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Warehouse Design and Control: Framework and Literature Review

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Abstract

In this paper we present a reference framework and a classification of warehouse design and control problems. Based on this framework, we review the existing literature on warehousing systems and indicate important gaps. In particular, we emphasize the need for design oriented studies, as opposed to the strong analysis oriented research on isolated subproblems that seems to be dominant in the current literature.

Keywords: Survey, warehouse, design, performance analysis.

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1. Introduction

The ever increasing trend towards more product variety and short response times has placed a tremendous emphasis on the ability to establish smooth and efficient logistic operations. These operations even play a vital role in determining a company's competitiveness, since logistic costs constitute an important part of the overall production costs. The efficiency and effectiveness in any distribution network in turn is largely determined by the operation of the nodes in such a network, i.e. the warehouses. Indeed, the innovations in warehouse technology are numerous during the last decade. With respect to warehouse management, topics like planning and control have deserved wide attention in both the popular and scientific literature, see e.g. van den Berg [11] and the references therein. In contrast, a sound theoretical basis for a warehouse design methodology still seems to be lacking.

The logistic costs that are made inside a warehouse are to a large extent already determined during the design phase. Typically, a design runs from a functional description, through a technical specification, to equipment selection and determination of a layout. In each stage, target performance criteria (costs, throughput, storage capacity, response times) have to be met. As such, warehouse design is a highly complex task, where in each stage trade-offs have to be made between often conflicting objectives. Another difficulty is the large number of feasible designs. Up to now, no overall accepted systematic procedure exists to design warehouses. Therefore, there is a clear need for research that can support such a systematic design approach.

This paper is meant to provide a framework for warehouse design and to review the literature while using this framework as a reference model. Within this paper, we restrict ourselves to topics concerning the internal warehouse structure and operations. Topics like economic justification of warehouses, the warehouse location problem and external logistics are not addressed. Also, human resource management and quality control are excluded.

In this paper we analyze problems that are encountered during the (re)design of a warehouse or a warehouse subsystem. Based on these analyses, we review the existing literature on warehouse design and control. We determine clusters of publications concerning specific problems as well as open areas for future research. An important drawback concerns the fact that the overwhelming majority of scientific papers address well-defined isolated problems and are typically of an analytical nature (performance analysis, evaluation of control policies, etc.). A design oriented approach on the other hand primarily aims at a synthesis of a large number of both technical systems and planning and control procedures. Since most problems encountered during warehouse design are unfortunately not well-defined and often can not be reduced to multiple isolated subproblems, design often requires a mixture of analytical skills and creativity. Anyhow, research aiming at an integration of various models and methods is badly needed in order to develop a methodology for systematic warehouse design.

The paper is organized as follows. In Section 2, we define three different axes along which warehouses may be viewed upon: processes, resources, and organization. In Section 3 we discuss performance criteria as well as the process of warehouse design on a strategic, tactical and operational level. Section 4 discusses the most important problems encountered on each of these three levels. Based on this framework, we review in Section 5 the existing literature on warehouse design and control. In addition, we point out important areas that have received relatively little attention so far and emphasize the need for more design oriented research (Section 6). Finally, in Section 7, we conclude the paper.

2. Warehouse Characterizations

In order to provide a characterization, this section discusses three different angles from which a warehouse may be viewed: processes, resources, and organization. Products arriving at a warehouse subsequently are taken through a number of steps called *processes*. *Resources* refer to all means, equipment and personnel needed to operate a warehouse. Finally, *organization* includes all planning and control procedures used to run the system.

Some definitions are needed for clarity. A *product* is defined as a type of good, for example shampoo bottles of a specific brand. The individual bottles are called *items* (or Stock Keeping Units, SKU's) and the combination of several items of several products that are requested by a customer is called a customer *order*.

2.1. Warehouse Processes

The flow of items through the warehouse can be divided in several distinct phases, or *processes*.

- The *receiving* process is the first process encountered by an arriving item. Products arrive by truck or internal transport (in case of a production warehouse). At this step, the products may be checked or transformed (e.g., repacked into different storage modules) and wait for transportation to the next process.

- In the *storage* process items are placed in storage locations. The storage area may consist of two parts: the *reserve area*, where products are stored in the most economical way (bulk storage area) and the *forward area* where products are stored for easy retrieval by an orderpicker. Products in the forward area are often stored in smaller amounts in easily to access storage modules. For example, the reserve storage may consist of pallet racks while the forward storage may consist of shelves. The transfer of items from the reserve storage to the forward storage is called a *replenishment*.

- *Orderpicking* refers to the retrieval of items from their storage locations and can be performed manually or (partly) automated. In succession, these items may be transported to the *sorting-* and/or *consolidation* process. Consolidation here refers to the grouping of items destined for the same customer.

- At the *shipping* area, orders are checked, packed and eventually loaded in trucks, trains or any other carrier.

2.2. Warehouse Resources

A number of resources can be distinguished (see also Frazelle [41] for an extensive review):

- The *storage unit*, in (or on) which products may be stored. Examples of storage units are pallets, carton boxes and plastic boxes.

- The *storage system*. This may consist of multiple subsystems that store different types of products. Storage systems are very diverse; they may range from simple shelves up to highly automated systems, containing automated cranes and conveyors.

- The retrieval of items from the storage system can be performed manually or by means of *pick equipment*. An example of often used pick equipment is a reach truck.

- Other equipment that supports the orderpicker are called *orderpick auxiliaries*, for example bar code scanners.

- A *computer system* may be present to enable computer control of the processes by a warehouse management system.

- The material handling equipment for preparation of the retrieved items for the expedition includes *sorter systems, palletizers* and *truck loaders.*

- Finally, *personnel* constitutes an important resource, since warehouse performance largely depends on their availability.

2.3. Warehouse Organization

In this subsection, we discuss organizational issues in a warehouse.

- The far most important decision concerns the definition of the *process flow* at the design stage. Examples include: the decision to use a *separate reserve area* since this implies that a replenishment process will be part of the warehouse operation, the retrieval of items in *batches* or the splitting of the pick area in *zones* which both require a sorting process and/or a consolidation process, or the use of separate storage and retrieval aisles.

Furthermore, some processes require specific organizational policies:

- At the receiving process, an *assignment policy* determines the allocation of trucks to docks.

- At the storage process, items are transported to the storage system and are allocated to storage locations. Several *storage policies* exist. A *dedicated storage policy* prescribes a particular location for each product to be stored, whereas a *random storage policy* leaves the decision to the operator. In between, a *class based storage policy* (ABC zoning) allocates zones to specific product groups, often based upon their turnover rate. Other storage policies include *correlated storage* or *family grouping*, aimed at storing products at nearby positions if they are often required simultaneously. If the storage system has a separate reserve area, a *storage policy* for the reserve area is also needed. Which articles in what quantity are stored in the forward area and how replenishments are timed, is decided by *forward/reserve* and *replenishment policies*, respectively. Note that the latter control problems highly depend on decisions made already at the design stage.

- At the orderpicking process, (parts of) orders are assigned to one or more orderpickers. Various control problems deserve attention here. First, the total pick area may be divided into picking zones, to be served by different orderpickers, through a *zoning policy*. Two alternative policies exist: *parallel* or *sequential zoning*. Second, orders are picked one by one (*single order picking*) or in batches (*batch picking*). If a batch picking policy is selected, this directly implies that the picked orders must be sorted. Again, two sorting policies exist: *pick and sort* (sequentially) and *sort while pick* (simultaneously). Third, a *routing policy* may define the sequence of retrievals and the route to visit the retrieval locations. Finally, a *dwell point policy* may prescribe the position of idle orderpick equipment.

- If a consolidation and sorting process is present, orders are allocated to output lanes by an *sorter lane assignment policy*.

- At the shipping process, orders and trucks are allocated to docks by a *dock assignment policy*.

- Finally, allocation of tasks to personnel and equipment are addressed by *operator and equipment assignment policies*.

3. Warehouse Design

From the preceding section it becomes clear that the design of a warehouse system concerns a large number of interrelated decisions. In this section we attempt to structure these decisions in a hierarchical framework. In addition, we discuss a number of performance criteria that serve to evaluate alternative designs.

3.1. Warehouse Design Methods

As mentioned already in Section 1, a design process typically runs through a number of consecutive phases: concept, data acquisition, functional specification, technical specification, selection of means and equipment, layout, and selection of planning and control policies. Alternatively, these decisions may be situated at a strategic, tactical or operational level. For instance, decisions concerning the process flow and the level of automation typically belong to the functional and partly technical specification and are of a strategic nature. Also the selection of basic storage systems is a strategic one, whereas the dimensioning of these systems and the determination of a layout are tactical decisions. Detailed control policies typically belong to the operational level. The conceptual and data acquisition phase as well as the implementation phase are beyond the scope of this paper and therefore excluded. Obviously, most decisions are interrelated but the hierarchical framework outlined above reflects the horizon of the decisions (long term, medium term, short term) while solutions chosen at a higher level provide the constraints for lower level design problems.

Starting with limited detail, a rough first design is outlined while at subsequent stages this design is refined. This is also known as the top-down approach, as opposed to the bottom-up approach. The ideal design method clusters related problems at the same design level and derives a solution by simultaneously optimizing the various subproblems in order to reach a global optimum. It is important to recognize the relations between subproblems, in order to avoid suboptimal solutions.

3.2. Warehouse Performance Criteria

In order to evaluate a particular warehouse design, clearly defined performance criteria are needed. Within the field of warehousing we distinguish the following criteria: investment and operational costs, volume and mix flexibility, throughput, storage capacity, response time, and order fulfillment quality (accuracy). In this section we will discuss some criteria in more detail and relate them to the various design levels and to different environments.

The relative importance of a particular criterion varies with the types of warehouses. Two types can be distinguished: the *distribution warehouse* and the *production warehouse.*

The function of a *distribution warehouse* is to store products and to fulfill external customer orders typically composed of a large number of *order lines* (where each order line specifies a quantity of one particular product). The number of different products in a distribution warehouse may be large, while the quantities per order line may be small, which often results in a complex and relatively costly orderpicking process. Therefore, distribution warehouses are often optimized for cost-efficient orderpicking. The prominent design criterion is the *maximum throughput*, to be reached at minimum *investment* and *operational costs*. These two cost parameters are often combined in a single cost performance criterion. The *NPV* (Net Present Value) represents the value of the investment at the present time. Costs and profits that are planned in the future are discounted.

The *ROI* (Return On Investment) is another cost performance criterion, defining the expected profit per year, divided by the investment costs. These criteria are taken into account primarily at the strategic and tactical decision levels. Often, the combination of a desired throughput and a required short response time rules out already a number of technical solutions and indicates the use of more automated systems. A typical example of a warehouse system, suitable for a distribution warehouse, is an A-frame, a highly automated but costly orderpicking system.

The function of a *production warehouse* is to store raw materials, work-in-process and finished products, associated with a manufacturing and/or assembly process. Raw materials and finished products may be stored for long periods. This occurs for example when the procurement batch of incoming parts is much larger than the production batch, or when the production batch exceeds the customer order quantity of finished products. Storage of goods for long periods must be cost-efficient and is usually done in large quantities in an inexpensive storage system, such as a palletrack. The prominent design criterion is the *storage capacity.* The main design objectives are low investment costs and operational costs. The storage of work-in-process has other requirements, since the demand is mostly unknown in advance and the retrieval from the warehouse must be fast, in order to avoid delay in the production. This may lead to a design constraint with respect to the time between an order request and its completion, the *response time.*

Performance criteria can be handled as either a design objective or a design constraint. When formulating a criterion as a constraint, we request that a pre-specified target value of the criterion has to be met. In addition to constraints, related to these target criterion values, a number of technical or physical or even safety constraints are formulated. An example of the latter is the maximum height of a storage system in order to fit in a specific building. Investment costs are often treated as a constraint. A severe limitation on the investment costs may lead to a conventional warehouse design.

Finally, other performance criteria may be difficult to quantify, such as environmental or ergonomic conditions. These conditions will not be discussed further in this paper.

4. Warehouse Design Problems

In Section 2, we provided three views on warehouse operations, and in Section 3 we defined warehouse design as a structured approach of decision making at a strategic, tactical and operational level, in an attempt to meet a number of well-defined performance criteria. At each level, multiple decisions are interrelated and therefore it is often necessary to cluster relevant problems that are to be solved simultaneously. We define a *warehouse design problem* to be such a coherent cluster of decisions and we define decisions to be coherent when a sequential optimization does not guarantee a globally optimal solution.

This section discusses problems arising at the various design levels. For each level, the problems are placed in perspective using the three axes defined in Section 2: processes, resources and organization.

4.1. Strategic Level

At the strategic level we consider decisions that have a long term impact, mostly decisions that concern high investments. The two main groups are the decisions concerning the design of the process flow and the decisions concerning the selection of the types of warehousing systems.

The process flow design defines the required processes. A basic flow consists of the stages receiving, storage, orderpicking, and shipment. Additional processes may be included which have an immediate impact on the selection of technical means and equipment. For example, a sorting process may be needed in order to batch and sort orders, requiring a sorter system. The inclusion of a forward/reserve replenishment system requires the presence of a bulk storage and an orderpick area.

The selections of the warehouse system types at the strategic level concern all systems that require a high investment like the storage system and the sorting system. As we have seen, the selection of processes requires the availability of specific systems but the reverse statement is also true. For example, a sorting process may only be selected if a sorter system exists that is capable to handle the products. Hence the two groups of decisions are interrelated. However, the complete selection process can be decomposed into two sequential decision problems: one based upon technical capabilities and the other one based on economic considerations.

The first problem concerns technical capabilities. The storage unit, the storage systems and the equipment have to be suitable for the products, suitable for the orders, and should not conflict with each other. This warehouse design problem concerns both the design of the process flow and the selection of the main warehouse system types. The input for this problem are the characteristics of the products and the orders. The output of this design problem specifies which combinations of systems are technically capable of handling the products and meeting the performance constraints. Hence, the outcome is not a specified system, or even a small number of alternatives, but a, hopefully limited, number of possible combinations of warehouse systems that fulfills the technical and performance requirements (in particular throughput, response times and storage capacity).

The second warehouse design problem concerns the design of the process flow and the selection of warehouse systems based upon economic considerations. This results in an optimization over the range of possible system combinations selected in the preceding phase, aiming at minimum investment and operational costs.

The following observations can be made concerning the relations between several decisions:

- The warehouse investment costs are mainly determined by the (number of) resources.
- The warehouse storage capacity is mainly determined by the type and dimensions of the storage system. Of minor importance is the storage policy (dedicated storage, class-based storage or random storage).
- The maximum warehouse throughput is partly determined by the type and dimensions of the resources. A large number of other factors may also influence the maximum throughput: the separate reserve area decision, the storage policy, the batch policy, the routing policy and assignment policies (personnel, equipment and docks).
- The warehouse response time is partly determined by the factors related to the maximum throughput. However, it is also influenced by a number of other organizational decisions, such as the zoning policy, the sorting policy and the dwell point policy.

These observations once again underline the strong interrelationship between various decision problems at the strategic level. Ideally, these problems therefore should be grouped into one simultaneous decision problem. For practical reasons some decomposition seems unavoidable but it remains extremely important to explicitly model the relationships in any possible decomposition.

Figure 4.1 lists a number of design problems at the strategic level, related to the three axes defined in Section 2 (see also Mantel and Rouwenhorst [80]). All the decision problems in the shaded area are related. Recall that each individual decision on this level puts a constraint and additional requirements at decisions on lower levels. For instance, the strategic decision to use a separate reserve area implies that, at the tactical level, this reserve area is to be dimensioned, and that, at the operational level, replenishment policies have to be defined.

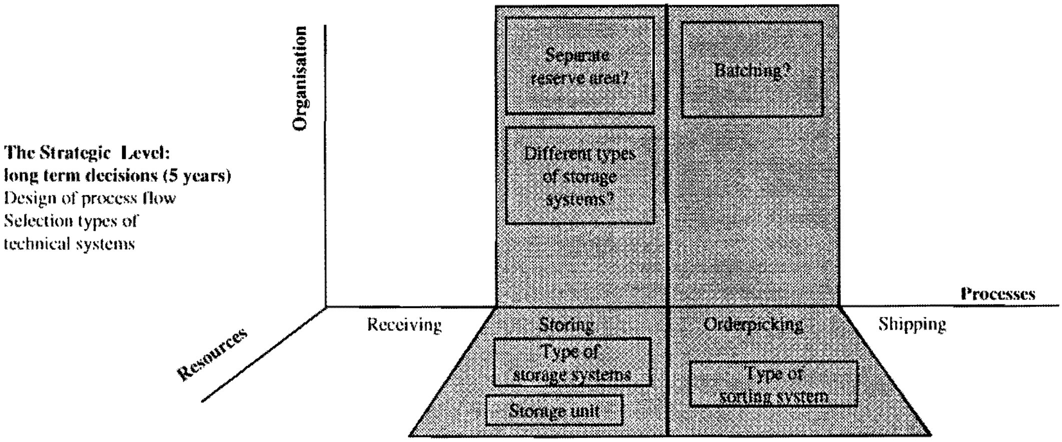

Figure 4.1: The Strategic Level.

4.2. Tactical Level

On the tactical design level, a number of medium term decisions are to be made, based on the outcomes of the strategic decisions discussed in the preceding subsection. The tactical decisions have a lower impact than the strategic decisions, but still require some investments and should therefore not be reconsidered too often. Tactical decisions typically concern the dimensions of resources (storage system sizes but also number of employees), the determination of a layout and a number of organizational issues.

Clusters of problems that arise at the tactical level and should be treated simultaneously include:

- organizational problems including the dimensioning of the picking zones and the ABC zones, the determination of replenishment policies and batch sizes, and the selection of a storage concept (random, dedicated, class-based),
- determining the dimensions of the storage systems, including the forward and reserve areas,

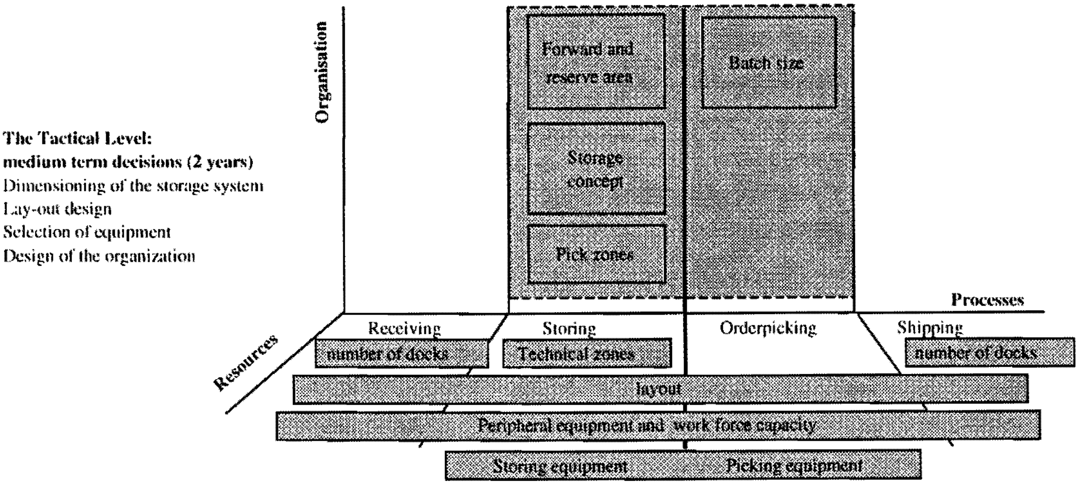

Figure 4.2: The Tactical Level.

- determining the dimensions of the dock area's,
- determining the number of material handling equipment,
- establishing a layout of the overall system,
- determining the number of personnel.

The design problems on the tactical level and their interaction are visualized in figure 4.2.

The relations between the various problems is less strong than at the strategic level. However, the different storage rules that constitute the storage policy again are strongly interrelated. Also, the storage policies relate to the other organizational policies, since they all influence the maximum throughput of the warehouse, and can not be optimized independently.

All these design problems aim at optimizing performance criteria, such as the throughput, the response times and the storage capacities while minimizing additional investment and operational costs. Minimizing operational costs in particular often boils down to minimizing the required work force.. Obviously, the outcomes of the decisions made here have a strong impact on the remaining problems to be solved at the operational level.

4.3. Operational Level

At the operational level, processes have to be carried out within the constraints set by the strategic and tactical decisions made at the higher levels. Since interfaces between different processes are typically handled within the design problems at the strategic and tactical level, this implies that at the operational level policies have less interaction and therefore can be analyzed independently. The main decisions at this level concern assignment and control problems of people and equipment. Decisions concerning the storage process at the operational level are:

- the assignment of replenishment tasks to personnel,
- the allocation of incoming products to free storage locations, according to the storage concept determined at the tactical level.

  Concerning the orderpicking process, decisions are related to:

- batch formation or order sequencing, in line with the batch sizes determined at the tactical level,
- the assignment of picking task to orderpickers,
- the sequencing of picks per order (routing),
- the selection of a dwell point for idle orderpick equipment,
- the assignment of products to sorter chutes (or lanes).

Finally, the assignment of arriving and departing trucks to docks is also a control decision.

The design problems on the operational level are visualized in figure 4.3.

In closing this section we again emphasize the strong hierarchical relationships between decisions made at the strategic, tactical and operational level. In addition, various problems at the strategic level appear to be highly interrelated as well. To a lesser extent this holds also for the tactical level, whereas decisions made at the operational level often can be considered independently.

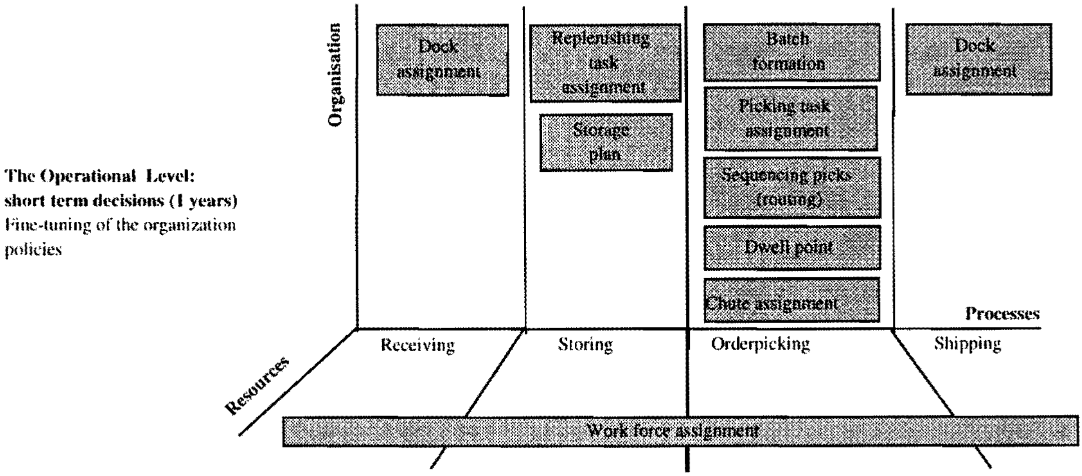

Figure 4.3: The Operational Level.

5. A Review of Warehousing Models

In this section we present an overview of models and algorithms proposed in the literature for warehouse design, planning and control. In doing so, we follow the classification of problems at a strategic, tactical or operational level. At each level, we further discuss papers within specific problem domains but in addition classify them along the lines outlined at each of the three levels in Section 4 (see also figure 5.1). Apart from the design problems, we briefly discuss some previous literature overviews and some papers on warehouse design methods.

5.1. Warehouse Literature Overviews

In 1971, 1982 and 1983 respectively, Miebach [86], Matson and White [83] and McGinnis et al. [46] reviewed the operations research and material handling literature. They concluded that important gaps in the research fields existed and that most research seemed to concentrate on rather limited problems. In 1992, Goedschalckx created a WWW-page[1] with an extensive list of publications. In 1996, Van den Berg [10] surveyed the literature on planning and organization of warehousing systems.

[1] http://www.isye.gatech.edu/people/faculty/Marc_Goetschalckx/research.html

5.2. Warehouse Design Methods

Apart from specific warehouse design problems, a number of publications deal with the structure of the design method as such.

Ashayeri and Gelders [3] review the literature concerning warehouse design and concluded that a pure analytical approach, as well as an approach that solely uses simulation, will in general not lead to a practical general design method. However, they suggest that a combination of the two approaches may lead to a good design method. Ashayeri and Goetschalckx [4] provide a step-wise general design procedure. Duve and Böcker [28] propose a step-wise design method for warehouse design and provide several examples. Yoon and Sharp [125], [126] and [127] suggest an elaborate conceptual procedure for the design of an orderpick system. Duve and Mantel [29] discuss Logitrace, a decision support system based on a step-wise design procedure. Frazelle and Hackman [42] provide an empirical study concerning the evaluation of warehouses by means of benchmarking. Brynzér et al. [22] propose an evaluation method based on the Zero-Based-Analysis method. Rupp [109] suggests an hierarchical design method. Gray et al. [52] also propose a hierarchical design method and describe the application of their method by an example design. Rink and Waibel [99] describe Lasys, a German decision support system for warehouse design.

5.3. Warehouse Design Problems: Strategic Level

At the strategic level, two problem clusters have been identified: one dealing with the selection of systems and equipment based on technical capabilities, and the second one dealing with the design of the process flow and the selection of warehouse systems based on economic considerations. With respect to the first cluster, we found no publications that specifically concern this problem. A limited number of publications deals with problems in the second cluster. Roll et al. [101] propose a systematic procedure for determining the size of a warehouse container. Oser [88] provides an analysis of an automated transfer car storage and retrieval system by comparing this system to some alternatives, based on approximations of system performance. Keserla and Peters [68] compare the performance of a standard AS/RS with a dual-shuttle AS/RS, using analytical expressions and simulation. Dunkin [27] develops a design algorithm for warehouses containing tote-sized loads. A very interesting study has been published by Sharp et al. [117], who compare, on a cost basis, several competing storage and retrieval equipment types for item picking. Both strategic design problems are discussed by Schmidt [111].

He evaluates an automated satellite storage system, by analyzing the hardware attributes, as well as the organization and the resulting warehouse performance.

In conclusion, the number of publications concerning design problems on a strategic level appears to be limited, despite the fact that at this level the most far-reaching decisions are made. Most publications analyze the performance of a warehouse in order to be able to compare the system with alternative ones. Only one publication explicitly analyzes multiple competing warehouse systems.

5.4. Warehouse Design Problems: Tactical Level

At the tactical level, most decisions concern the determination of resource dimensions and the design of the organization. The publications in this subsection are classified according to storage system type. A classification following the topics of Subsection 4.2 is presented in figure 5.1.

Determining the size and layout of conventional warehouses has been the topic of several publications. Berry [13] and Bassan et al. [8] analyze the layout of a conventional warehouse. They provide an optimization model to determine the optimal dimensions of the layout, in order to minimize handling distance, handling time, space utilization or costs. Rosenblatt and Roll [103] present a design procedure comprising both simulation and analytical methods in order to determine the size and layout of a conventional warehouse, concentrating on the storage capacity. Also, they present an analysis of the required storage capacity as a function of product and order characteristics (see [104]). Pandit and Palekar [93] study the effect of the layout of a conventional warehouse on the response time, using analytical models and simulation.

De Koster [69] proposes a modeling and analysis method for pick-to-belt orderpick systems that uses analytical expressions to approximate the maximum throughput.

Marnix and Sharp [81] and Sharp et al. [115] evaluate the performance of several configurations of a carousel system. Rouwenhorst et al. [108] determine the maximum throughput and the response time of a carousel system, using stochastic models. Spee [118] analyzes a carousel system in combination with an orderpick robot and derives analytical expressions for the maximum throughput.

Bozer et al. [20] consider end-of-aisle orderpicking systems. They model the performance of a storage system that consists of multiple miniload systems by deriving analytical expressions, and develop a design algorithm to determine the optimal configuration. In [21], they generalize their algorithm to other configurations of the orderpick system. Foley and Frazelle [39] derive closed-form analytical expressions for the maximum throughput of a miniload system.

Karasawa [66] and Ashayeri et al. [2] analyze the AS/RS by deriving formulas that approximate the performance of the system as a function of several design characteristics and provide an optimization model to design an economical AS/RS. Bozer and White [19] present analytical expressions for the travel time in an AS/RS. These results have been extended by Chang et al. [24] who incorporate acceleration and deceleration effects. Pan and Wang [92] provide analytical expressions for the maximum throughput of an AS/RS with dual commands and a class-based storage policy and evaluate the approximation of the discrete storage rack by a continuous rack. Meller and Mungwattana [84] develop analytical expressions for the maximum throughput of a multi-shuttle AS/RS. Rosenblatt et al. [105] suggest a procedure, including both simulation and analytical methods, to determine the size of an AS/RS system, considering constraints on the maximum throughput and the response time. Randhawa and Schroff [97] extend this study by including an analysis of the storage capacity and the influence of the location of the I/O-point, using simulation. Hwang and Ko [60] propose a procedure to determine the size of multi-aisles AS/RS's, based on analytical expressions, by varying the number of cranes and the storage policy. Meller and Mungwattana [85] analyze the maximum throughput of a multi-shuttle AS/RS by means of stochastic models and simulation. Linn and Wysk [74] determine the dwell point, the storage policy and the retrieval sequences of an AS/RS with the aid of simulation, and propose a decision tree. In addition, the authors propose an expert system on the operational control of an AS/RS [75]. Van den Berg and Gademann [12] analyze multiple organization policies of the AS/RS on the influence on storage capacity, the maximum throughput and the response time. Forward/reserve division has been analyzed, together with routing, ABC-classification and sequencing of the storage requests, with the aid of simulation.

Stadtler [120] analyzes the impact of the size of a Chaotic Direct Sorted (CDS) warehouse, proposing a procedure consisting of simulation and enumeration.

Apart from storage systems, some publications concern other systems or are more general. By means of a simulation study, Bozer and Sharp [18] and Bozer et al. [15] and [16] analyze the performance of a sorting system under variation of the number of output lanes, order characteristics, and control policies. Larson et al. [71] develop a procedure for class-based storage, related to both the system dimensions and the layout. Sharp et al. [116] perform a simulation study to analyze the configuration of input/output conveyors of an AS/RS, and focus both on layout and control. Gromann [53] analyzes the selection of equipment for the loading of a truck with packages, providing a qualitative comparison. Sharp et al. [114] determine the selection of orderpick equipment; they compare pick-to-light systems to alternative systems through both a quantitative and a qualitative comparison within some case studies. Bunde and Graves [23] provide analytical expressions of the maximum throughput of a palletizer system as a function of its dimension. Pliskin and Dori [96] propose an evaluation procedure for warehouse layouts by a multi-criteria analysis based on user preferences.

In conclusion, many papers at the tactical level concern the performance of, mostly automated, warehousing systems.

5.5. Warehouse Design Problems: Operational Level

At the operational level, most decisions concern the assignment of tasks to, and the scheduling and control of people and equipment. The publications in this subsection are grouped according to list of topics discussed in Subsection 4.3.

5.5.1. Batching

Elsayed and Stern [35] test 24 batching algorithms with the aid of simulation. Elsayed and Unal [36] derive analytical expressions to evaluate batching algorithms. Rosenwein [107] analyzes the maximum throughput in a conventional warehouse with batching by means of a simulation study. Gibson and Sharp [44] analyze order batching procedures for sort-while-pick orderpick operation, and in [45] they study two new batching procedures, again by simulation. Armstrong et al. [1] evaluate batching algorithms for a pick-to-belt warehouse with a sorter system. Pan and Liu [91] analyze batching for a person-on-board AS/RS using simulation in an attempt to maximize the throughput. Elsayed [33] proposes an algorithm for batch formation in a multi-aisles AS/RS system with a sorting system. Hwang et al. [59] and Hwang and Lee [61] analyze batching algorithms for an AS/RS with the aid of simulation.

5.5.2. Storage policies

Goetschalckx and Ratliff [50] evaluate storage policies for block storage through an analytical study. Marsh [82] has been working on the same problem but evaluates two alternative policies. Jarvis and McDowell [64] propose a heuristic for the storage policy in a conventional warehouse. Roll and Rosenblatt [100] analyze the storage capacity of conventional warehouses with alternative storage policies, using simulation. Van den Berg and Sharp [122] propose a procedure based on linear programming for product allocation in a warehouse consisting of a forward and a reserve area, to minimize the costs of orderpicking and replenishment. Bartholdi and Platzman [7] provide a storage policy for a carousel, based on the numbering of bins. Van Oudheusden and Zwu [90] propose a storage algorithm for a person-on-board AS/RS with recurrent orders, and evaluate the algorithm by means of a simulation study. Wilhelm and Shaw [123] present an empirical study concerning the storage policy of an AS/RS. Hausman et al. [58], Yang [124], Rosenblatt and Eynan [102], Goetschalckx and Ratliff [49], Eynan and Rosenblatt [38], Kouvelis and Papanicolaou [70], and Malmborg [78] all analyze class-based storage in an AS/RS, assuming single commands. They develop analytical methods to determine the optimal dimensions of the zones, considering storage capacity and maximum throughput. Malmborg [77] evaluates the storage policy for an AS/RS with zoning constraints, and proposes a simulated annealing algorithm, to maximize the storage capacity. Ashayeri et al. [5] evaluate the maximum throughput of an AS/RS under different storage policies, by deriving analytical expressions. Jaikumar and Solomon [63] analyze the relocation of items in an AS/RS and develop an algorithm. Muralidharan et al. [87] evaluate three heuristics for the same problem through a simulation study. Guenov and Reaside [55] and Lee [72] analyze class-based storage for a multi-command AS/RS through simulation. Kaylan and Medeiros [67] evaluate storage policies for a miniload system with multiple I/O points. Stadtler [119] suggests storage algorithms for the Deep Lane Storage System that minimize the number of relocations. Frazelle and Sharp [40] and Rosenwein [106] analyze correlated storage policies and develop a general solution approach. Beavers [9] presents a paper on the same topic and discusses a computerized implementation. Malmborg and Bhaskaran [79] evaluate the Cube per Order Index storage policy for different kinds of warehouses, based on analytical expressions for the maximum throughput. Park and Webster [94] derive analytical expressions for the maximum throughput of multiple three-dimensional storage systems with the cubic-in-time storage policy.

5.5.3. Routing and sequencing

Gelders and Heeremans [43] analyze routing in a conventional warehouse. Goetschalckx and Ratliff [47] and [48], Hall [56] and De Koster and Van der Poort [26] determine analytical expressions to evaluate the routing in a conventional warehouse. Ratliff and Rosenthal [98] present an algorithm for the routing in a conventional warehouse, based on dynamic programming, which focuses on the maximum throughput. Guenov and Reaside [54] analyze three heuristics for two-dimensional item picking in a conventional warehouse. Bozer et al. [17] suggest an algorithm for routing in a two-dimensional rack with more than two locations to be visited, and test its performance with the aid of a simulation study. Kanet and Gonzalo-Ramirez [65] evaluate sequencing policies in an AS/RS. In addition to the usual costs associated with retrieval, this study considers also the cost of a location breakdown. Cormier [25] presents an algorithm for sequencing retrievals with due-dates in a AS/RS, using dynamic programming. Linn and Xie [76] suggest an sequencing rule for the same problem. Elsayed et al. [34] and Lee and Kim [73] extend this problem with penalties for early retrieval and suggest a sequencing procedure. Han et al. [57] analyze the nearest-neighbor and the shortest-leg retrieval policies for an AS/RS, based on analytical expressions and simulation. Eynan and Rosenblatt [37] evaluate the nearest-neighbor retrieval policy for an AS/RS with class-based storage. Eben-Chaime [30] analyze the difference between block scheduling and dynamic sequencing in an AS/RS. Seidmann [113] proposes an adapted sequencing rule that incorporates seasonal demand fluctuations of the products.

5.5.4. Dwell point selection

Egbelu [31] presents an algorithm for the dwell point selection, using linear programming. Also, Egbelu and Wu [32] evaluate several dwell point policies with the aid of simulation. Hwang and Lim [62] improve these algorithms. Peters et al. [95] present an analysis to approximate the response time for multiple AS/RS configurations and dwell point policies.

5.5.5. Storing and sequencing

Graves et al. [51] evaluate the impact of sequencing and class-based storage policies on warehouse performance, based on analytical expressions for continuous racks and numerical procedures for discrete systems. Van Oudheusden et al. [89] analyze this problem for a person-on-board AS/RS, by means of a case study using simulation. Stadtler [119] proposes a concept for the operational control of an CDS-warehouse, which incorporates tabu search. Schwartz et al. [112] use simulation to approximate the maximum throughput of an AS/RS as a function of storage and sequencing policies.

5.5.6. Miscellaneous

Sarker and Babu [110] review the literature concerning the operational control of AS/RS's. Van den Berg [11] analyzes a number of operational control problems: forward reserve allocation, class based storage, routing in carousels and AS/RS's, and dwell point selection. Askin and Standridge [6] make some general remarks on organizational issues for conventional and automated warehouses.

5.6. Overview

Figure 5.1 presents a clustering of the literature discussed above, following the list of topics discussed in Section 4. Publications that cover more than one category are accounted more than once.

From Figure 5.1 we observe that most of the research seems to concentrate on fine-tuning the warehouse organization, i.e. on the tactical and in particular on the operational level. About 70 publications analyze isolated optimization problems concerning warehouse organization, which sharply contrasts with the 6 publications concerning strategic design problems. Since most costs of a warehouse are determined at an early stage, more research on strategic issues is badly needed.

Also, the review indicates that most of the research concerning the tactical and the operational design level analyzes automated storage systems. In particular the AS/RS is a popular research theme; only a few publications discuss conventional warehouses or warehouse equipment. More research on conventional systems should be encouraged. Furthermore, no publications were found on tactical design problems like the dimensioning of the dock area and the determination of the number of personnel, although these problems are far from trivial and often represent substantial costs.

In addition, most papers seem to focus on isolated warehouse organizational policies. Optimizing such a policy may at best lead to a local optimization. As an example, consider an optimal batch size policy that neglects the possible effects of ABC-zoning. We strongly advocate research aiming at an integration of problems that have to be clustered at one level (compare the discussion in Section 4).

In conclusion, the overall picture that emerges seems to suggest that current research, although useful in itself, is still too much scattered, almost completely analytical of nature, and much less oriented towards a synthesis of models and methods. In particular more research is needed on strategic design problems and on the integration of various models and methods in order to develop a systematic

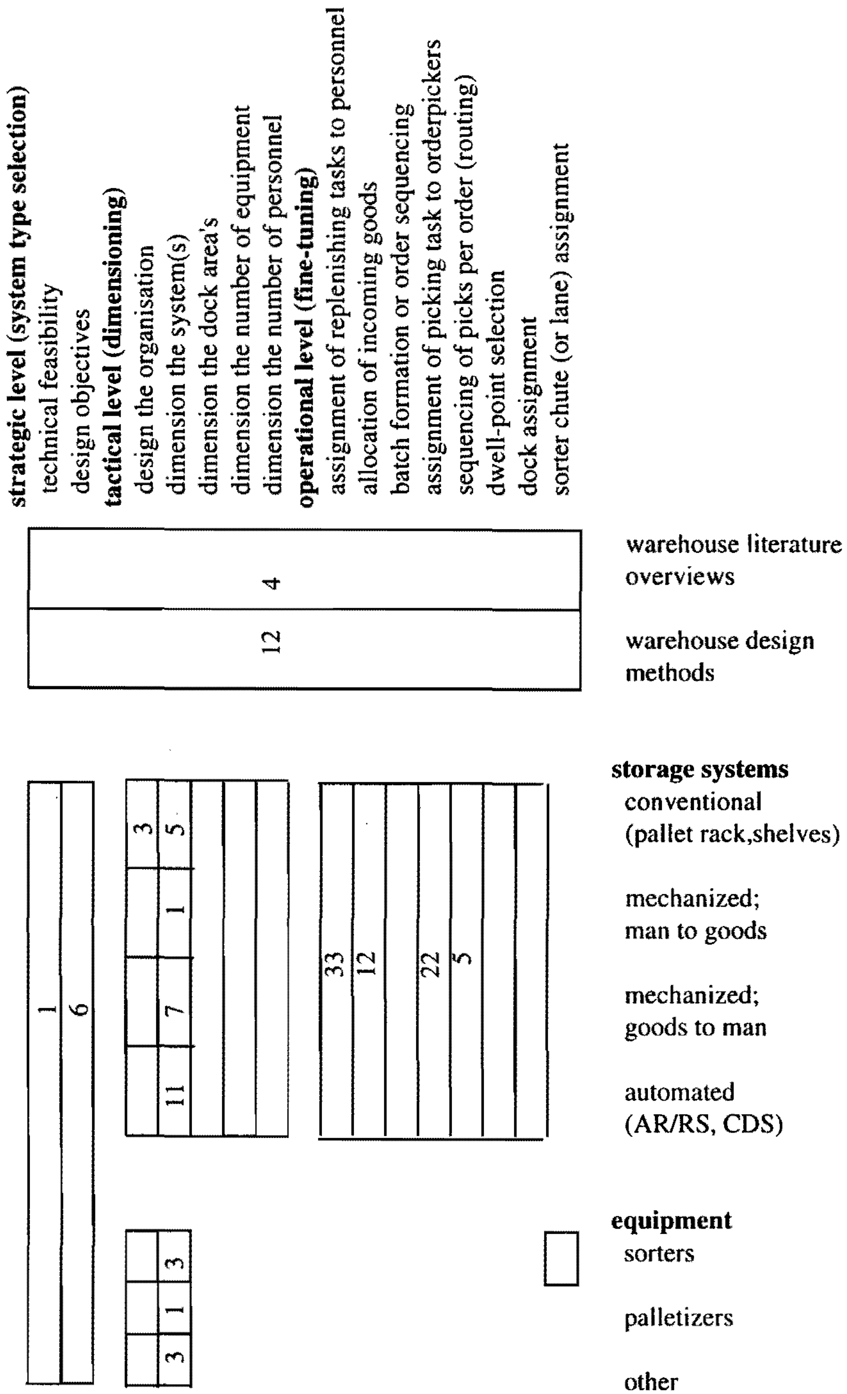

Figure 5.1: An overview of the classification.

design methodology.

6. Design Oriented Research

In the preceding section, the literature review showed that most of the current research is primarily devoted to the analysis of relatively clean, isolated systems, instead of to a synthesis of models into an overall design model. Basically, a similar remark holds for the majority of studies devoted to operations management problems. The lack of design oriented papers is in sharp contrast with the need for integrated models and techniques. In this section we elaborate on the differences between analysis oriented and design oriented research and offer some guidelines to support a greater emphasis on the latter.

Typically, analysis oriented research is concerned with limited, well-defined problems. These problems often satisfy the following properties (see also De Boer [14]):

- the performance function (or goal function) can be expressed analytically or can be quantified,
- the set of available alternatives is fully known,
- the probability of uncertain events is known and the effects can be quantified,
- the interaction with the environment is neglected or easily modelled.

Although analysis oriented research may comprise highly complex models and methods, it is generally easy to value and to communicate. The review presented in Section 5 reveals that the research on warehousing systems primarily falls within this category. An example is provided by the optimization of routes in an automated storage and retrieval system (AS/RS). This problem concerns the sequencing of storage and retrieval operations in an AS/RS, in order to decrease the expected route length and thereby to increase the throughput. This problem has all properties mentioned above. Indeed, no less than 42 publications concern route length optimization for an AS/RS.

In contrast, problems encountered on a strategic level during warehouse design often are less well-defined:

- The performance function that evaluates a solution is often complex; it consists of multiple objectives, and is partly qualitative. For instance, flexibility is hard to quantify.

- The set of alternatives is large, since many alternatives of warehouse hardware systems and organization policies exist and can be combined in multiple ways; e.g., a warehouse may have three or more types of warehouse storage systems and may use multiple organization policies. Enumeration of all feasible designs in order to find the optimal solution is often practically impossible.

- Stochastic behavior such as the failure of warehouse equipment and human faults during orderpicking are difficult to quantify.

- The judgement of a complete design can at best be partial, since future warehouse capacity demand, as well as the future product types to be stored, are hard to predict.

- The design of subsystems or policies can not be isolated, due to the interaction with other subsystems and policies. In Section 4 we found that warehouse design problems at a strategic or tactical level can not easily be decomposed into multiple isolated subproblems.

Although we do not offer a complete road map, we strongly advocate a more design oriented research approach for warehousing problems. Below, we offer some guidelines that may help in pursuing such research.

- The use of a reference model to place design problems in a general perspective. The characterization along the three axes processes, resources and organization of Section 2, and the classification of problems in Sections 3 and 4 may provide the basis for such a reference model.

- An inventory of warehouse systems, equipment and techniques is indispensable as a basis for comparing alternatives (see also Tompkins et al. [121]). In particular, the suitability of systems for particular product market combinations (slow movers or fast movers, item picking or case picking) should be investigated.

- At the strategic level, the development of more cost oriented models is needed. Also, the translation from a functional to a technical specification, based upon knowledge of existing systems, deserves more attention.

- Studies that aim at an integration of various subsystems and that concentrate on interfacing problems should be encouraged.

In summary, we emphasize the need for research oriented towards a synthesis of currently isolated models and techniques, as a basis for decision support in designing complete warehousing systems. Such research is felt to fill an important gap between the scientific literature and the practice of warehouse design and management.

7. Conclusions

In this paper, we have presented a characterization of warehouses along the views processes, resources and organization. In addition, we have presented a classification of warehouse design and control problems along these three axes at a strategic, tactical and operational level, respectively. In addition, we presented an extensive review of the literature and concluded that the majority of papers is primarily analysis oriented and does not pursue a synthesis of models and techniques as a basis for warehouse design. Some guidelines towards a more design oriented approach have been offered.

Future work will concentrate on the development of a complete reference model and a systematic design approach for warehousing systems. In particular trade-offs between costs and operational performance of integrated systems will be the subject of future studies.

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