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Invited Review

Research on warehouse design and performance evaluation: A comprehensive review

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ABSTRACT

This paper presents a detailed survey of the research on warehouse design, performance evaluation, practical case studies, and computational support tools. This and an earlier survey on warehouse operation provide a comprehensive review of existing academic research results in the framework of a systematic classification. Each research area within this framework is discussed, including the identification of the limits of previous research and of potential future research directions.

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1. Introduction

This survey and a companion paper (Gu et al., 2007) present a comprehensive review of the state-of-art of warehouse research. Whereas the latter focuses on warehouse operation problems related to the four major warehouse functions, i.e., receiving, storage, order picking, and shipping, this paper concentrates on warehouse design, performance evaluation, case studies, and computational support tools. The objectives are to provide an all-inclusive overview of the available methodologies and tools for improving warehouse design practices and to identify potential future research directions.

Warehouse design involves five major decisions as illustrated in Fig. 1: determining the overall warehouse structure; sizing and dimensioning the warehouse and its departments; determining the detailed layout within each department; selecting warehouse equipment; and selecting operational strategies. The overall structure (or conceptual design) determines the material flow pattern within the warehouse, the specification of functional departments, and the flow relationships between departments. The sizing and dimensioning decisions determine the size and dimension of the warehouse as well as the space allocation among various warehouse departments. Department layout is the detailed configuration within a warehouse department, for example, aisle configuration in the retrieval area, pallet block-stacking pattern in the reserve storage area, and configuration of an Automated Storage/Retrieval System (AS/RS). The equipment selection decisions determine an appropriate automation level for the warehouse, and identify equipment types for storage, transportation, order picking, and sorting. The selection of the operation strategy determines how the warehouse will be operated, for example, with regards to storage and order picking. Operation strategies refer to those decisions about operations that have global effects on other design decisions, and therefore need to be considered in the design phase. Examples of such operation strategies include the choice between randomized storage or dedicated storage, whether or not to do zone picking, and the choice between sort-while-pick or sort-after-pick. Detailed operational policies, such as how to batch and route the order picking tour, are not considered design problems and therefore are discussed in Gu et al. (2007).

It should be emphasized that warehouse design decisions are strongly coupled and it is difficult to define a sharp boundary between them. Therefore, our proposed classification should not be regarded as unique, nor does it imply that any of the decisions should be made independently. Furthermore, one should not ignore operational performance measures in the design phase since operational efficiency is strongly affected by the design decisions, but it can be very expensive or impossible to change the design decisions once the warehouse is actually built.

Performance evaluation is important for both warehouse design and operation. Assessing the performance of a warehouse in terms of cost, throughput, space utilization, and service provides feedback about how a specific design or operational policy performs compared with the requirements, and how it can be improved. Furthermore, a good performance evaluation model can help the designer to quickly evaluate many design alternatives and narrow down the design space during the early design stage. Performance

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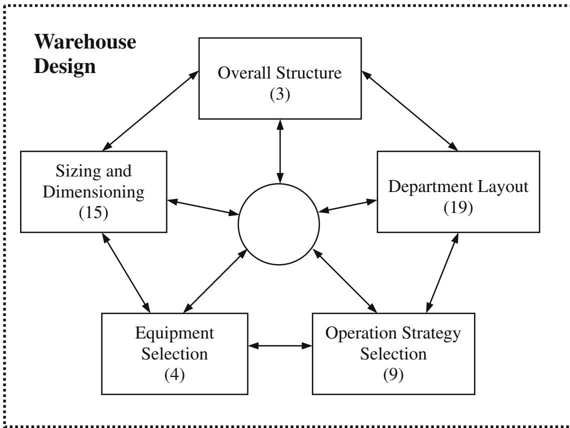

Fig. 1. Warehouse design problems and publication frequency.

evaluation methods include benchmarking, analytical models, and simulation models. This review will mainly focus on the former two since simulation results depend greatly on the implementation details and are less amenable to generalization. However, this should not obscure the fact that simulation is still the most widely used technique for warehouse performance evaluation in the academic literature as well as in practice.

Some case studies and computational systems are also discussed in this paper. Research in these two directions is very limited. However, it is our belief that more case studies and computational tools for warehouse design and operation will help to bridge the significant gap between academic research and practical application, and therefore, represent a key need for the future.

The study presented in this paper and its companion paper on operations, Gu et al. (2007), complements previous surveys on warehouse research, for example, Cormier (2005), Cormier and Gunn (1992), van den Berg (1999) and Rowenhorst et al. (2000). Over 250 papers are included within our classification scheme. To our knowledge, it is the most comprehensive review of existing research results on warehousing. However, we make no claim that it includes all the literature on warehousing. The scope of this survey has been mainly focused on results published in available English-language research journals.

The topic of warehouse location, which is part of the larger area of distribution system design, is not addressed in this current review. A recent survey on warehouse location is provided by Daskin et al. (2005).

The next four sections will discuss the literature on warehouse design, performance evaluation, case studies, and computational systems, respectively. The final section gives conclusions and future research directions.

2. Warehouse design

2.1. Overall structure

The overall structure (or conceptual design) of a warehouse determines the functional departments, e.g., how many storage departments, employing what technologies, and how orders will be assembled. At this stage of design, the issues are to meet storage and throughput requirements, and to minimize costs, which may be the discounted value of investment and future operating costs. We can identify only three published papers addressing overall structural design.

Park and Webster (1989) assume the functions are given, and select equipment types, storage rules, and order picking policies to minimize total costs. The initial investment cost and annual operational cost for each alternative is estimated using simple analytic equations. Gray et al. (1992) address a similar problem, and propose a multi-stage hierarchical approach that uses simple calculations to evaluate the tradeoffs and prune the design space to a few superior alternatives. Simulation is then used to provide detailed performance evaluation of the resulting alternatives. Yoon and Sharp (1996) propose a structured approach for exploring the design space of order picking systems, which includes stages such as design information collection, design alternative development, and performance evaluation.

In summary, published research on the design of the overall warehouse structure is limited to the use of rough approximations or qualitative models in combination with limited exploration of a design space, which itself may be restricted by simplifying assumptions. Two kinds of research contributions are needed: (1) principle-based assessment of appropriate decision aiding for these high level design decisions which are taken with uncertain knowledge of future operating conditions; and (2) simple, validated models that actually give results useful for guiding overall structural design.

As an aside, we note that there is a reasonably robust research literature on the general facility layout problem, see , e.g., Meller and Gau (1996). This research assumes the definition of the departments is given, and contemporary approaches remain challenged by the modeling of the department interactions, particularly material handling. Warehouse design, in contrast, is largely concerned with defining the departments, and a major issue in resolving that decision is to understand the interactions. Thus, at this point, the research on general facility design does not offer much to inform warehouse design.

2.2. Sizing and dimensioning

Warehouse sizing and dimensioning has important implications on such costs as construction, inventory holding and replenishment, and material handling. Previous research has been focused on a single storage department and treated the sizing and dimensioning decisions as two separate problems.

2.2.1. Warehouse sizing

Warehouse sizing determines the storage capacity of a warehouse. There are two scenarios in modeling the sizing problem: (1) Inventory levels are determined externally so the warehouse has no direct control over when incoming shipments will arrive and their quantities (e.g., in a third-party warehouse) and all the exogenous requirements for storage space have to be satisfied by the warehouse; and (2) The warehouse can directly control the inventory policy (e.g., an independent wholesale distributor). A major difference is that in the latter case, inventory policy and inventory costs should be considered in solving the sizing problem.

Assuming the warehouse has no control over inventory, warehouse sizing determines an appropriate storage capacity to satisfy the stochastic demand for storage space. White and Francis (1971) study this problem for a single product over a finite planning horizon. Costs considered include those due to warehouse construction, storage of products within the warehouse, and storage demand not satisfied by storage in the warehouse. Problems with either fixed or changeable storage size are modeled. The second model allows changes in the storage size over the planning horizon (e.g. by leasing additional storage space), so the decision variables are the storage sizes for each time period. A linear programming formulation is presented for the second model, and the optimal solution is found by solving a network flow problem (see also Lowe et al. (1979)). Similar problems of determining fixed and changeable warehouse size are also discussed by Hung and Fisk (1984) and Rao and Rao (1998) with different cost formulations.

Levy (1974), Cormier and Gunn (1996) and Goh et al. (2001) consider warehouse sizing problems in the case where the warehouse is responsible for controlling the inventory. Therefore, the costs in their models include not only warehouse construction cost, but also inventory holding and replenishment cost. Levy (1974) presents analytic models to determine the optimal storage size for a single product with either deterministic or stochastic demand. Assuming additional space can be leased to supplement the warehouse, Cormier and Gunn (1996) propose closed-form solution that yields the optimal warehouse size, the optimal amount of space to lease in each period, and the optimal replenishment quantity for a single product case with deterministic demand. The multi-product case is modeled as a nonlinear optimization problem assuming that the timing of replenishments is not managed. Cormier and Gunn (1999) developed a nonlinear programming formulation for the optimal warehouse expansion over consecutive time periods. Goh et al. (2001) find the optimal storage size for both single-product and multi-product cases with deterministic demand. They consider a more realistic piecewise linear model for the warehouse construction cost instead of the traditional linear cost model. Furthermore, they consider the possibility of joint inventory replenishment for the multi-product case, and propose a heuristic to find the warehouse size. The effects of inventory control policies (e.g., the reorder point and ordering quantity) on the total required storage capacity are shown by Rosenblatt and Roll (1988) using simulation.

Our ability to answer warehouse sizing questions would be significantly enhanced by two types of research. First, assessing capacity requirements should consider seasonality, storage policy, and order characteristics, because these three factors interact to impact the achievable storage efficiency, i.e. that fraction of warehouse capacity that can actually be used effectively. Second, sizing models all employ cost models, and validation studies of these models would be a significant contribution.

2.2.2. Warehouse dimensioning

The warehouse dimensioning problem translates capacity into floor space in order to assess construction and operating costs, and was first modeled by Francis (1967), who used a continuous approximation of the storage area without considering aisle structure. Bassan et al. (1980) extends Francis (1967) by considering aisle configurations. Rosenblatt and Roll (1984) integrate the optimization model in Bassan et al. (1980) with a simulation model which evaluates the storage shortage cost, a function of storage capacity and number of zones. They assume single-command tours in order to evaluate the effect of warehouse dimension on the operational cost, and therefore their approach is not applicable to warehouses that perform multi-command operations (e.g., interleaving put-away and retrieval, or retrieving multiple items per trip).

The work discussed so far has approached the sizing and dimensioning problem assuming the warehouse has a single storage department. In reality, a warehouse might have multiple departments, e.g., a forward-reserve configuration, or different storage departments for different classes of Stock Keeping Units (SKUs). These different departments must be arranged in a single warehouse and compete with each other for space. Therefore, there are tradeoffs in determining the total warehouse size, allocating the warehouse space among departments, and determining the dimension of the warehouse and its departments. Research studying these tradeoffs in the warehouse area is scarce. Pliskin and Dori (1982) propose a method to compare alternative space allocations among different warehouse departments based on multi-attribute value functions, which explicitly capture the tradeoffs among different criteria. Azadivar (1989) proposes an approach to optimally allocate space between two departments: one is efficient in terms of storage but inefficient in terms of operation, while the other is the opposite. The objective is to achieve the best system performance by appropriately allocating space between these two departments to balance the storage capacity and operational efficiency tradeoffs. Heragu et al. (2005) consider a warehouse with five functional areas, i.e., receiving, shipping, cross-docking, reserve, and forward. They propose an optimization model and a heuristic algorithm to determine the assignment of SKUs to the different storage areas as well as the size of each functional area to minimize the total material handling and storage costs.

A key issue with all research on the dimensioning problem is that it requires performance models of material handling; these models are often independent of the size or layout of the warehouse. Research is needed to either validate these models, or develop design methods that explicitly consider the impact of sizing and dimensioning on material handling.

2.3. Department layout

In this section we discus layout problems within a warehouse department, primarily a storage department. The storage problems are classified as:

- (P1) pallet block-stacking pattern, i.e., storage lane depth, number of lanes for each depth, stack height, pallet placement angle with regards to the aisle, storage clearance between pallets, and length and width of aisles;
- (P2) storage department layout, i.e., door location, aisle orientation, length and width of aisles, and number of aisles; and
- (P3) AS/RS configuration, i.e., dimension of storage racks, number of cranes.

These layout problems affect warehouse performances with respect to:

- (O1) construction and maintenance cost;
- (O2) material handling cost;
- (O3) storage capacity, e.g., the ability to accommodate incoming shipments;
- (O4) space utilization; and
- (O5) equipment utilization.

Each problem is treated in the literature by different authors considering a subset of the performance measures, as summarized in Table 1.

2.3.1. Pallet block-stacking pattern (P1)

In the pallet block-stacking problem, a fundamental decision is the selection of lane depths to balance the tradeoffs between space utilization and ease of storage/retrieval operations, considering the SKUs' stackability limits, arriving lot sizes, and retrieval patterns. Using deep lane storage could increase space utilization because fewer aisles are needed, but on the other hand could also cause decreased space utilization due to the "honeycombing" effect that creates unusable space for the storage of other items until the whole lane is totally depleted. The magnitude of the honeycombing effect depends on lane depths as well as the withdrawal rates of individual products. Therefore, it might be beneficial to store different classes of products in different lane depths. A careful determination and coordination of the lane depths for different products is necessary in order to achieve the best storage space utilization. Besides lane configuration, the pallet block-stacking problem also determines such decisions as aisle widths and orientation, stack height, and storage clearance, which all affect storage space utilization, material handling efficiency, and storage capacity.

Table 1
A summary of the literature on warehouse layout design.

Problem	Citation	Objective	Method	Notes
P1	Moder and Thornton (1965)	O4	Analytical formulae	
	Berry (1968)	O2, O4	Analytical formulae	
	Marsh (1979) Marsh (1983)	O3, O4	Simulation models	
	Goetschalckx and Ratliff (1991)	O4	Heuristic procedure	Mainly on lane depth determination
	Larson et al. (1997)	O2, O4	Heuristic procedure	For class-based storage
P2	Roberts and Reed (1972)	O1, O2	Dynamic Programming	Consider the configuration of storage bays (unit storage blocks)
	Bassan et al. (1980)	O1, O2	Optimal design using analytical formulation	Consider horizontal and vertical aisle orientations, locations of doors, and zoning of the storage area
	Rosenblatt and Roll (1984)	O1, O2, O3	Optimal two-dimensional search method	Based on Bassan et al's work with additional costs due to the use of grouped storage
	Pandit and Palekar (1993)	O2	Queuing model	Include not only the ordinary travel time, but also waiting time when all vehicles are busy
P3	Karasawa et al. (1980)	O1, O2, O3	Nonlinear mixed integer problem	The model is solved by generalized Lagrange multiplier method
	Ashayeri et al. (1985)	O1, O2	Nonlinear mixed integer problem	Given rack height, the model can be simplified to a convex problem
	Rosenblatt et al. (1993)	O1, O2, O3	Nonlinear mixed integer problem	System service is evaluated using simulations, if not satisfactory, new constraints are added and the optimization model is solved again to get a new solution
	Zollinger (1996)	O1, O5	Rule of thumb heuristic	
	Malmborg (2001)	O1, O5	Rule of thumb heuristic	A more elaborated variation of Zollinger's rules that consider explicitly operational policies
	Lee and Hwang (1988)	O1	Nonlinear integer program	For the design of an automated carousel system. The model is solved with a simple search algorithm

A number of papers discuss the pallet block-stacking problem. Moder and Thornton (1965) consider ways of stacking pallets in a warehouse and the influence on space utilization and ease of storage and retrieval. They consider such design factors as lane depth, pallet placement angle with regards to the aisle, and spacing between storage lanes. Berry (1968) discusses the tradeoffs between storage efficiency and material handling costs by developing analytic models to evaluate the total warehouse volume and the average travel distance for a given storage space requirement. The factors considered include warehouse shape, number, length and orientation of aisles, lane depth, throughput rate, and number of SKUs contained in the warehouse. It should be noted that the models for total warehouse volume and models for average travel distance are not integrated, and the warehouse layout that maximizes storage efficiency is different from the one that minimizes travel distance. Marsh (1979) uses simulation to evaluate the effect on space utilization of alternate lane depths and the rules for assigning incoming shipments to lanes. Marsh (1983) compares the layout design developed by using the simulation models of Marsh (1979) and the analytic models proposed by Berry (1968). Goetschalckx and Ratliff (1991) develop an efficient dynamic programming algorithm to maximize space utilization by selecting lane depths out of a limited number of allowable depths and assigning incoming shipments to the different lane depths. Larson et al. (1997) propose a three-step heuristic for the layout problem of class-based pallet storage with the purpose to maximize storage space utilization and minimize material handling cost. The first phase determines the aisles layout and storage zone dimensions; the second phase assigns SKUs to storage configurations; and the third phase assigns floor space to the storage configurations.

The research addressing the pallet block-stacking problem suggests different rules or algorithms, usually with restrictive assumptions, e.g., the replenishment quantities and retrieval frequencies for each SKU are known. In reality, not only do these change dynamically, but the SKU set itself changes, and pallet block-stacking patterns that are optimized for current conditions may be far from optimum in the near future. Research is needed that will identify a robust solution in the face of dynamic uncertainty in the storage and retrieval requirements.

2.3.2. Storage department layout (P2)

The storage department layout problem is to determine the aisle structure of a storage department in order to minimize the construction cost and material handling cost. The decisions usually include aisle orientations, number of aisles, length and width of aisles, and door locations. In order to evaluate operational costs, some assumptions are usually made about the storage and order picking policies; random storage and single-command order picking are the most common assumptions.

By assuming a layout configuration, or a small set of alternative configurations, models can be formulated to optimize each configuration. Roberts and Reed (1972) assume storage space is available in units of identical bays. Bassan et al. (1980) consider a rectangular warehouse, and aisles that are either parallel or perpendicular to the longest walls. In addition, they also discuss the optimal door locations in the storage department, and the optimal layout when the storage area is divided into different zones. Roll and Rosenblatt (1983) extend Bassan et al. (1980) to include the additional cost due to the use of grouped storage policy. Pandit and Palekar (1993) minimize the expected response time of storage and/or retrieval requests using a queuing model to calculate the total response time including waiting and processing time for different types of layouts. With these response times, an optimization model is solved to find the optimal storage space configurations.

Roodbergen and Vis (2006) present an optimization approach for selecting the number and length of aisles and the depot location so as to minimize the expected length of a picking tour. They developed models for both S-shaped tours and a largest gap policy, and concluded that the choice of routing policy could, in some cases, have a significant impact on the size and layout of the department.

The conclusion from Roodbergen and Vis (2006) is quite significant, since it calls into question the attempt to optimize storage department layout without knowing what the true material handling performance will be. There is a need for additional research that helps to identify the magnitude of the impact of layout (for reasonably shaped departments) on total costs over the life of the warehouse, considering changing storage and retrieval requirements.

2.3.3. AS/RS configuration (P3)

The AS/RS configuration problem is to determine the numbers of cranes and aisles, and storage rack dimension in order to minimize construction, maintenance, and operational cost, and/or maximize equipment utilization. The optimal design models or rule-of-thumb procedures summarized in Table 1 typically utilize some empirical expressions of the costs based on simple assumptions for the operational policies, and known storage and retrieval rates.

Karasawa et al. (1980) present a nonlinear mixed integer formulation with decision variables being the number of cranes and the height and length of storage racks and costs including construction and equipment costs while satisfying service and storage capacity requirements. Ashayeri et al. (1985) solve a problem similar to Karasawa et al. (1980). Given the storage capacity requirement and the height of racks, their models can be simplified to include only a single design variable, i.e., the number of aisles. Furthermore, the objective function is shown to be convex in the number of aisles, which allows a simple one-dimensional search algorithm to optimally solve the problem. Rosenblatt et al. (1993) propose an optimization model that is a slight modification of Ashayeri et al. (1985), which allows a crane to serve multiple aisles. A combined optimization and simulation approach is proposed, where the optimization model generates an initial design, and a simulation evaluates performance, e.g., service level. If the constraints evaluated by simulation are satisfied, then the procedure stops. Otherwise, the optimization model is altered by adding new constraints that have been constructed by approximating the simulation results. Zollinger (1996) proposes some rule of thumb heuristics for designing an AS/RS. The design criteria include the total equipment costs, S/R machine utilization, service time, number of jobs waiting in the queue, and storage space requirements. Closed form equations compute these criteria as functions of the number of aisles and the number of levels in the storage rack. Malmborg (2001) uses simulation to refine the estimates of some of the parameters which then are used in the closed form equations.

The design of automated carousel storage systems is addressed by Lee and Hwang (1988). They use an optimization approach to determine the optimal number of S/R machines and the optimal dimensions of the carousel system to minimize the initial investment cost and operational costs over a finite planning horizon subject to constraints for throughput, storage capacity, and site restrictions.

Some other less well-discussed AS/RS design problems include determining the size of the basic material handling unit and the configuration of I/O points. Roll et al. (1989) propose a procedure to determine the single optimal container size in an AS/RS, which is the basic unit for storage and order picking. Container size has a direct effect on space utilization, and therefore on the equipment cost since the storage capacity requirement needs to be satisfied. Randhawa et al. (1991) and Randhawa and Shroff (1995) use simulations to investigate different I/O configurations on performance such as throughput, mean waiting time, and maximum waiting time. The results indicate that increased system throughput can be achieved using I/O configurations different from the common one-dock layout where the dock is located at the end of the aisle.

There are two important opportunities for additional research on AS/RS configuration: (1) results for a much broader range of technology options, e.g., double deep rack, multi-shuttle cranes, etc.; and (2) results demonstrating the sensitivity of configurations to changes in the expected storage and retrieval rates or the effects of a changing product mix.

2.4. Equipment selection

The equipment selection problem addresses the level of automation in a warehouse and what type of storage and material handling systems should be employed. These decisions obviously are strategic in nature in that they affect almost all the other decisions as well as the overall warehouse investment and performance. Determining the best level of automation is far from obvious in most cases, and in practice it is usually determined based on the personal experience of designers and managers.

Academic research in this category is extremely rare. Cox (1986) provides a methodology to evaluate different levels of automation based on a cost-productivity analysis technique called the hierarchy of productivity ratios. White et al. (1981) develop analytical models to compare block stacking, single-deep and double-deep pallet rack, deep lane storage, and unit load AS/RS in order to determine the minimum space design. Matson and White (1981) extend White et al. (1981) to develop a total cost model incorporating both space and material handling costs, and demonstrate the effect of handling requirements on the optimum storage design. Sharp et al. (1994) compare several competing small part storage equipment types assuming different product sizes and dimensions. They considered shelving systems, modular drawers, gravity flow racks, carousel systems, and mini-load storage/retrieval systems. The costs they considered include operational costs, floor space costs, and equipment costs. In summary, research on equipment selection is quite limited and preliminary, although it is very important in the sense that it will affect the whole warehouse design and the overall lifetime costs.

There are two fundamental issues for equipment selection: (1) how to identify the equipment alternatives that are reasonable for a given storage/retrieval requirement; and (2) how to select among the reasonable alternatives. A very significant contribution would be to develop a method for characterizing requirements and characterizing equipment in such a way that these two issues could be addressed in a unified manner.

2.5. Operation strategy

This section discusses the selection of operation strategies in a warehouse. The focus is on operation strategies that, once selected, have important effects on the overall system and are not likely to be changed frequently. Examples of such strategies are the decision between randomized and dedicated storage, or the decision to use zone picking. Two major operation strategies are discussed: the storage strategy and the order picking strategy. Detailed operation policies and their implementations are discussed in Gu et al. (2007).

2.5.1. Storage

The basic storage strategies include random storage, dedicated storage, class-based storage, and Duration-of-Stay (DOS) based storage, as explained in Gu et al. (2007). Hausman et al. (1976), Graves et al. (1977) and Schwarz et al. (1978) compare random storage, dedicated storage, and class-based storage in single-command and dual-command AS/RS using both analytical models and simulations. They show that significant reductions in travel time are obtainable from dedicated storage compared with random storage, and also that class-based storage with relatively few classes yields travel time reductions that are close to those obtained by dedicated storage. Goetschalckx and Ratliff (1990) and Thonemann and Brandeau (1998) show theoretically that DOS-based storage policies are the most promising in terms of minimizing traveling costs. Historically, DOS-based policies were difficult to implement since they require the tracking and management of each stored unit in the warehouse, but modern WMS's have this capability. Also the performance of DOS-based policies depends greatly on factors such as the skewness of demands, balance of input and output flows, inventory control policies, and the specifics of implementation. In a study by Kulturel et al. (1999), class-based storage and DOS-based storage are compared using simulations, and the former is found to consistently outperform the latter. This conclusion may have been reached because the assumptions of the DOS model rarely hold true in practice.

All the results on operational strategies are for unit-load AS/RS. Studies on other storage systems are rarely reported. Malmborg and Al-Tassan (1998) develop analytic models to evaluate the performance of dedicated storage and randomized storage in less-than-unit-load warehouses, but no general conclusions comparable to the unit-load case are given.

A strong case can be made that additional research is needed, especially to clarify the conditions under which the storage policy does or does not have a significant impact on capacity or travel time.

2.5.2. Order picking

In a given day or shift, a warehouse may have many orders to pick. These orders may be similar in a number of respects; for example, some orders are shipped using the same carrier, or transportation mode, or have the same pick due date and time. If there are similarities among subsets of orders that require them to be shipped together, then they also should be picked roughly during the same time period to avoid intermediate storage and staging. Thus, it is common practice to use wave picking, i.e., to release a fraction of the day's (shift's) orders, and to expect their picking to be completed within a corresponding fraction of the day (shift).

In addition to wave picking, two other commonly used order-picking strategies are batch picking and zone picking. Batch picking involves the assignment of a group of orders to a picker to be picked simultaneously in one trip. In zone picking, the storage space is divided into picking zones and each zone has one or more assigned pickers who only pick in their assigned zone. Zone picking can be divided into sequential and parallel zone picking. Sequential zone picking is similar to a flow line, in which containers that can hold one or more orders are passed sequentially through the zones; the pickers in each zone pick the products within their zone, put them into the container, and then pass the container to the next zone. (Bartholdi et al. (2000) propose a Bucket Brigades order picking method that is similar to sequential zone picking, but does not require pickers to be restricted to zones). In parallel zone picking, an order is picked in each zone simultaneously. The picked items are sent to a downstream sorting system to be combined into orders.

The organization and planning of the order picking process has to answer the following questions:

1. Will product be transported to the picker (part-to-picker) or will the picker travel to the storage location (picker-to-part)?
2. Will orders be picked in waves? If so, how many waves of what duration?
3. Will the warehouse be divided into zones? If so, will zones be picked sequentially or concurrently?
4. Will orders be picked in batches or separately? If they are batched, will they be sorted while picking or after picking?

Depending on the operating principles selected, the order picking methods will be:

- Single order picking.
- Batching with sort-while-pick.
- Batching with sort-after-pick.
- Sequential zoning with single order picking.
- Sequential zoning with batching.
- Concurrent zoning without batching.
- Concurrent zoning with batching.

Research on the selection of an order picking strategy is very scarce, which might be a result of the complexity of the problem itself. Lin and Lu (1999) compare single-order picking and batch zone picking for different types of orders, which are classified based on the order quantity and the number of ordered items. Petersen (2000) simulates five different order-picking policies: single-order picking, batch picking, sequential zone picking, concurrent zone picking, and wave picking. Two control variables in the simulation study are the numbers of daily orders and the demand skewness, while the other factors such as warehouse layout, storage assignment, and zone configuration (when zone and wave picking are used) are fixed. The performance measures used to compare the different policies include: the mean daily labor, the mean length of day, and the mean percentage of late orders. For each order picking policy, the simplest rules regarding batching, routing, and wave length are used. It also should be noted that the performance measures are mainly related to order picking efficiencies and service quality; additional costs caused by downstream sorting with batch, zone, and wave picking are not considered. Furthermore, comparison of these policies are made mainly with regards to the order structures, while other important factors such as storage assignment and detailed implementations of the order picking policies are assumed to be fixed. Therefore, the results should not be considered generic and more research in this direction is required to provide more guidance for warehouse designers.

Order picking strategy selection remains a largely unresolved design problem. Additional research would be valuable, especially if it could begin to characterize order picking alternatives in ways that were easy to apply in design decision making. As an example, could researchers develop performance curves for different order picking strategies?

3. Performance evaluation

Performance evaluation provides feedback on the quality of a proposed design and/or operational policy, and more importantly, on how to improve it. There are different approaches for performance evaluation: benchmarking, analytic models, and simulations. This section will only discuss benchmarking and analytic models.

3.1. Benchmarking

Warehouse benchmarking is the process of systematically assessing the performance of a warehouse, identifying inefficiencies, and proposing improvements. Data Envelopment Analysis (DEA) is regarded as an appropriate tool for this task because of its capability to capture simultaneously all the relevant inputs (resources) and outputs (performances), to construct the best performance frontier, and to reveals the relative shortcomings of inefficient warehouses. Schefczyk (1993), Hackman et al. (2001), and Ross and Droge (2002) shows some approaches and case studies of using DEA in warehouse benchmarking. An Internet-based DEA system (iDEAS) for warehouses is developed by the Keck Lab at Georgia Tech, which includes information on more than 200 warehouses (McGinnis, 2003).

3.2. Analytical models

Analytic performance models fall into two main categories: (1) aisle based models which focus on a single storage system and address travel or service time; and (2) integrated models which address either multiple storage systems or criteria in addition to travel/service times.

3.2.1. Aisle based models

Table 2 summarizes research on travel time models for aisle-based systems. A significant fraction of research focuses on the expected travel time for the crane in an AS/RS, for either single command (SC) or dual command (DC) cycles. For both, there is research addressing three different storage policies: in randomized storage, any SKU can occupy any location; in dedicated storage, each SKU has a set of designated locations; and in class based storage, a group of storage locations is allocated to a class of SKUs, and randomized storage is allowed within the group of storage locations. The issue with DC cycles is matching up storages and retrievals to minimize the dead-head travel of the crane, which may involve sequencing retrievals, and selecting storage locations. The results in this category usually assume infinite acceleration to simplify the travel time models, although some develop more elaborate models by considering acceleration for the various axes of motion (see, e.g., Hwang and Lee, 1990; Hwang et al., 2004b; Chang and Wen, 1997; Chang et al., 1995). There are a few papers that attack the more mathematically challenging issue of deriving the distribution of travel time (see Foley and Frazelle (1991) and Foley et al. (2002)). The research on carousel travel time models generally parallels corresponding AS/RS research.

Given some knowledge of travel time, AS/RS service time models can be developed, considering the times required for load/unload and store/retrieve at the storage slot. Queuing models have been developed assuming various distributions for travel time, see e.g., Lee (1997), Chow (1986), Hur et al. (2004), Bozer and White (1984), Park et al. (2003a) for AS/RS, Chang et al. (1995) for conventional multi-aisle systems, and for end-of-aisle picking systems, see Bozer and White (1991, 1996), Park et al. (2003a), and Park et al. (1999). Stochastic optimization models have been developed for estimating AS/RS throughput, with constraints on storage queue length and retrieval request waiting time (Azadivar, 1986).

The throughput of carousel systems is modeled by Park et al. (2003b) and Meller and Klote (2004). The former consider a system with two carousels and one picker, and derive analytic expressions for the system throughput and picker utilization assuming deterministic and exponential pick time distributions. Meller and Klote (2004) develop throughput models for systems with multiple carousels using an approximate two-server queuing model approach.

For conventional multi-aisle storage systems (bin shelving, e.g.), two kinds of travel time results have been developed: (1) models which estimate the expected travel time; and (2) models of the pdf of travel times. These models require an assumption about the structure of the tour, e.g., traversal (Hall, 1993), return (Hall, 1993 or Caron et al., 1998), or largest gap (Roodbergen and Vis, 2006). As long as these models are parameterized on attributes of the storage system design, they can be used to support design by searching over the relevant parameters.

As with AS/RS and carousels, there has been research to incorporate travel time models into performance models. Chew and

Table 2
Literature of travel time models for different warehouse systems.

		Randomized storage	Dedicated storage	Class-based storage
Unit-load AS/RS	Single-command	Hausman et al. (1976) Bozer and White (1984) Thonemann and Brandeau (1998) Kim and Seidmann (1990) Hwang and Ko (1988) Lee (1997) Hwang and Lee (1990) Chang et al. (1995) Chang and Wen (1997) Koh et al. (2002) Lee et al. (1999)	Hausman et al. (1976) Thonemann and Brandeau (1998) Kim and Seidmann (1990)	Hausman et al. (1976) Thonemann and Brandeau (1998) Rosenblatt and Eynan (1989) Eynan and Rosenblatt (1994) Kouvelis and Papanicolaou (1995) Kim and Seidmann (1990) Pan and Wang (1996) Ashayeri et al. (2002)
	Dual-command	Graves et al. (1977) Bozer and White (1984) Kim and Seidmann (1990) Hwang and Ko (1988) Lee (1997) Han et al. (1987) Hwang and Lee (1990) Chang et al. (1995) Chang and Wen (1997) Koh et al. (2002) Lee et al. (1999)	Graves et al. (1977) Kim and Seidmann (1990)	Graves et al. (1977) Kouvelis and Papanicolaou (1995) Kim and Seidmann (1990) Pan and Wang (1996) Ashayeri et al. (2002)
	Multi-shuttle	Meller and Mungwattana (1997) Potrc et al. (2004)		
Man-on-board AS/RS		Hwang and Song (1993)		
End-of-aisle AS/RS		Bozer and White (1990) Bozer and White (1996) Foley and Frazelle (1991) Park et al. (1999)	Park et al. (2003a)	
Carousel and rotary racks		Han and McGinnis (1986) Han et al. (1988) Su (1998) Hwang and Ha (1991) Hwang et al. (1999)		Ha and Hwang (1994)
Conventional multi-aisle system		Hall (1993) Jarvis and McDowell (1991) Chew and Tang (1999) Hwang et al. (2004a)	Caron et al. (1998) Caron et al. (2000) Jarvis and McDowell (1991) Chew and Tang (1999) Hwang et al. (2004a)	Jarvis and McDowell (1991) Chew and Tang (1999) Hwang et al. (2004a)

Tang (1999) use their model of the travel time pdf to analyze order batching and storage allocation using a queuing model. Bhaskaran and Malmborg (1989) present a stochastic performance evaluation model for the service process in multi-aisle warehouses with an approximated distribution for the service time that depends on the batch size and the travel distance. de Koster (1994) develops queuing models to evaluate the performance of a warehouse that uses sequential zone picking where each bin is assigned to one or more orders and is transported using a conveyer. If a bin needs to be picked in a specific zone, it is transported to the corresponding pick station. After it is picked, it is then put on the conveyor to be sent to the next pick station. The proposed queuing network model evaluates performance measures such as system throughput, picker utilization, and the average number of bins in the system based on factors such as the speed and length of the conveyor, the number of picking stations, and the number of picks per station.

Throughput analysis of sorting systems is addressed in Johnson and Meller (2002). They assume that the induction process is the bottleneck of the sorting process, and therefore governs the throughput of the sorting system. This model is later incorporated into a more comprehensive model in Russell and Meller (2003) that integrates order picking and sorting to balance the tradeoffs between picking and packing with different order batch sizes and wave lengths. Russell and Meller (2003) also demonstrate the use of the proposed model in determining whether or not to automate the sorting process and in designing the sorting system.

3.2.2. Integrated models

Integrated models combine travel time analysis and the service quality criteria with other performance measures, e.g., storage capacity, construction cost, and operational cost. Malmborg (1996) proposes an integrated performance evaluation model for a warehouse having a forward-reserve configuration. The proposed model uses information about inventory management, forward-reserve space allocation, and storage layout to evaluate costs associated with: storage capacity and space shortage; inventory carrying, replenishing, and expediting; and order picking and internal replenishment for the forward area. Malmborg (2000) evaluates several performance measures for a twin-shuttle AS/RS. Malmborg and Al-Tassan (2000) present a mathematical model to estimated space requirements and order picking cycle times for less than unit load order picking systems that uses randomized storage. The inputs of the model include product parameters, equipment specifications, operational policies, and storage area configurations. Malmborg (2003) models the dependency of performance measures such as expected total system construction cost and throughput on factors such as the vehicle fleet size, the number of lifts, and the storage rack configurations for warehouse systems that use rail guided vehicles.

Analytic travel time and performance models of storage systems represent a major contribution to warehouse design related research, and a rich set of models is available. Yet despite this wealth of prior results, there is no unified approach to travel time modeling or performance modeling for aisle based systems – every system and every set of assumptions leads to a different model. A significant research contribution would be to present a unified theory of travel time in aisle-based systems.

4. Case studies

There are some published industrial case studies, which not only provide applications of the various design and operation methods in practical contexts, but more importantly, also identify possible future research challenges from the industrial point of view. Table 3 lists these case studies, identifying the problems and the types of warehouse they investigated. It is difficult to generalize from such a small set of specific cases, but one conclusion is that substantial benefits can achieved by appropriately designing and operating a warehouse, see for example Zeng et al. (2002), van Oudheusden et al. (1988), and Dekker et al. (2004). On the other hand, one might conclude from these cases that there are few generic simple rules. As just one example, the COI-based storage location assignment rule proposed by Kallina and Lynn (1976) ignores many practical considerations, such as varying weights, item-dependent travel costs, or dependencies between items. Some of these complications have been addressed in the academic research (for example see Table 3 in Section 5.2 of Gu et al. (2007)), but many others remain unexplored. What these cases illustrate is the gap between the assumption-restricted models in research publications and the complex reality of most warehouses. There is a significant need for more industrial case studies, which will assist the warehouse research community in better understanding the real issues in warehouse design. In turn, research results that have been tested on more realistic data sets will have a more substantial impact on practice. A warehouse design problem classification, such as we have proposed here, might be used to structure such future case studies.

5. Computational systems

There are numerous commercial Warehouse Management Systems (WMS) available in the market, which basically help the warehouse manager to keep track of the products, orders, space, equipment, and human resources in a warehouse, and provide rules/algorithms for storage location assignment, order batching, pick routing, etc. Detailed review of these systems is beyond the scope of this paper. Instead, we focus on the academic research addressing computational systems for warehouse design. As previous sections show, research on various warehouse design and

Table 3
A Summary of the literature on warehouse case studies.

Citation	Problems studied	Type of warehouse
Cormier and Kersey (1995)	Conceptual design	A warehouse for perishable goods that requires Just-In-Time operations
Yoon and Sharp (1995)	Conceptual design	An order picking system
Zeng et al. (2002)	Storage location assignment; warehouse dimensioning; storage and order picking policies	A distribution center
Kallina and Lynn (1976)	Storage location assignment using the COI rule	A distribution center
Brynzer and Johansson (1995)	Process flow; batching; zone picking;	Kitting systems that supply materials to assembly lines
Burkard et al. (1995)	Vehicle routing	An AS/RS where a S/R machine can serve any aisle using a switching gangway
van Oudheusden et al. (1988)	Storage location assignment; batching; routing	A man-on-board AS/RS in an integrated steel mill
Dekker et al. (2004)	Storage and routing policies	A multi-aisle manual order picking system
Luxhoj and Skarpness (1986)	Manpower planning	A distribution center
Johnson and Lofgren (1994)	Simulation by decomposition	A distribution center

operation problems has been conducted for almost half a century, and as a result, a large number of methodologies, algorithms, and empirical studies have been generated. However, successful implementations of these academic results in current commercial WMS systems or in engineering design software are rare. The prototype systems discussed in this section might shed some light on how academic research results could be utilized to develop more sophisticated computer aided warehouse design and operation systems.

Perlmann and Bailey (1988) present computer-aided design software that allows a warehouse designer to quickly generate a set of conceptual design alternatives including building shape, equipment selection, and operational policy selection, and to select from among them the best one based on the specified design requirements. To our knowledge, this is the only research paper addressing computer aided warehouse design.

There are several papers on the design of warehouse control systems. Linn and Wysk (1990) develop an expert system for AS/RS control. A control policy determines decisions such as storage location assignment, which item to retrieve if multi-items for the same product are stored, storage and retrieval sequencing, and storage relocation. Several control rules are available for each decision and the control policy is constructed by selecting one individual rule for each decision in a coherent way based on dynamically changing system state variables such as demand levels and traffic intensity. A similar AS/RS control system is proposed by Wang and Yih (1997) based on neural networks.

Ito et al. (2002) propose an intelligent agent based system to model a warehouse, which is composed of three subsystems, i.e., agent-based communication system, agent-based material handling system, and agent-based inventory planning and control system. The proposed agent-based system is used for the design and implementation of warehouse simulation models. Kim et al. (2002) present an agent based system for the control of a warehouse for cosmetic products. In addition to providing the communication function, the agents also make decisions regarding the operation of the warehouse entities they represented in a dynamic real-time fashion.

The absence of research prototypes for computer aided warehouse design is particularly puzzling, given the rapid advancement in computing hardware and software over the past decade. Academic researchers have been at the forefront of computer aided design in other disciplines, and particularly in developing computational models to support design decision making. Warehousing design, as a research domain, would appear to be ripe for this kind of contribution.

6. Conclusions and discussion

We have attempted a thorough examination of the published research related to warehouse design, and classified papers based on the main issues addressed. Fig. 1 shows the numbers of papers in each category; there were 50 papers directly addressing warehouse design decisions. There were an additional 50 papers on various analytic models of travel time or performance for specific storage systems or aggregates of storage systems. Benchmarking, case studies and other surveys account for 18 more papers.

One clear conclusion is that warehouse design related research has focused on analysis, primarily of storage systems rather than synthesis. While this is somewhat surprising, an even more surprising observation is that only 10% of papers directly addressing warehouse design decisions have a publication date of 2000 or later. Given the rapid development of computing hardware and solvers for optimization, simulation, and general mathematical problems, one might reasonably expect a more robust design-centric research literature.

We conjecture two primary inhibiting factors:

1. The warehouse design decisions identified in Fig. 1 are tightly coupled, and one cannot be analyzed or determined in isolation from the others. Yet, the models available are not unified in any way and are not "interoperable". A researcher addressing one decision would require a research infrastructure integrating all the other decisions. The scope and scale of this infrastructure appears too great a challenge for individual researchers.
2. To properly evaluate the impact of changing one of the design decisions requires estimating changes in the operation of the warehouse. Not only are future operating scenarios not specified in detail, even if they were, the total warehouse performance assessment models, such as high fidelity simulations, are themselves a considerable development challenge.

From this, we conclude that the most important future direction for the warehouse design research community is to find ways to overcome these two hurdles. Key to that, we believe, will be the emergence of standard representations of warehouse elements, and perhaps some research community based tools, such as open-source analysis and design models.

Other avenues for important contributions include studies describing validated or applied design models, and practical case studies that demonstrate the potential benefits of applying academic research results to real problems, or in identifying the hidden challenges that prevent their successful implementation.

Finally, both analytic and simulation models are proposed to solve warehouse problems and each has its respective advantages and disadvantages. Analytic models are usually design-oriented in the sense that they can explore many alternatives quickly to find solutions, although they may not capture all the relevant details of the system. On the other hand, simulation models are usually analysis-oriented – they provide an assessment of a given design, but usually have limited capability for exploring the design space. There is an important need to integrate both approaches to achieve more flexibility in analyzing warehouse problems. This is also pointed out by Ashayeri and Gelders (1985), and its applicability has been demonstrated by Rosenblatt and Roll (1984) and Rosenblatt et al. (1993).

There is an enormous gap between the published warehouse research and the practice of warehouse design and operations. Cross fertilization between the groups of practitioners and researchers appears to be very limited. Effectively bridging this gap would improve the state-of-the-art in warehouse design methodology. Until such communication is established, the prospect of meaningful expansion and enhancement of warehouse design methodology appears limited.

Warehousing is an essential component in any supply chain. In the USA, the value of wholesale trade inventories is approximately half a trillion dollars (BEA, 2008), and 2004 inventory carrying costs (interest, taxes, depreciation, insurance, obsolescence and warehousing) have been estimated at 332 billion dollars (Trunick, 2005). To date the research effort focusing on warehousing is a very small fraction of the overall supply chain research. There are many challenging research questions and problems that have not received any attention. The challenge for the academic research community is to focus on the integrated design and operation of warehouses, while the challenge for industrial practitioners is to provide realistic test cases.

References

Ashayeri, J., Gelders, L.F., 1985. Warehouse design optimization. European Journal of Operational Research 21, 285–294.

Ashayeri, J., Gelders, L., Wassenhove, L.V., 1985. A microcomputer-based optimization model for the design of automated warehouses. International Journal of Production Research 23 (4), 825–839.

Ashayeri, J., Heuts, R.M., Valkenburg, M.W.T., Veraart, H.C., Wilhelm, M.R., 2002. A geometrical approach to computing expected cycle times for zone-based storage layouts in AS/RS. International Journal of Production Research 40 (17), 4467–4483.

Azadivar, F., 1986. Maximizing of the throughput of a computerized automated warehousing system under system constraints. International Journal of Production Research 24 (3), 551–566.

Azadivar, F., 1989. Optimum allocation of resources between the random access and rack storage spaces in an automated warehousing system. International Journal of Production Research 27 (1), 119–131.

Bartholdi, J.J., Eisenstein, D.D., Foley, R.D., 2000. Performance of bucket brigades when work is stochastic. Operations Research 49 (5), 710–719.

Bassan, Y., Roll, Y., Rosenblatt, M.J., 1980. Internal layout design of a warehouse. AIIE Transactions 12 (4), 317–322.

BEA, 2008. Table 5.7.5B. Private Inventories and Domestic Final Sales by Industry accessed at >http://bea.gov/national/nipaweb/TableView.asp?SelectedTable=153&FirstYear=2005&LastYear=2007&Freq=Qtr>.

Berry, J.R., 1968. Elements of warehouse layout. International Journal of Production Research 7 (2), 105–121.

Bhaskaran, K., Malmborg, C.J., 1989. Modelling the service process in a multi-address warehousing system. Applied Mathematical Modelling 13 (7), 386–396.

Bozer, Y.A., White, J.A., 1984. Travel-time models for automated storage/retrieval systems. IIE Transactions 16 (4), 329–338.

Bozer, Y.A., White, J.A., 1990. Design and performance models for end-of-aisle order picking systems. Management Science 36 (7), 852–866.

Bozer, Y.A., White, J.A., 1996. A generalized design and performance analysis models for end-of-aisle order-picking systems. IIE Transactions 28, 271–280.

Brynzer, H., Johansson, M.I., 1995. Design and performance of kitting and order picking systems. International Journal of Production Economics 41, 115–125.

Burkard, R.E., Fruhwirth, B., Rote, G., 1995. Vehicle routing in an automated warehouse: Analysis and optimization. Annals of Operations Research 57, 29–44.

Caron, F., Marchet, G., Perego, A., 1998. Routing policies and COI-based storage policies in picker-to-part systems. International Journal of Production Research 36 (3), 713–732.

Caron, F., Marchet, G., Perego, A., 2000. Optimal layout in low-level picker-to-part systems. International Journal of Production Research 38 (1), 101–117.

Chang, D.-T., Wen, U.-P., 1997. The impact of rack configuration on the speed profile of the storage and retrieval machine. IIE Transactions 29, 525–531.

Chang, D.-T., Wen, U.-P., Lin, J.T., 1995. The impact of acceleration/deceleration on travel-time models for automated storage/retrieval systems. IIE Transactions 27, 108–111.

Chew, E.P., Tang, L.C., 1999. Travel time analysis for general item location assignment in a rectangular warehouse. European Journal of Operational Research 112, 582–597.

Chow, W.-M., 1986. An analysis of automated storage and retrieval systems in manufacturing assembly lines. IIE Transactions 18 (2), 204–214.

Cormier, G., 2005. Operational research methods for efficient warehousing. In: Langevin, A., Riopel, D. (Eds.), Logistics Systems: Design and Optimization. Springer, Berlin, pp. 93–122.

Cormier, G., Gunn, E.A., 1992. A review of warehouse models. European Journal of Operational Research 58, 3–13.

Cormier, G., Gunn, E.A., 1996. On coordinating warehouse sizing, leasing and inventory policy. IIE Transactions 28, 149–154.

Cormier, G., Gunn, E.A., 1999. Modelling and analysis for capacity expansion planning in warehousing. Journal of the Operational Research Society 50 (1), 52–59.

Cormier, G., Kersey, D.F., 1995. Conceptual design of a warehouse for just-in-time operations in a bakery. Computers and Industrial Engineering 29 (1-4), 361–365.

Cox, B., 1986. Determining economic levels of automation by using a hierarchy of productivity ratios techniques, in: Proceedings of 7th International Conference on Automation in Warehousing.

Daskin, M.S., Snyder, L.V., Berger, R.T., 2005. Facility location in supply chain design. In: Langevin, A., Riopel, D. (Eds.), Logistics Systems: Design and Optimization. Springer Science, Business Media, Inc., New York, pp. 39–65.

Dekker, R., de Koster, M.B.M., Roodbergen, K.J., van Kalleveen, H., 2004. Improving order-picking response time at Ankor's warehouse. Interfaces 34 (4), 303–313.

de Koster, R., 1994. Performance approximation of pick-to-belt orderpicking systems. European Journal of Operational Research 72 (3), 558–573.

Eynan, A., Rosenblatt, M.J., 1994. Establishing zones in single-command class-based rectangular AS/RS. IIE Transactions 26 (1), 38–46.

Foley, R., Frazelle, E.H., 1991. Analytical results for miniload throughput and the distribution of dual command travel time. IIE Transactions 23 (3), 273–281.

Foley, R., Frazelle, E.H., Park, B.C., 2002. Throughput bounds for miniload automated storage/retrieval systems. IIE Transactions 34 (10), 915–920.

Francis, R.L., 1967. On some problems of rectangular warehouse design and layout. The Journal of Industrial Engineering 18, 595–604.

Goetschalckx, M., Ratliff, H.D., 1990. Shared storage policies based on the duration stay of unit loads. Management Science 36 (9), 1120–1132.

Goetschalckx, M., Ratliff, H.D., 1991. Optimal lane depths for single and multiple products in block stacking storage systems. IIE Transactions 23 (3), 245–258.

Goh, M., Ou, J., Teo, C.-P., 2001. Warehouse sizing to minimize inventory and storage costs. Naval Research Logistics 48 (4), 299–312.

Graves, S.C., Hausman, W.H., Schwarz, L.B., 1977. Storage-retrieval interleaving in automatic warehousing systems. Management Science 23 (9), 935–945.

Gray, A.E., Karmarkar, U.S., Seidmann, A., 1992. Design and operation of an order-consolidation warehouse: models and applications. European Journal of Operational Research 58, 14–36.

Gu, J.X., Goetschalckx, M., McGinnis, L.F., 2007. Research on warehouse operation: A comprehensive review. European Journal of Operational Research 177 (1), 1–21.

Ha, J.-W., Hwang, H., 1994. Class-based storage assignment policy in carousel system. Computers and Industrial Engineering 26 (3), 489–499.

Hackman, S.T., Frazelle, E.H., Griffin, P.M., Griffin, S.O., Vlasta, D.A., 2001. Benchmarking warehouse and distribution operations: An input–output approach. Journal of Productivity Analysis 16, 79–100.

Hall, R.W., 1993. Distance approximation for routing manual pickers in a warehouse. IIE Transactions 25 (4), 76–87.

Han, M.H., McGinnis, L.F., 1986. Carousel Application for Work-in-process: Modelling and Analysis. Material Handling Research Center, Georgia Institute of Technology, Atlanta, Georgia.

Han, M.H., McGinnis, L.F., Shieh, J.S., White, J.A., 1987. On sequencing retrievals in an automated storage/retrieval system. IIE Transactions 19 (1), 56–66.

Han, M.H., McGinnis, L.F., White, J.A., 1988. Analysis of rotary rack operation. Material Flow 4, 283–293.

Hausman, W.H., Schwarz, L.B., Graves, S.C., 1976. Optimal storage assignment in automatic warehousing systems. Management Science 22 (6), 629–638.

Heragu, S.S., Du, L., Mantel, R.J., Schuur, P.C., 2005. Mathematical model for warehouse design and product allocation. International Journal of Production Research 43 (2), 327–338.

Hung, M.S., Fisk, C.J., 1984. Economic sizing of warehouses – A linear programming approach. Computers and Operations Research 11 (1), 13–18.

Hur, S., Lee, Y.H., Lim, S.Y., Lee, M.H., 2004. A performance estimating model for AS/RS by M/G/1 queuing system. Computers and Industrial Engineering 46, 233–241.

Hwang, H., Ha, J.-W., 1991. Cycle time models for single/double carousel system. International Journal of Production Economics 25, 129–140.

Hwang, H., Ko, C.S., 1988. A study on multi-aisle system served by a single storage/retrieval machine. International Journal of Production Research 26 (11), 1727–1737.

Hwang, H., Lee, S.B., 1990. Travel-time models considering the operating characteristics of the storage and retrieval machine. International Journal of Production Research 28 (10), 1779–1789.

Hwang, H., Song, J.Y., 1993. Sequencing picking operations and travel time models for man-on-board storage and retrieval warehousing system. International Journal of Production Economics 29, 75–88.

Hwang, H., Kim, C.-S., Ko, K.-H., 1999. Performance analysis of carousel systems with double shuttle. Computers and Industrial Engineering 36, 473–485.

Hwang, H., Oh, Y.H., Lee, Y.K., 2004a. An evaluation of routing policies for order-picking operations in low-level picker-to-part system. International Journal of Production Research 42 (18), 3873–3889.

Hwang, H., Song, Y.-K., Kim, K.-H., 2004b. The impacts of acceleration/deceleration on travel time models for carousel systems. Computers and Industrial Engineering 46, 253–265.

Ito, T., Abadi, J., Mousavi, S.M., 2002. Agent-based material handling and inventory planning in warehouse. Journal of Intelligent Manufacturing 13 (3), 201–210.

Jarvis, J.M., McDowell, E.D., 1991. Optimal product layout in an order picking warehouse. IIE Transactions 23 (1), 93–102.

Johnson, M.E., Lofgren, T., 1994. Model decomposition speeds distribution center design. Interfaces 24 (5), 95–106.

Johnson, M.E., Meller, R.D., 2002. Performance analysis of split-case sorting systems. Manufacturing & Service Operations Management 4 (4), 258–274.

Kallina, C., Lynn, J., 1976. Application of the cube-per-order index rule for stock location in a distribution warehouse. Interfaces 7 (1), 37–46.

Karasawa, Y., Nakayama, H., Dohi, S., 1980. Trade-off analysis for optimal design of automated warehouses. International Journal of Systems Science 11 (5), 567–576.

Kim, J., Seidmann, A., 1990. A framework for the exact evaluation of expected cycle times in automated storage systems with full-turnover item allocation and random service requests. Computers and Industrial Engineering 18 (4), 601–612.

Kim, B.-I., Graves, R.J., Heragu, S.S., Onge, A.S., 2002. Intelligent agent modeling of an industrial warehousing problem. IIE Transactions 34 (7), 601–612.

Koh, S.G., Kim, B.S., Kim, B.N., 2002. Travel time model for the warehousing system with a tower crane S/R machine. Computers and Industrial Engineering 43 (3), 495–507.

Kouvelis, P., Papanicolaou, V., 1995. Expected travel time and optimal boundary formulas for a two-class-based automated storage/retrieval system. International Journal of Production Research 33 (10), 2889–2905.

Kulturel, S., Ozdemirel, N.E., Sepil, C., Bozkurt, Z., 1999. Experimental investigation of shared storage assignment policies in automated storage/retrieval systems. IIE Transactions 31 (8), 739–749.

Larson, N., March, H., Kusiak, A., 1997. A heuristic approach to warehouse layout with class-based storage. IIE Transactions 29, 337–348.

Lee, H.S., 1997. Performance analysis for automated storage and retrieval systems. IIE Transactions 29, 15–28.

Lee, M.-K., Hwang, H., 1988. An approach in the design of a unit-load automated carousel storage system. Engineering Optimization 13, 197–210.

Lee, Y.H., Tanchoco, J.M.A., Chun, S.J., 1999. Performance estimation models for AS/RS with unequal sized cells. International Journal of Production Research 37 (18), 4197–4216.
Levy, J., 1974. The optimal size of a storage facility. Naval Research Logistics Quarterly 21 (2), 319–326.
Lin, C.-H., Lu, I.-Y., 1999. The procedure of determining the order picking strategies in distribution center. International Journal of Production Economics, 301–307.
Linn, R.J., Wysk, R.A., 1990. An expert system framework for automated storage and retrieval system control. Computers and Industrial Engineering 18 (1), 37–48.
Lowe, T.J., Francis, R.L., Reinhardt, E.W., 1979. A greedy network flow algorithm for a warehouse leasing problem. AIIE Transactions 11 (3), 170–182.
Luxhoj, J.T., Skarpness, B.O., 1986. A manpower planning model for a distribution center: A case study. Material Flow 3, 251–261.
Malmborg, C.J., 1996. An integrated storage system evaluation model. Applied Mathematical Modelling 20 (5), 359–370.
Malmborg, C.J., 2000. Interleaving models for the analysis of twin shuttle automated storage and retrieval systems. International Journal of Production Research 38 (18), 4599–4610.
Malmborg, C.J., 2001. Rule of thumb heuristics for configuring storage racks in automated storage and retrieval systems design. International Journal of Production Research 39 (3), 511–527.
Malmborg, C.J., 2003. Design optimization models for storage and retrieval systems using rail-guided vehicles. Applied Mathematical Modelling 27 (12), 929–941.
Malmborg, C.J., Al-Tassan, K., 1998. Analysis of storage assignment policies in less than unit load warehousing systems. International Journal of Production Research 36 (12), 3459–3475.
Malmborg, C.J., Al-Tassan, K., 2000. An integrated performance model for order picking systems with randomized storage. Applied Mathematical Modelling 24 (2), 95–111.
Marsh, W.H., 1979. Elements of block storage design. International Journal of Production Research 17 (4), 377–394.
Marsh, W.H., 1983. A comparison with Berry. International Journal of Production Research 21 (2), 163–172.
Matson, J.O., White, J.A., 1981. Storage System Optimization. Production and Distribution Research Center. Georgia Institute of Technology, Atlanta, Georgia.
McGinnis, L.F., 2003. Best of breed warehouse performance assessment. In: Council on Logistics Management Annual Conference. Chicago, IL. <http://www.isye.gatech.edu/ideas/>.
Meller, R.D., Gau, K.Y., 1996. Journal of Manufacturing Systems 15 (5), 351.
Meller, R.D., Klote, J.F., 2004. A throughput model for carousel/VLM pods. IIE Transactions 36 (8), 725–741.
Meller, R.D., Mungwattana, A., 1997. Multi-shuttle automated storage/retrieval systems. IIE Transactions 29 (10), 925–938.
Moder, J.J., Thornton, H.M., 1965. Quantitative analysis of the factors affecting floor space utilization of palletized storage. The Journal of Industrial Engineering 16 (1), 8–18.
Pan, C.-H., Wang, C.-H., 1996. A framework for the dual command cycle travel time model in automated warehousing systems. International Journal of Production Research 34 (8), 2099–2117.
Pandit, R., Palekar, U.S., 1993. Response time considerations for optimal warehouse layout design. Journal of Engineering for Industry 115, 322–328.
Park, Y.H., Webster, D.B., 1989. Modelling of three-dimensional warehouse systems. International Journal of Production Research 27 (6), 985–1003.
Park, B.C., Frazelle, E.H., White, J.A., 1999. Buffer sizing models for end-of-aisle order picking systems. IIE Transactions 31, 31–38.
Park, B.C., Foley, R.D., White, J.A., Frazelle, E.H., 2003a. Dual command travel times and miniload system throughput with turnover-based storage. IIE Transactions 35 (4), 343–355.
Park, B.C., Park, J.Y., Foley, R.D., 2003b. Carousel system performance. Journal of Applied Probability 40, 602–612.
Perlmann, A.M., Bailey, M., 1988. Warehouse logistics systems – A CAD model. Engineering Costs and Production Economics 13, 229–237.
Petersen, C.G., 2000. An evaluation of order picking policies for mail order companies. Production and Operations Management 9 (4), 319–335.
Pliskin, J.S., Dori, D., 1982. Ranking alternative warehouse area assignments: A multiattribute approach. IIE Transactions 14 (1), 19–26.
Potrc, I., Lerher, T., Kramberger, J., Sraml, M., 2004. Simulation model of multi-shuttle automated storage and retrieval systems. Journal of Materials Processing Technology, 236–244.
Randhawa, S.U., Shroff, R., 1995. Simulation-based design evaluation of unit load automated storage/retrieval systems. Computers and Industrial Engineering 28 (1), 71–79.
Randhawa, S.U., McDowell, E.D., Wang, W.-T., 1991. Evaluation of scheduling rules for single- and dual-dock automated storage/retrieval system. Computers and Industrial Engineering 20 (4), 401–410.
Rao, A.K., Rao, M.R., 1998. Solution procedures for sizing of warehouses. European Journal of Operational Research 108, 16–25.
Roberts, S.D., Reed, R., 1972. Optimal warehouse bay configurations. AIIE Transactions 4 (3), 178–185.
Roll, Y., Rosenblatt, M.J., Kadosh, D., 1989. Determining the size of a warehouse container. International Journal of Production Research 27 (10), 1693–1704.
Roodbergen, K.J., Vis, I.F.A., 2006. A model for warehouse layout. IIE Transactions 38 (10), 799–811.
Rosenblatt, M.J., Eynan, A., 1989. Deriving the optimal boundaries for class-based automatic storage/retrieval systems. Management Science 35 (12), 1519–1524.
Roll, Y., Rosenblatt, M.J., 1983. Random versus grouped storage policies and their effect on warehouse capacity. Material Flow 1, 199–205.
Rosenblatt, M.J., Roll, Y., 1984. Warehouse design with storage policy considerations. International Journal of Production Research 22 (5), 809–821.
Rosenblatt, M.J., Roll, Y., 1988. Warehouse capacity in a stochastic environment. International Journal of Production Research 26 (12), 1847–1851.
Rosenblatt, M.J., Roll, Y., Zyser, V., 1993. A combined optimization and simulation approach for designing automated storage/retrieval systems. IIE Transactions 25 (1), 40–50.
Ross, A., Droge, C., 2002. An integrated benchmarking approach to distribution center performance using DEA modeling. Journal of Operations Management 20, 19–32.
Rowenhorst, B., Reuter, B., Stockrahm, V., van Houtum, G.J., Mantel, R.J., Zijm, W.H.M., 2000. Warehouse design and control: Framework and literature review. European Journal of Operational Research 122, 515–533.
Russell, M.L., Meller, R.D., 2003. Cost and throughput modeling of manual and automated order fulfillment systems. IIE Transactions 35, 589–603.
Schefczyk, M., 1993. Industrial benchmarking: A case study of performance analysis techniques. International Journal of Production Economics 32, 1–11.
Schwarz, L.B., Graves, S.C., Hausman, W.H., 1978. Scheduling policies for automatic warehousing systems: Simulation results. AIIE Transactions 10 (3), 260–270.
Sharp, G.P., Vlasta, D.A., Houmas, C.G., 1994. Economics of storage/retrieval systems for item picking. Material Handling Research Center, Georgia Institute of Technology, Atlanta, Georgia.
Su, C.-T., 1998. Performance evaluation of carousel operation. Production Planning and Control 9 (5), 477–488.
Thonemann, U.W., Brandeau, M.L., 1998. Optimal storage assignment policies for automated storage and retrieval systems with stochastic demands. Management Science 44 (1), 142–148.
Trunick, P.A., 2005. Can we hold the line on logistics costs? Logistics Today. <http://www.logisticstoday.com/displayStory.asp?sNO=7359>.
van den Berg, J.P., 1999. A literature survey on planning and control of warehousing systems. IIE Transactions 31, 751–762.
van Oudheusden, D.L., Tzen, Y.-J., Ko, H.-T., 1988. Improving storage and order picking in a person-on-board AS/R system: A case study. Engineering Costs and Production Economics 13, 273–283.
Wang, J.-Y., Yih, Y., 1997. Using neural networks to select a control strategy for automated storage and retrieval systems (AS/RS). International Journal of Computer Integrated Manufacturing 10 (6), 487–495.
White, J.A., Francis, R.L., 1971. Normative models for some warehouse sizing problems. AIIE Transactions 9 (3), 185–190.
White, J.A., DeMars, N.A., Matson, J.O., 1981. Optimizing storage system selection, in: Proceedings of the 4th International Conference on Automation in Warehousing, Tokyo, Japan.
Yoon, C.S., Sharp, G.P., 1995. Example application of the cognitive design procedure for an order pick system: Case study. European Journal of Operational Research 87, 223–246.
Yoon, C.S., Sharp, G.P., 1996. A structured procedure for analysis and design of order pick systems. IIE Transactions 28, 379–389.
Zeng, A.Z., Mahan, M., Fluet, N., 2002. Designing an efficient warehouse layout to facilitate the order-filling process: An industrial distributor's experience. Production and Inventory Management Journal 43 (3-4), 83–88.
Zollinger, H.A., 1996. Expanded methodology to concept horizontal transportation problem solutions. In: Graves, R.J., McGinnis, L.F., Medeiros, D.J., Ward, R.E., Wilhelm, M.R. (Eds.), Progress in Material Handling Research, pp. 651–663.