the economic-order-quantity (EOQ) inventory model considering the costs of the warehouse (Lee & Elsayed, 2005). The optimum capacity expansion for the warehouse for the rolling periods was analytically examined in another study (Cormier & Gunn, 1999). A more recent study asserts that the optimal shape of a storage system with a given capacity that minimises the total travel time is independent of the storage policy being used (Zaerpour, de Koster, & Yu, 2013).

Among these studies, linear programming and dynamic programming are used to find the area of the warehouses in ft2 that minimises the costs (Hung & Fisk, 1984; Rao & Rao, 1998). Another study proposes the layout equations with the cost formulas; however, in this case, some of the parameters including the height of the warehouse that affect the number of stock positions along the z-axis are given by the decision maker (Berry, 1968).

The problem of determining the dimensions is first modelled to assess the construction and operating costs without considering the aisle structure (Francis, 1967). This model is extended by considering the aisle configurations, and then an integrated model is developed with a simulation that evaluates the storage shortage cost, which is valid for only single-command operations (Bassan, Yaakov, & Rosenblatt, 1980; Rosenblatt & Roll, 1984). The determination of the warehouse aisle configurations that minimise the costs of handling and the construction for random storage locations is examined in another study (Roberts & Ruddell, 1972). The optimal allocation of spaces between different departments is also examined in a few studies (Azadivar, 1989; Heragu, Du, Mantel, & Schuur, 2005).

Another study proposes a conceptual model for the warehouse layout (Hassan, 2002). Moreover, there are many different studies in the literature that focus on the warehouse dimensions and layouts that minimise the travel time of both the conventional and automatic warehouse equipment (Hwang & Ko, 1988; Park & Webster, 1989; Sarker & Babu, 1995; Koh, Kim, & Kim, 2002; Roodbergen & Vis, 2006, 2008; Pohl, Meller, & Gue, 2009; Parikh & Meller, 2010; Lerher, Potrc, Sraml, & Tollazi, 2010).

In addition, a study in the literature proposes a queuing theoretical approach for the optimal internal design of an automated warehouse with the consideration of the response times (Pandit & Palekar, 1993). One of the recent studies regarding the AS/RS design also treats the height of the rack as a given parameter that is used within different scenarios by rule of thumb heuristics (Malmborg, 2001). The calculation formulas for the warehouse aisle dimensions (horizontal and vertical directions) are proposed, with the objective of minimising the total travel distance and time (Ghiani, Laporte, & Musmanno, 2004). Additionally, these formulas are even enhanced for determining the size and design of flow type and U-type warehouses (Cakmak, Gunay, Aybakan, & Tanyaş, 2012). However, both studies do not consider the technical parameters of the different equipment through the z-axis.

The aim of this paper is to calculate the optimum number of stock positions for three dimensions by considering the technical parameters of different equipment and determine the optimum aisle dimensions accordingly. From this perspective, as a result of a literature review, it is asserted that there is a need to calculate the warehouse aisle dimensions by determining the optimal number of stock positions along three dimensions using a model considering the technical parameters (e.g., speed per each axis) of the different equipment (e.g., reach truck, turret truck, AS/RS, etc.). The existing studies proposed optimal models that use the height under the rafter of the warehouse building as a parameter. In other words, these models determine the size of the warehouses in ft2, which is the two-dimensional area, and some models consider the costs of the warehouse including the equipment. Moreover, the technical performance attributes of equipment, such as the speed across each axis, are not considered within the existing models, especially for the z-axis, even though it is the main criterion for deciding on the equipment, such as the reach truck, turret truck, or AS/RS.

Thus, the proposed model not only calculates the optimum number of stock positions and warehouse dimensions along the x-, y-, and z-axes but also generates a key direction as an input for the conventional/automatic warehouse decision problem, which is one of the most important strategic design decisions in the warehouse design process (Karakış, Baskak, & Tanyaş, 2013a).

All of the formulas stated in the literature consider the two-dimensional optimality and allow decision makers to provide the necessary inputs regarding the -axis as a parameter. However, the stock positions through the z-axis are treated as a variable in this model, and the optimum number of the stock positions along this axis is calculated. Thus, this paper is aimed at developing an analytical model for determining the optimum warehouse dimensions to address this gap in the literature. The proposed model determines the optimum number of stock positions as well as the warehouse dimensions through the z-axis (e.g., height under the rafter of the warehouse) based on the equipment alternative to be used in the warehouse.

2. AIM AND FOCUS OF THE STUDY

This paper proposes an analytical model that considers the three dimensions of a warehouse per different types of equipment. The objective of the model is to enhance the formulas used to determine the warehouse dimensions reported in the references of Ghiani, Laporte, & Musmanno (2004) and Cakmak, Gunay, Aybakan, & Tanyaş (2012) by considering the height under the rafter of the warehouse (z-axis) and the technical parameters of the equipment (speed), which both depend on the equipment type. The existing formulas in the literature treat the stock positions through the z-axis as a parameter provided by the decision maker.

This study focuses on the optimum storage volume calculations of a warehouse that enable the determination of the optimum shape and the dimensions of the warehouse and generate significant inputs for the conventional/automatic warehouse decision, which is a key strategic warehouse decision problem (Karakış, Baskak, & Tanyaş, 2012).

3. AIM AND FOCUS OF THE STUDY

The analytical model is formulated as a non-linear mathematical model. The notations and details regarding the analytical model are stated below for the sample warehouse plan shown in Fig. 1 (Ghiani, Laporte, & Musmanno, 2004):

m = Required stock position (e.g., pallets)

α_x = The length of the stock position along the x-axis

α_y = The length of the stock position along the y-axis

α_z = The length of the stock position along the z-axis

w_x = The length of the interim aisle along the x-axis

w_y = The length of the main aisle along the x-axis
w_z = The distance between the top of the racks and the roof of the building
n_z = Stock position along the z-axis
n_x = Stock position along the x-axis
n_y = Stock position along the y-axis
v_i = Speed of equipment (reach truck, turret truck, AS/RS) along axis i (i = x, y, z)

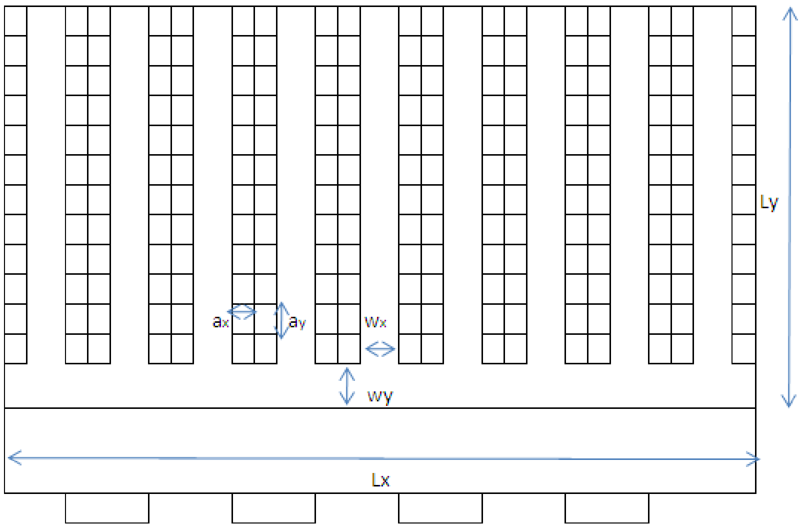

Fig. 1 Sample warehouse layout plan

The length of the warehouse is calculated as follows:

$$L_x = (\alpha_x + w_x / 2)\, n_x \tag{1}$$
$$L_y = (\alpha_y\, n_y + w_y) \tag{2}$$
$$L_z = (\alpha_z\, n_z + w_z) \tag{3}$$

L_z is calculated using this model, with α_z as a parameter, which is the height of the storage type with the product (e.g., height of a single pallet with the product on it). Therefore, α_z can be changed according to the different storage types, such as pallet, package, box, etc., and which products will be stored within them. Based on these factors, the average distance for one cycle of the equipment is stated as follows:

$$2\,(L_x / 4 + L_y / 2 + L_z / 2) \tag{4}$$

The objective is to minimise the average travel time of the equipment per cycle; therefore, the objective function is given below:

Minimise $[(\alpha_x + w_x / 2).\ n_x) / 2v_x) + (\alpha_y\ n_y + w_y) / v_y + (\alpha_z\ n_z + w_z) / v_z]$ (5)

Subject to $n_x\ n_y\ n_z \geq m$ (6)

$n_x, n_y, n_z \geq 0$ (7)

If it is assumed that the variables A, B, and C are equal to the each term of Eqs. (8), (9), and (10), respectively, then:

$$A = (\alpha_x + w_x / 2) / 2v_x \quad (8)$$
$$B = (\alpha_y / v_y) \quad (9)$$
$$C = (\alpha_z / v_z) \quad (10)$$

Then, the objective function can be written in the following form:

Minimise $A.n_x + B.n_y + C.n_z$ (11)

At this stage, the variable n can be written as $n = e^P$, and the objective function and the constraints can be written as follows:

Minimise $A.e^{Px} + B.e^{Py} + C.\ e^{Pz}$ (12)

Subject to $P_x + P_y + P_z \geq ln(m)$ (13)

$n_x, n_y,\ n_z \geq 0$ (14)

This is a simple convex programming problem, and using the following optimality conditions, the optimum analytical solution can be determined (Bazaraa, Sherali, & Shetty, 2006):

$$A.e^{Px} = B.e^{Py} = C.\ e^{Pz} \quad (15)$$
$$P_x + P_y + P_z = ln(m) \quad (16)$$

Thus, the optimum number of the stock positions along each axis (x-, y-, and z-axis) is calculated as well as the minimum average travel time as follows:

$$n_x = (B.C.m / A^2)^{1/3} \quad (17)$$
$$n_y = (A.C.m / B^2)^{1/3} \quad (18)$$
$$n_z = (A.B.m / C^2)^{1/3} \quad (19)$$

The assumptions are stated below:

- The equipment travels half of the distance of the warehouse width and the entire distance through the warehouse length and height under the rafter of the warehouse building during one cycle of the operation.
- The racking system is back to back, as shown in Fig. 1.

- Only one unit of the stocks is picked up or stored per each travel or cycle.
- The probability of accessing each aisle is equal.
- There is no diagonal movement for AS/RS.
- There is only one piece of equipment that operates at each aisle.

The following inputs for these calculations are parametric:

- Storage type and its dimensions (e.g. Europallet)
- The length of the stock position along the x-axis, y-axis, and z-axis, depending on the product and storage type
- The length of the interim aisle along the x-axis
- The length of the main aisle along the x-axis
- The distance between the top of the racks (height under the rafters) and the roof of the building
- The width of the order preparation area
- The unit speed and the other technical parameters that belong to each piece of equipment (e.g., reach truck, turret truck, AS/RS, etc.)

Next, the proposed model is applied to solve a sample problem. The numbers of the stock positions along the three-dimensional axes are determined with reference to equations (17), (18), and (19) stated above. In addition, the dimensions of the warehouse are calculated using equations (1), (2), and (3), as mentioned above. The average distances travelled for one cycle for each type of equipment are calculated using equation (4), and the average travel times for one cycle of the operation are calculated using equation (5). The results of the calculations are given per piece of equipment.

4. RESULTS AND DISCUSSION

The solution of the sample problem is presented in (Table 1). According to the given number of storage locations (m) in (Table 1), all of the data are translated into the floor space of the warehouse, which is known as dimensioning of the warehouse. The calculations are performed in terms of the optimum number of stock positions, the dimensions and the area of the warehouse, the average distance travelled, and the average travel time per cycle for each of the different types of warehouse equipment: reach truck, turret truck, and AS/RS crane.

Table 1 Warehouse dimensioning calculations

	Reach Truck	Turret Truck	AS/RS
***m* (required stock position)**	48,832	48,832	48,832
Pallet width (m)	0.8	0.8	0.8
Rack width (α_y) (m)	1	1	1

Pallet length (m)	1.2	1.2	1.2
Rack length (α_x) (m)	1	1	1
Pallet height (α_z) (m)	1.2	1.2	1.2
Main aisle (w_y) (m)	4	2	2
Interim aisle (w_x) (m)	3.3	1.95	1.95
Distance from the top of the racks to the roof (w_z) (m)	0.15	0.1	0.08
Equipment speed for x-axis (v_x) (m/sn)	3	2.5	15
Equipment speed for y-axis (v_y) (m/sn)	0.5	0.4	12
Equipment speed for z-axis (v_z) (m/sn)	0.18	0.3	10
Number of pallet locations (n_x)	150	147	49
Number of pallet locations (n_y)	33	25	39
Number of pallet locations (n_z)	10	15	27
Total number of pallet locations	49,504	55,125	51,597
Width of stock area (L_x) (m)	398	291	97
Length of stock area (L_y) (m)	37	27	41
Height of stock area (L_z) (m)	13	19	33
Stock area (m^2)	14,728	7,857	3,977
Width of order preparation area (m)	13.5	13.5	13.5
Warehouse area (m^2)	15,277	8,222	4,531
Average distance travelled (m/cycle)	249	191,05	122,50
Average travel time (sec/cycle)	212.56	189.03	9.95

If the optimum value of nz is calculated as a greater value than the equipment lifting height capacity, then a new constraint $\alpha z.nz \leq H$, where H is the height of the warehouse under the rafters of the building, can be entered into the model by the decision maker. In this situation, the optimum nx and ny values can be recalculated using the formulas stated in the reference (Ghiani, Laporte, & Musmanno, 2004).

The same sample problem is also solved using the existing model given by Ghiani, Laporte, & Musmanno (2004), which is only optimising the nx and ny values, and the decision maker gives the nz values externally. The details of the solution are stated in Karakış, Baskak, & Tanyaş (2014) in which nz values are given as 7, 9, and 23 for the reach truck, turret truck, and AS/RS crane, respectively. The total cost of the investment is also calculated by the analytical model stated in Karakış Baskak, & Tanyaş (2013b) for each type of equipment. The cost figures of the equipment consist of land cost, rack cost, construction cost and initial investment costs (Karakış, Baskak, & Tanyaş, 2013b). The comparison of the warehouse area requirements, the average distances and travel time per cycle for each type of equipment for these two different approaches is given in (Table 2).

Table 2 Number of stock positions and warehouse dimensions comparison

	Reach Truck			Turret Truck			AS/RS		
	Model in Ghiani, Laporte, & Musmanno, (2004)	Proposed Model	Improvement (%)	Model in Ghiani, Laporte, & Musmanno, (2004)	Proposed Model	Improvement (%)	Model in Ghiani, Laporte, & Musmanno, (2004)	Proposed Model	Improvement (%)
Stock area (m^2)	18,871	14,728	22	10,862	7,857	28	4,285	3,977	7
Warehouse area (m^2)	21,521	15,227	29	12,866	8,222	36	5,548	4,531	18
Average distance travelled (m/cycle)	252.90	249.00	2	195.90	191.50	2	144.15	122.50	15
Average distance travelled along the x and y axes (m/cycle)	244.35	236.00	3	185.00	172.50	7	116.47	89.50	23
Average travel time (sec/cycle)	456.09	212.56	53	421.96	189.03	55	12.09	9.95	18
	Model in Karakış, Baskak, & Tanyaş. (2013b)	Proposed Model	Improvement (%)	Model in Karakış, Baskak, & Tanyaş (2013b)	Proposed Model	Improvement (%)	Model in Karakış, Baskak, & Tanyaş (2013b)	Proposed Model	Improvement (%)
Total investment costs (1,000 TL)	46,362	33,772	27	28,095	18,942	33	39,813	37,574	6

As observed from (Table 2), the proposed model in this paper is able to generate a better solution regarding the warehouse area, the average travelled distance, and the average travel time per cycle for all of the warehouse equipment.

The new proposed model enables 22% savings for the stock area of the reach truck, 28% for the turret truck, and 7% for the AS/RS crane. With regard to the warehouse area, the new model enables savings of 29% for the reach truck, 36% for the turret truck, and 18% for the AS/RS crane. The new model also provides average distance travelled savings of 2% each for the reach truck and the turret truck and 15% for the AS/RS crane during one cycle. If the distances of the x- and y-axes are considered, then the new model enables savings from the average distance travelled per cycle of 3%, 7%, and 23% for the reach truck, turret truck, and AS/RS crane, respectively. The savings are higher for the AS/RS crane compared to the other two types of equipment, especially for the average distance travelled per cycle. One possible reason for this difference is that the number of the stock positions through the z-axis (nz) is most critical for the AS/RS because automatic warehouses can particularly utilise the height under the rafters of the buildings. The proposed new model generates the following savings in the average travel time of each type of equipment for one cycle of operation: 53% for the reach truck, 55% for the turret truck, and 18% for the AS/RS crane.

Moreover, in this solution, it is assumed that there is no diagonal movement of the AS/RS crane, so in the case of diagonal movement, the savings percentage is even higher. Moreover, this result is in line with practical applications because it is always more feasible to build higher warehouse buildings with a smaller base area that utilise AS/RS cranes. However, it is more common to build conventional warehouses with a larger base area and reduced height. Therefore, the outcome of this model also supports real-life applications. Based on these savings for the area, the total investment costs of the warehouse for each piece of equipment are improved as well.

Compared to the analytical model reported in Karakış, Baskak, & Tanyaş (2013b), the total investment costs are reduced using the proposed model in this paper. The results indicate the opportunity for investment cost savings of 27% for the reach truck, 33% for the turret truck, and 6% for the AS/RS crane.

5. CONCLUSIONS AND FUTURE RESEARCH

Warehouses are essential for any supply chain. Because most of the parameters that affect warehouse operations in terms of both costs and performance are determined during the design phase, warehouse dimensioning, as a part of a strategic warehouse design, is becoming more crucial.

It is obvious from the findings of the literature review that there is a gap regarding the solution of the optimum number of stock positions for three dimensions by considering the technical parameters of different types of equipment and the determination of the corresponding optimal aisle dimensions (Baker, 2010; Karakış, Baskak, & Tanyaş, 2011, 2012).

The analytical model developed in this paper is able to determine the optimum warehouse (e.g., optimum storage area) dimensions for different types of equipment. Moreover, the speed information of the equipment is considered. This model also determines the best fit height under the rafters of the warehouse for each situation in terms of the different equipment usage. All formulas stated in the literature consider the two-dimensional optimality and allow the decision makers to provide the necessary inputs regarding the z-axis as a parameter. However, the stock positions through the z-axis are treated as a variable in this model, and the optimum number of stock positions along this axis is calculated. From the average travel time, the distance per cycle, and the area perspectives, the dimensioning formulas given by Ghiani, Laporte, & Musmanno (2004), Cakmak, Gunay, Aybakan, & Tanyaş (2012), and Karakış, Baskak, & Tanyaş (2014) are enhanced and improved. The results generated from the proposed new model represent optimal reference solutions for decision makers that work on warehouse dimensions and the selection of equipment. Because the proposed model generates a better solution regarding the area of the warehouse, the solution also implies savings opportunities regarding the total investment costs of the different types of equipment compared to the analytical model provided in the reference (Karakış, Baskak, & Tanyaş, 2013b).

For further research, this model can be improved by considering the costs of the equipment, including operational and investment costs per axis, because the average travel time and the distance are also dependent on the costs of the equipment, which differ from each other and affect the solution. In addition, this model can be extended to other different types of products, including different demand patterns, storage units (e.g., package, box, etc.), rack system alternatives (e.g., double deep), and material handling equipment.

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BIOGRAPHICAL NOTES

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