A Process Model and Support Tools for Warehouse Design

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ABSTRACT

Design of efficient industrial logistics systems increasingly is important to the global internet-based economy. Although significant research has been performed in this area, few results are used by industry design practitioners. Instead, they typically rely on accumulated expertise for their design decision-making. While top-down approaches to formulating the design problem are useful, our research focuses on understanding and formalizing the procedures used by industry experts. In this paper, we discuss results to date based on case study observations using the methodology of ethnographic studies, and we present a decision support architecture for aiding warehouse design.

1. INTRODUCTION

The modern global economy depends on the efficient flow of products, beginning from raw material, moving to end-products, and resulting in final delivery to the consumer. This flow occurs through a network of facilities and transportation systems collectively called the supply chain. Within the supply chain, facilities include various types of factories and warehouses. Designing these facilities is an important engineering problem that has consequences for their ability to meet specified requirements and for their capital and operational costs.

Consider a warehouse that functions as a distribution center. Its requirements fall into two major categories. First, it receives incoming products. It must arrange to store these products. Important considerations include storage capacity and efficient space utilization. Second, it receives orders from its customers. It must arrange to ship these orders. Important considerations include timeliness and order-filling efficiency. Of course, these two types of requirements interact. For example, in the order-filling process, one would like for products to be stored in a manner that facilitates order-picking efficiency. Also, in a steady-state system, the amount of goods received should equal the amount of products ordered, over a long time horizon.

Requirements typically are posed as the ability to handle a certain order pattern. To be certain, an order pattern is fairly complex, and is characterized by such things as order frequency, order size, the products ordered, and the handling units of the products. To meet this type of requirement, a warehouse contains systems and processes. Processes generally include receiving, storage, order picking and shipping, although some warehouses also may have value added processing or order sortation. Systems are designed to implement processes and include material handling systems, sortation systems, storage systems, etc. The overall warehouse design problem then is to specify these systems and processes and their relation to one another, which is governed by material and information flows, so that requirements are met. A typical objective function is to minimize capital and operating costs discounted over a time horizon.

While significant research has been done in the area of warehouse design, we have found in our interactions with industry practitioners that these research results are rarely used in practice. Our approach in addressing this problem is two-fold. First, we are studying the design process as it occurs in practice. This is being accomplished through the use of ethnographic studies methodology to study expert designers, in an effort to formalize their design processes, information usage, decision-making criteria and evaluation procedures. Second, we seek to link this formalization with existing or new research results to start formulating a science-based warehouse design methodology, and to implement computational tools to aid designers in practice.

In this paper, we discuss our progress to date. The remainder of this paper is organized as follows. Section 2 discusses expertise and the warehouse design problem. Section 3 proposes a process model of the design process resulting from studies of industry experts. Section 4 then describes a computational decision-support architecture for aiding designers. We conclude with thoughts on future research.

2. EXPERT DESIGN OF WAREHOUSING SYSTEMS

A. Warehouse Design Research

Warehouse design problems can be posed in a number of ways. In the research literature, two major categories of design problems are studied. The first category addresses the overall design problem and concentrates on the formulation of top-down, iterative, optimization-based approaches (e.g., Ashayeri and Gelders, 1985; Gray *et al*. 1992, Rouwenhorst *et al*. 2000). Certainly, the overall design problem is complex enough to warrant a decomposition approach. For the most part, these models provide a generic conceptual framework for the design problem. Beyond this framework, however, validation of these types of models is a significant issue. Even in the case when a proposed design procedure is applied to a case study as with Gray *et al*. (1992), it is not always clear how results can be validated beyond the case study domain.

The second category addresses specific design sub-problems, for example, design of a storage system or an order-picking system. Examples include (Bozer and White, 1996; Goetschalckx, 1992; Jarvis and McDowell, 1991; Rosenblatt *et al*., 1993; Yoon and Sharp, 1996). These models are useful. However, it may be difficult to integrate models for different sub-problems into an overall design procedure due to different assumptions or data representations.

In our interaction with industry practitioners, we have discovered that expert practitioners rarely use the results of the extensive research done in the warehouse design domain. Rather, they rely on their experience and expertise. One reason behind this phenomenon is that most research results have not been implemented as computational tools in forms that are amenable to use by the practitioner. In fact, experts commonly use *ad-hoc* desktop computing tools such as spreadsheets and databases. A more fundamental reason is the lack of a unifying procedure that integrates conceptual design frameworks with models for specific design sub-problems, through the application of a common database architecture. In this paper, we seek to understand and formalize the procedures used by expert designers, as a contribution toward the specification of a science-based design procedure for warehousing systems.

B. Design Expertise

Design expertise is an important consideration in engineering design. As a designer gains experience in his or her domain, this experience is assimilated into knowledge. Vincenti (1990) describes a model of how this process occurs in the aerospace design domain. In the warehouse design domain, this experience and knowledge may be augmented by the use of a well-established design procedure such as Systematic Layout Planning (Muther, 1973). In any case, over time an expert develops methods for decision-making, as well as specific information requirements that are integral to design decisions. Information is key to the design-decision-making process (Hazelrigg, 1996), and in the warehouse design domain, today's computerized information systems provide the designer with large historical datasets that can be used in the design process. We seek to formalize the decision-making process and sequence, the information used, the criteria applied, and the evaluation methods utilized. Green (1992) outlines a number of relevant attributes possessed by experts: supplying context, ordering decisions, abstracting parameters, and classifying heuristics.

Clearly, it is not a straightforward matter to characterize the decision processes used by experts. In fact, it can be the case that there are differences between an expert's description of these processes and the actual processes used by the expert (Speelman, 1998). For these reasons, we are using the methodology of ethnographic studies (Bucciarelli, 1987) to develop a characterization of expert design processes. Ethnography has a long tradition of application in the engineering design domain (Court *et al*., 1995; Hubka *et al*., 1987; Pejterson *et al*., 1995; Ullman, 1997). In an ethnographic study, designers are studied as they perform design work, and observational data are collected. The data from different case studies are then analyzed and synthesized into a model. In this study, we are concerned with the following types of data: (i) the work domain (i.e., prototypical work situations and functions), (ii) information flows and decision and control functions, and (iii) cognitive strategies and styles used by designers (e.g., to collect data, discern preferences, formulate and solve design problems, and generalize from the experience for the future).

3. A PROCESS MODEL OF DESIGN

A. Model Structure

Based on initial discussions with design experts in a series of one-day focus groups, we hypothesized an initial structure for the warehouse design process. In this process, the design has a client, a term used to represent the person or organization for whom the design is performed. The designers may be part of a consulting group, or they may be from a third-party logistics provider or an internal corporate design group. The design process occurs in at least two phases. In the first, the designers perform preliminary work to provide scope for the design. The result of this phase may be a proposal or project definition document, to be accepted by the client after potential modification. The second phase consists of the design work itself. The result of this phase consists of a design specification. Here, we do not consider a potential third phase, which includes design implementation (or implementation support).

Within the design work phase, there is a structure that describes actions taken by an expert designer. This structure describes information flows and decision processes and sequences. Our initial model for this structure is shown below in Figure 1.

In the first step of the process, the designers requests data from the client, consisting of four major categories: (i) all products (stock-keeping units or SKUs) to be handled by the warehouse, (ii) vendor shipment history, (iii) inventory history, and (iv) customer order history. Of course, all data may not be available, in which case estimates must be used. In addition, growth in business must be projected. The designers then engage in a process known as profiling, in which the data are analyzed for important patterns that can affect the design. Much of profiling consists of Pareto analysis, for example, to identify important SKUs that may need to be treated differently than the general SKU population. The designers, based on their expertise, use the results of profiling to generate functional requirements and functional costs. This process is generally implicit. The output of the process is what we call an architectural design, or a specification of the high-level functions to be supported by the warehouse. Features of this specification include, for example, whether the warehouse should have a forward pick function(s) for high-volume SKUs, or whether the warehouse should batch orders during the order-picking process, which implies the need for an order sortation function. A forward pick function enables more efficient order picking of the SKUs stored there, while batching is another strategy to improve order picking efficiency. Once the architectural design is specified, the focus shifts to the specification and optimization of the systems that implement the needed functions, for example the selection, sizing and configuration of storage technologies. Of course, the entire process is iterative in nature, and different alternative architectural designs are likely to result. Moreover, while this structure applies mainly to the design work, its first stages can be used to describe the more superficial process of project scope specification.

B. Case Study and Process Model

Based on a case study and other interactions with expert designers, a process model of the design model has begun to emerge. The case study involves the redesign of an existing apparel warehouse to meet a projected increase in demand. Redesign is a common type of design problem in facility design, since facilities are large capital assets, and since it generally is sensible to adapt them to meet changing requirements. The design team in this case was a team of consultants. Details of the case study and process model are described in Zerangue (2001) and Zerangue *et al.* (2001). However, the approach used by the design team followed roughly the hypothesized design process structure, and in this sense confirms the hypothesis.

At the architectural level, design decisions focused in several areas. We mention four here. The first was whether to redesign all processes in the warehouse, or to concentrate on redesigning or reconfiguring a subset of them. The second related to the usage of a novel storage technology – trailers. The warehouse already was operating beyond its capacity, so trailers were used to store inventory. The architectural decision involved discontinuing their use in favor of another type of storage, or making their use more efficient to accommodate the additional inventory needed for the projected growth in business. Third, since the existing warehouse mostly was manual, an architectural decision involved installation of automated shipping/receiving and storage systems to improve throughput. The fourth architectural decision involved segmenting the customers or eliminating broken case orders from small customers, either of which would involve designing a new process or processes for the warehouse. Through profiling and analysis, as well as expertise, the designers developed a set of alternatives and focused next on system specification and optimization.

In the end, the alternative selected embodied the following architectural decisions: (i) the focus was on redesigning and reconfiguring a subset of warehouse process; (ii) the trailers were kept, but their operation was redesigned to be more efficient; (iii) limited automation was recommended in the receiving process to make it operate more efficiently; and (iv) limited customer segmentation was recommended. Since this was a redesign, the degrees of freedom in the design process were somewhat limited. Once the architectural design decisions were made, the systems affected were studied and recommendations were made to select equipment, reconfigure systems and improve operation. The designer also performed rough-cut analysis using spreadsheet tools to determine that the recommended system design would allow the warehouse to meet the increased growth in its business.

An important feature of the case study involves interaction with the client, both in terms of gathering data and determining the client's preferences about certain alternatives. In this instance, since the designers were recommending a design as consultants, the designers made extensive efforts to discern the client's preferences in terms of economic and labor considerations, as well as process and equipment decisions.

If it is abstracted, the design process can be considered to consist of activities and work products. An activity may include data gathering, profiling or decision-making, while a work product is a high-level result needed to continue the design process. Generally, a work product results from a set of decisions and includes such items as the project definition, major design alternatives and the final design specification. A general pattern of activities and work products is shown in Figure 2, which illustrates the activities that were observed to be involved in yielding a work product. This pattern is a sequence that includes iterations between steps, and it also shows the increasing importance of expertise closer to completion of the work product. This sequence can be considered as a generic building block for the overall design process model, which we hypothesize as being the proposed design process structure.

4. COMPUTATIONAL DECISION SUPPORT TOOLS

An important consideration in our efforts is the specification of computational tools to aid the designer. Currently, many expert designers use *ad-hoc* spreadsheet and database tools developed during the course of previous design projects. The goal is to provide a web-based platform hosted on a central server that would be accessible to remote designers in the field, who would access it via a "thin-client" web browser. One advantage to this arrangement is that powerful third-party design decision-aiding technology could be hosted on the server instead of on individual client machines, or that such technology could be accessed through a third party server. We currently are using WebObjects™ from Apple Computer as a development platform. WebObjects™ is an application server that facilitates development of websites using database interaction and secure login.

The computational tools will be implemented using a common database structure currently under development. This database structure, based on an object model of warehousing systems (Govindaraj *et al*., 2000), is designed to provide a consistent data representation for the different design decisions that need to be made as a designer progresses through the different abstraction levels of the design process. The design database is based on a functional flow representation of the warehouse facility as the fundamental model of material flow through the functional areas of the warehouse. It includes information on products, orders, handling units, product location assignments, storage and handling equipment, labor, layout and zones, operating policies and costs.

Figure 3 shows a proposed computational architecture for the decision support tools. The current focus is on profiling, specification of the function flow network, selection and configuration of storage and handling equipment, and costing. At the beginning of a design, the user enters input data into the system, including SKU data, vendor shipment history, inventory history and customer order history. In addition, if there is an existing building or site, the user enters data about it. The system must enforce a standardized format for the data; hence, the user may need to engage in pre-processing, for example, to transform SKU data from a client into the required format. The profiling module will provide the user with functionality to profile the input data from the client, in support of making initial decisions about the types of architectural questions to be addressed. The functional flow analysis module will allow the user to specify the functions to be supported in the warehouse, size the capacity needed for each function, map those functions to areas in the warehouse layout, and analyze the material flow between areas according to the possible handling units (pallets, cases and items). This module primarily will support architectural decision-making and analysis. The storage and handling mode modules will allow the designer to specify equipment technologies, size them with respect to the capacity needed, and configure their implementation. For example, consider the design of a pallet storage area using the storage mode module. The designer might select from floor-stacking, rack storage or deep-lane storage. If floor-stacking is selected, the module should compute the number of pallets to be accommodated, and it should aid in configuring the lane depths for the SKUs to be stored. The costing module will allow the user to compute various cost figures for the system, ranging from capital investment, to operational costs such as labor.

As an example of the functionality to be supported, consider the profiling module. A prototype of the module has been developed using Microsoft® Access (McGinnis and Mulaik, 2000). Given a set of order data, a designer typically wants to know whether to consider a forward pick function (or functions) to facilitate the picking of fast-moving SKUs. The standard format for order data is a table whose records consist of lines on the orders and have the fields [`SKU Number|Order Date|Customer|Quantity|Handling Unit`]. Assuming a reasonably long horizon for the order data (e.g., the previous year), the frequency with which a particular SKU appears in this order table measures the frequency with which it is ordered, and hence is a measure of the order picking activity (labor cost) associated with the SKU. Using the table entries, a sort operation can be performed to show the SKUs in decreasing frequency with which they are ordered. A graph showing this sort is shown in Figure 4. The *x*-axis graphs the SKUs as sorted by frequency, with a SKU population totaling 10,000. The *y*-axis graphs the corresponding cumulative percentage of the lines represented. An expert designer may look at the top at the top 20% of the SKUs in terms of order frequency (i.e., the 20% of SKUs closest to the origin). Matching this with the *y*-intercept, the designer can determine a rough estimate z of the skew in the distribution of this graph. If $z > z_0$, the designer may decide that a forward pick function is likely warranted, and that further investigation is needed to specify its desired characteristics. One observed value of z_0 is 80%.

A similar type of profiling can support decisions regarding the selection of storage modes. If the order data are partitioned according to handling units, consider all SKUs that are stored and shipped in pallet quantities. Using essentially the same graph as in Figure 4, except graphing only the SKUs under consideration, an expert designer may use breakpoints in the graph to partition the SKUs further into sets that are assigned to different storage modes. This type of analysis seeks to match storage modes to SKU "families" based on the ability of the mode to facilitate order picking (i.e., assign fast-moving SKUs to those modes that facilitate efficient order picking). Figure 5 shows an example of this type of profiling.

5. CONCLUSION

This paper has discussed the development of a process model of warehouse design based on the methodology of ethnographic studies. The goal behind this effort is to characterize the design processes used by industry experts, in an effort to formalize a model that can be used to link research results with industry practice, and to identify computational tools that can aid in the design process. The ethnographic studies methodology was selected because it provides independent observations of experts at work as a basis for the model. Based on a case study and other interaction with industry experts, we have formulated an initial model and are in the process of identifying specific computational tools to use in the specified decision support architecture. Additional case studies will be used to refine and enhance the model and improve the computational tools to be implemented.

6. ACKNOWLEDGMENTS

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8. FIGURES

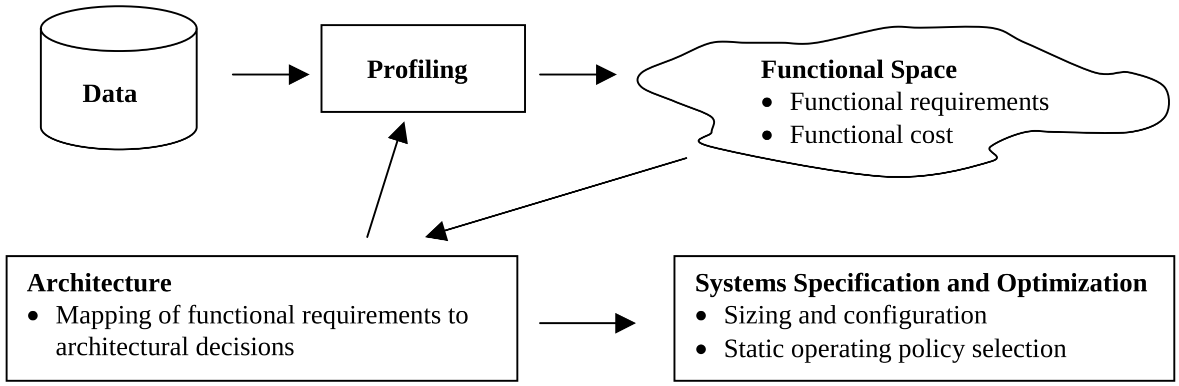

Figure 1. Structure for design process

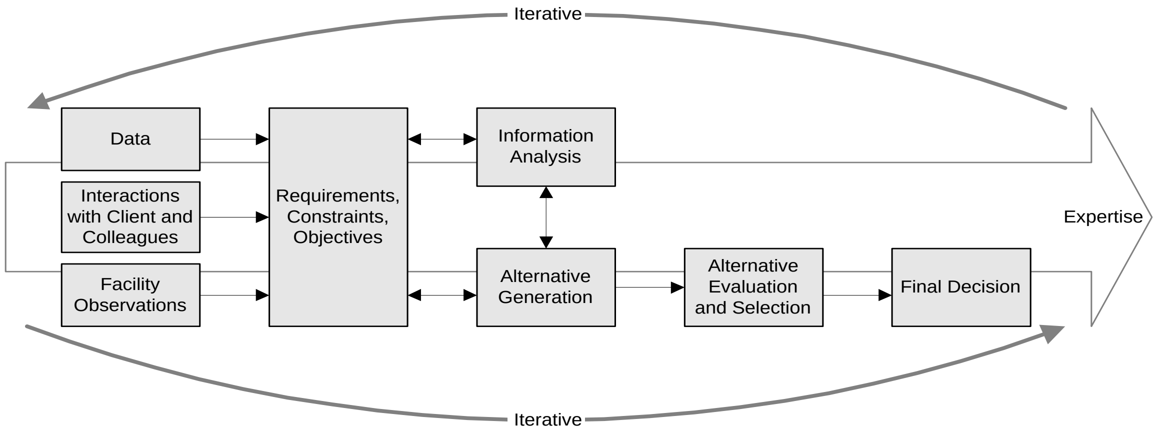

Figure 2. Work Product Activity Sequence

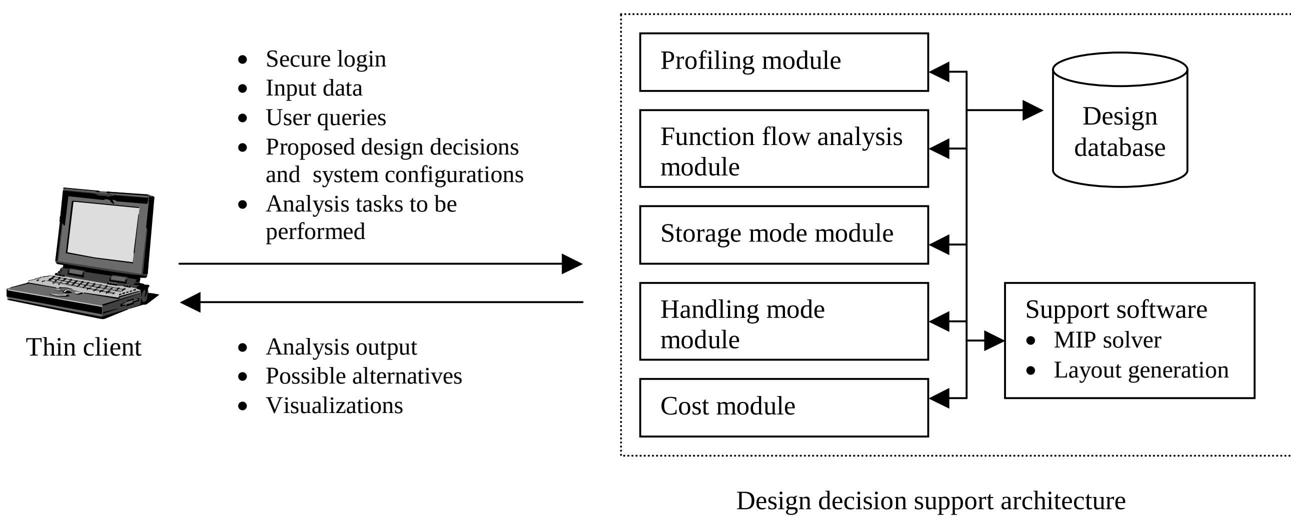

Figure 3. Proposed decision support architecture

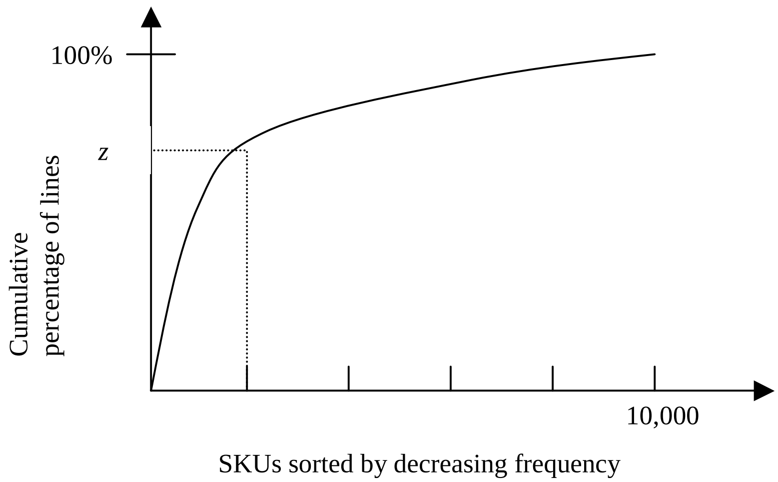

Figure 4. Profiling in support of forward function decision

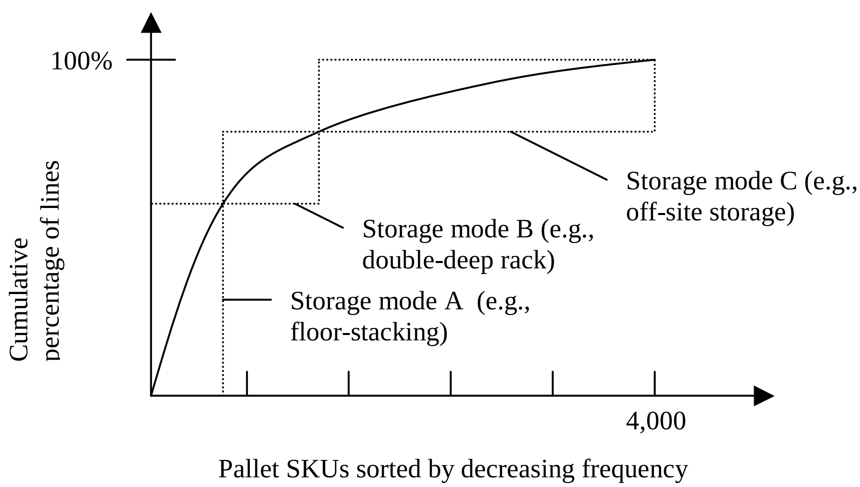

Figure 5. Profiling in support of storage mode selection