

Design of warehousing and distribution systems: an object model of facilities, functions and information *

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Abstract

Design of warehousing and distribution systems is more an art than a science that reflects the cultures of particular design teams. Warehouses are often designed and operated by third party logistics companies with tight margins. Therefore, there is increased pressure to design warehouses that are flexible and adaptable, even while the available information is incomplete. Also, designers lack coherent, and explicit, models of information and function flow. The primary goal of the research discussed here is to lay the foundation for developing such models. Working closely with expert designers, we have identified the key pieces of information and organized them in the form of an object model. Using this model, it should eventually be possible to provide relevant information to designers via context-sensitive (or ‘ecological’ or ‘intelligent’) displays. Upon further development, the model will be incorporated into an interactive system to assist in design. In this paper, we describe the object model, and outline plans for implementing a design system.

1 Introduction

Warehousing and distribution systems constitute a significant component of many so-called supply chains. These systems are global, and must be adaptive, due to the ever changing customer preferences and evolving alliances among the entities responsible for production, storage, and distribution.

Warehouses typically receive in-bound shipments from suppliers and manufacturers and prepare out-bound shipments to customers who may be other distributors, end users, or manufacturers. An in-bound shipment often contains a large quantity of one or a few stock keeping units (skus). An out-bound shipment may consist of a small amount of a few, or perhaps many skus relative to the typical in-bound shipment. In-bound and out-bound shipments are quite different in their makeup.

In the transformation of in-bound shipments to out-bound

shipments, three basic warehouse functions can be identified. They are: (1) *blending*, taking relatively homogeneous input streams and creating customer-specific “blends”, (2) *impedance matching*, synchronizing relatively large and infrequent in-bound flows of each sku to relatively small and frequent out-bound flows, and (3) *value adding*, repackaging (e.g., from a case to smaller quantities), labeling for specific customers, assembly (e.g., repackaging printers with destination-specific power cords and documentation). These functions (see Figure 1) require systems for: (1) *storage* of containers (e.g., pallets, cases, or broken cases), perhaps satisfying special environmental requirements for temperature, humidity, static electricity, etc.; (2) *transport* from receiving to storage, between various storage locations, to processing locations, to order accumulation/pack, to shipping; (3) *order picking* for efficiently retrieving the items required to satisfy a particular order, and doing so in a timely fashion; and (4) *order sortation/accumulation* to bring together all the items that have been picked for a particular order, and accumulating them so that they may be packed and shipped efficiently.

The key aspects of warehouse design are the selection and specification of systems to provide the required functionality, the arrangement and staffing of the systems, and the specification of operating protocols. In addition, it is often necessary to specify the size and configuration of each selected technology.

Research on warehouse design and control has generally been concerned with individual warehouse functions (e.g., [1], [2], [3], [4], [5]). For instance, when replenishment and order picking patterns are known, several models are available in the literature to compute alternatives for storing a specific number of pallets of a set of skus optimally, (e.g., [6], [7], [8]) and to evaluate the alternative with regard to performance and cost. The impact of the isolated research efforts on the *practice* of warehouse design has been relatively insignificant, however, since these results fail to offer guidance or suggest procedures for synthesis and design.

A design infrastructure and methodology to integrate the fragmentary research results or models is lacking. Rouwenhorst et al. [9] provide an excellent overview of the situation and attempt to develop an integrated framework centered around three levels of a hierarchy: strategic, tactical and operational, each of which is described in terms of processes, means (or resources), and organization.

What is needed is a top-down (or strategic) perspective on warehouse design, leading to a conceptual framework that

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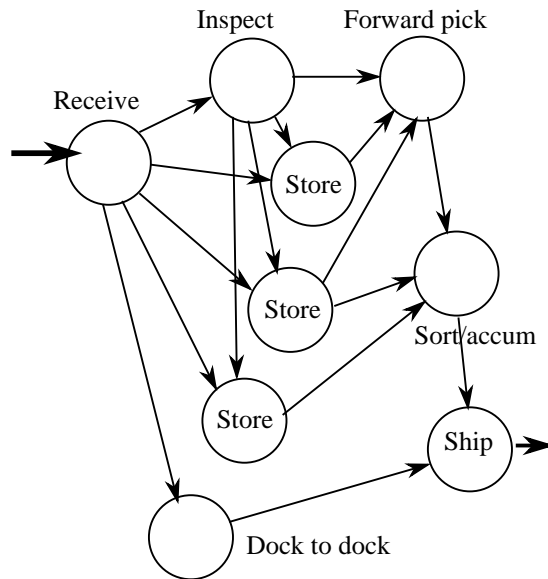


Figure 1: Function flow network

can help integrate the isolated research efforts and computational tools into a coherent design environment. We have developed an object model, described in this paper, as the first step towards formalizing and implementing an integrated framework. A necessary prerequisite for this is research on identifying functional requirements from operating data, characterizing the functions, and guidelines for selecting appropriate systems to provide a particular functionality. A key goal of our research is to develop a formal representation scheme and methods of analysis to aid warehouse designers in considering functional requirements.

We discuss next our understanding of how experts in warehousing and distribution systems carry out their designs, followed by a description of the object model. Some preliminary ideas on implementing the object model are described in the section that follows. We conclude with observations on future work.

2 Warehouse design process

From our interactions with expert warehouse designers [10], it is our understanding that a warehouse design team typically consists of an analyst and a designer. What is important here are these two roles that can be assumed by one or more individuals. The analyst has knowledge about warehouses, and is skilled in analyzing and extracting information from the available customer order database. The designer is an expert experienced in designing and improving warehouses.

Design starts with the analysis of information provided by clients via three databases: an item master, an inventory master, and an order master. The item master describes each

sku in terms of package type, weight, cube, value, or other relevant attributes. The inventory master describes the state of the inventory at various points in time, and perhaps the replenishments. The order master contains a year of customer orders (six months if the items are not seasonal); each order identifies a customer, an order date, and a series of lines, each specifying a product (sku) and a quantity.

The design process begins with the analyst computing a number of routine statistics from the order database. He may use spreadsheets, simulations, or algorithmic computations, or perhaps simply “eye ball” the data and decide on further action. For example, the analyst may prepare a series of Pareto charts in which the skus are sorted in decreasing order of frequency of selection, quantity of selection, cube ordered, value ordered, etc. The distribution of lines per order, quantity per order, cube per order, etc., also may be prepared. The analyst may evaluate the orders in terms of the mix of sku types ordered, i.e., fraction of orders that are A items only, B items only, etc.

This initial summary, or “profile” of the customer order data is presented to the designer, who typically will begin by focusing on one of two attributes—either the pick frequency of the skus, or the cube movement rate of the skus. The former leads to an initial focus on the order picking/sortation/accumulation functions, with the aim of establishing the design of the order picking systems. The latter leads to an initial focus on the storage systems, with the aim of specifying the storage technologies to be used.

At this point, it appears that the designer considers the data, and based on intuition, experience, and judgment, makes some initial design decisions about the overall system architecture. For example, the designer may decide that this particular warehouse is not suitable for automated storage, and that single order picking will be used. The effect of these architectural decisions is to significantly reduce the degrees of freedom in design, so that he can concentrate on specific decisions that could benefit from additional data analysis. For example, once the set of storage technologies has been specified, the remaining decisions involve sizing each technology, assigning skus to technologies, allocating storage space to each sku, and “slotting” or deciding where each sku will be stored.

The designer must consider some very complex trade-offs, many of which are not yet fully articulated. However, we can give some examples. All other things being equal, the designer prefers fewer transactions to more transactions, i.e., skus should be handled the fewest number of times possible. However, not all transactions are equally costly. If cases must be picked from pallets by going into a large pallet storage system, then each case pick is very expensive. By moving the pick operation to a forward pick area, perhaps utilizing flow rack, the individual picks are made much less expensive, but there is now an additional handling required in taking a pallet from the pallet storage system, and transferring the cases to a pick line. He must decide if there are enough skus that can be treated this way to justify the expense associated with the forward pick area.

All other things being equal, the designer prefers shorter pick waves (i.e., fewer orders picked simultaneously, in a shorter time interval) to longer ones, because shorter pick waves require fewer order accumulation lanes, and fewer dock doors, reducing the cost of the warehouse. However,

as the pick waves become shorter in duration, orders must be split over more order pickers, and it becomes increasingly difficult to balance the workload among pickers and merge the separately-picked items for each order. Thus, the design problem is to establish the target duration of a pick wave to balance between the costs of picking (related to the efficiency of picking), with the costs of sortation/accumulation systems and shipping dock doors.

The result of the expert designer's decision making is a specification of a warehouse design that includes the size of the warehouse, the arrangement of the space, the types and amounts of each material handling or storage technology, the staffing, and the operating policies. Our current research is focussed on articulating the process by which the expert designer considers the available data and information, and makes the design decisions that result in the specific warehouse design.

Based on preliminary research and discussions with experts [10], we believe that the design process can be viewed as a sequence of steps. The first step is the assembly of relevant data (e.g., the item master, inventory master, and order master). The designer uses analyses of these data to determine, usually implicitly, a set of functional requirements, and perhaps also functional cost targets. The "functional space" itself is not made explicit during design. The functional requirements drive high-level, or architectural, design decisions, such as the use of a forward pick area, or batch picking in zones, or the use of automated storage systems. Very likely, an understanding of functional costs drives the selection of particular technologies or warehousing methods. Once the architectural decisions are made, the designer and analyst can focus on detailed specification to optimize the individual warehouse systems, and on evaluating the detailed design with regard to capability and cost. The key observation is that in current practice, in the early stages of design, the understanding of functional requirements and costs is intuitive. This process is illustrated in Figure 2.

Experts often have access to a substantial amount of additional data, the use of which is not explicitly known. These include, for example, the relative costs of various equipment categories, or the "typical" pick rates for certain kinds of packages, and similar quantifiable attributes of specific warehouse systems or practices. In making design decisions, the expert may utilize non-quantifiable information, based on experience and intuition. Similarly, the expert uses particular concepts to organize the relevant information, and guide decision making. For example, the concept of zone order picking is explicit and well known; a particular expert designer may utilize other concepts that are implicit, and perhaps not even articulated by the designer.

3 An object model

Clearly, the process of warehouse design involves a complex set of information about products, systems, and relationships among entities. In this section, we outline an object-oriented (OO) model for warehouse design and control, together with examples of typical interactions that designers (including analysts) have with the entities. The latter are developed in terms of prototypical work situations [11] and characterized via use cases [12]. From the preceding discus-

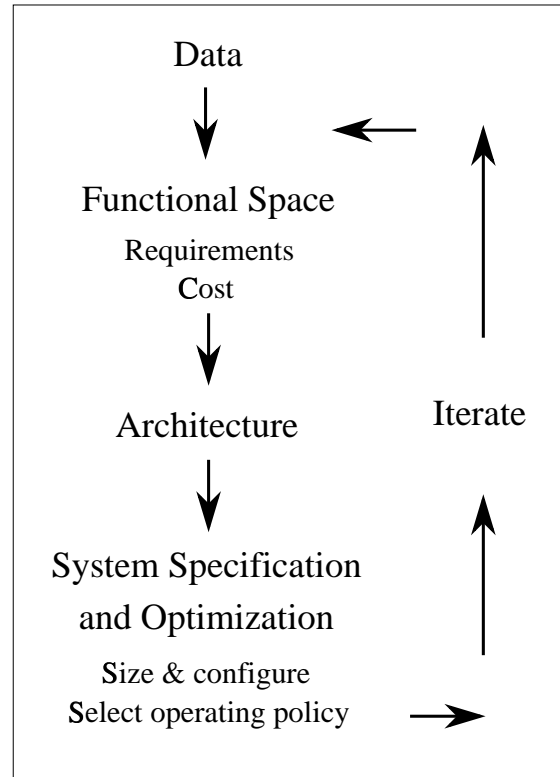


Figure 2: Steps in Warehouse Design

sion, it is apparent that an appropriate representation of the different types of information flow can be of significant help in formalizing the information.

For warehouse design to become a formalized process, a "science," rather than an "art", we need coherent models of data and information that influence the design. Models of data and/or information can help streamline the design process by structuring computations and facilitating communication through exchange of information between clients and designers.

An object-oriented approach is appropriate for information for the following reasons:

1. The physical objects inside a warehouse and their interactions can be mapped directly to objects.
2. Complex relationships and interactions can be specified transparently.
3. Objects are inherently reusable, and are readily amenable to be used for several types of decisions together with different decision models.
4. Different kinds of objects in a warehousing operation, e.g., documents, protocols, products, equipment, can be handled in a uniform manner.
5. Objects models are easily scalable, making it possible to handle large amounts efficiently.

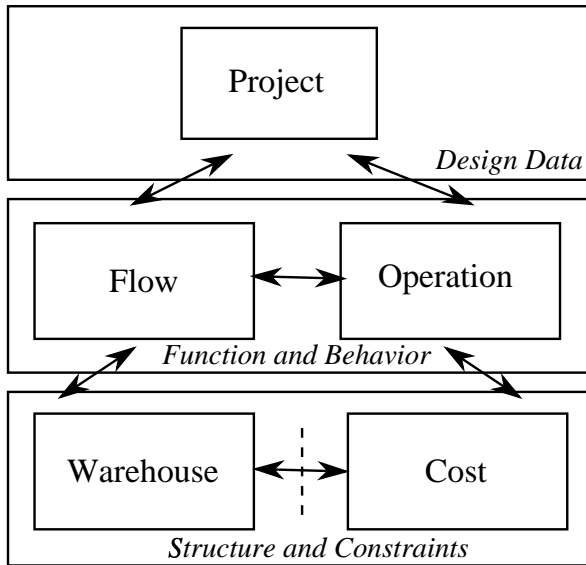


Figure 3: Object modules in warehouse design

6. The rich variety of interactions can be handled cleanly, making it possible to design and implement operational protocols for “intelligent decision making.”

We have developed an object model of the warehouse design process comprised primarily of four modules: the project module, the warehousing module, the flow and control module and the operation module. A cost module, though not inherently a component of the warehouse, is also necessary in actual designs and for operation. The cost module encapsulates the cost constraints and other supplementary information that is not inherent to the warehouse itself. The project module, at the highest level, provides the context for accessing the data for a specific design. The warehousing module describes the knowledge and the interactions among the different components of a warehouse (storage equipment, material handling equipment, warehouse areas and warehousing protocols). The information contained in this module will specify the “valid” relationships allowed in the design process, as well as the parameters required for designing *any* warehouse. The flow and control module is the description of the product flow specified by the user during a design process. The operation module specifies the physical operation of the warehouse based on the user design choices and the warehousing and flow and control specifications.

The *project module* encapsulates the overall design function by organizing data for user (i.e., designer) access. A designer may have one or more projects active at the same time. A project is a collection of several labor assignment (worker) and product warehousing specifications. The latter contains information about a product, the equipment used to handle it and the protocols used along the flow.

The *warehousing module* describes the structural relationships among the equipment (material handling, containers and storage) and the warehousing protocols. The classes that form this module are the following:

- Products placed in *containers* as they traverse the warehouse. Although many types of containers are available, the most frequently used ones are pallets, totes and containers.
- Products and containers placed in *storage modules* as they wait inside the warehouse. The most popular storage module are: floor stacking, racks, shelves, carousels, automated storage and moving aisles.
- *Handling equipment* that manipulate the products/containers through the warehouse operation. They are usually motorized vehicles but other types such as manual equipment, conveyors and automated retrieval components are available.
- The *warehouse function* class specifying the possible operations performed within a warehouse.
- The *protocol* class represents the different kinds of operational strategies that can be implemented in a warehouse. This class can also be thought as “roles” or even “method” supported by the different warehouse functions.

The *flow and control module* contains the “flow map” of the products in a project, and hence can be viewed as encapsulating the *functional* characteristics. A flow map is a directed graph that describes the different ways a product moves within a warehouse. A node is associated with a warehouse function (Figure 1) that is performed on the product. The arcs have a container type association that indicates how the product is moved between nodes. This flow map includes proposed protocols for each of the products. The product order information is also included as part of this module.

The *operation module* represents the operation of the system under a current specification, and encapsulates the system *behavior*. In other words, this module presents the warehouse after the design phase has been completed.

In terms of standard modeling and representation tools, e.g., Unified Modeling Language (UML) [12], the modules can be considered as aggregations of packages. Figure 3 illustrates the relationships among the modules.

4 Discussion and summary

The object modules described above encapsulate the information needed for warehouse design. The interaction among the objects influence the design depending on what happens in a warehouse. A number of perspectives are possible to model the information. A coherent view of how different methodologies and tools influence warehouse design and operation and why the design problem has not received the attention it deserves can be found in [9]. They classify the warehouse functions in terms of strategic, tactical, and operational decisions and point out that much of the research has been concerned with the tactical and operational decisions, whereas design is more concerned with the strategic issues.

One useful way to view the system for the purposes of design, in terms of functional abstractions and (physical) aggregations, is Rasmussen's abstraction hierarchy [11]. Prototypical situations [11] necessary to consolidate the rich set of interactions between users (who in this case may be designers) can also be viewed in terms of use cases [12], especially since the eventual goal is to develop an interactive system to assist in design¹.

The use cases are outlined in Figure 4 in terms of functions that are likely to be exercised together in the design process. These functions can be classified broadly under the following categories: data analysis (database management, profiling, and forecasting), requirements analysis (shipping and receiving and space requirements), space-related functions, space design (zone configuration and layout), and design of transport functions.

The process of warehouse design is difficult because there is a lack of formal models for how warehouses should be designed and operated for flexibility. Research described in this paper is aimed at developing models of information and function flow capable of bringing some order to their designs. Outlines of an object model based on our expertise and discussions with experts were described. An ethnographic study of expert designers is currently being performed to observe and understand the design process and develop insights into what constitutes expertise. Results of this research will be used to further refine the object model, which will be incorporated into an interactive system to assist in warehouse design.

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¹Fowler [12] describes a scenario as a "sequence of steps describing an interaction between a user and a system," and a use case as "a set of scenarios tied together by a common user goal" (pp 39-40). The prototypical work situations [11] are much more appropriate, from a conceptual viewpoint, since they "can faithfully represent the properties of a category" (p. 59) based on a thorough analysis and categorization of data related to a set of actual cases. However, use cases can illustrate the interactions to be considered in a "standard" manner familiar to software developers.

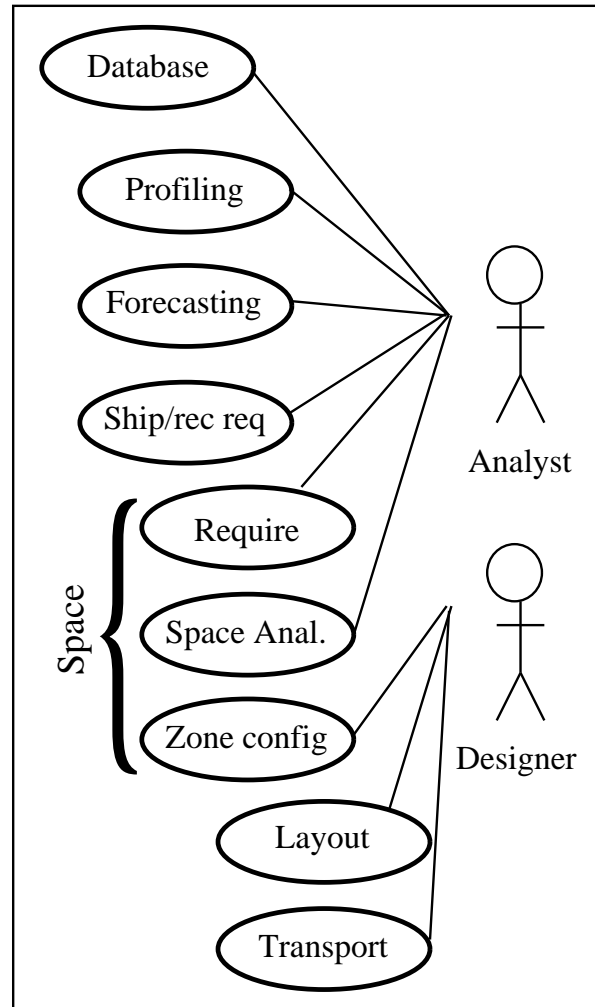


Figure 4: Important use cases

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