Expert Design of Industrial Systems: Formalizing the Design Process

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Abstract

A variety of analytic models have been developed by researchers to solve problems in the area of industrial systems design. Examples include storage technology selection models, capacity sizing models, and labor allocation models. Yet practitioners often do not use existing research results, instead relying on expertise and past experience. This research seeks to understand and formalize the process of design as it occurs in practice, and eventually link these results with existing research. Our approach is to study expert designers as they design facilities, focusing on warehouses, with the goal of formalizing design processes and developing methodologies and computational tools to aid in the design process. In this paper, we describe our research methodology, based on the concept of ethnographic studies, and we discuss results obtained to date. These include definitions of functional requirements, specifications of data used, and processes for formulating and evaluating design alternatives. We conclude with a discussion of the types of decision support tools that we are working to create.

Keywords

Expertise, ethnographic studies, industrial systems design, formalized design process.

1. Introduction

Design of industrial systems has been a hallmark of industrial engineering research, focusing on design of factories, warehouses and supply chains (e.g., [12], [13]). This area has witnessed a wealth of published research literature, providing valuable results to solve a number of problems. This paper addresses the relationship between these research results and the practice of design in industry. Here, for the sake of being specific, we focus on warehouse systems.

In our interaction with industry practitioners, it has become apparent that there is a disconnect between these research results and the practice of design. Essentially, practitioners, many of whom have accumulated expertise through years of experience, simply do not use most of the extant research. They typically rely on their knowledge from past experiences and on *ad-hoc* analysis techniques to perform design work. This applies to some extent even to those designers who use a well-established design approach (e.g., Systematic Layout Planning [12]). There are at least two reasons for this. First, from a practical perspective, research results are not widely available as computational tools that can be used by practitioners. Second, and more fundamental, there is a disconnect between the *process* of design as it is practiced and the *formulation* of design research results. In the warehousing domain, the literature has concentrated in two main areas: (i) generic frameworks for design (e.g., [1], [17]), and (ii) specific models and tools to solve specific types of problems (e.g., [4], [7], [16], [21]). In general, these two types of research results are not well integrated in the sense that there is a not a direct computational design procedure using both types of results. We might envision such a procedure that would (i) start from one of the generic frameworks, (ii) perform intermediate calculations, (iii) finish by solving specific design sub-problems such as storage technology selection, capacity sizing, layout or labor allocation, and (iv) output a final design. Such a procedure is needed by practitioners. Since it does not exist, the design practitioner faces an uncertain environment when using research results. Hence, designers, who usually operate under significant time constraints, create their own *ad-hoc* approaches that produce acceptable results.

What can be done to address this disconnect? Since research results should be useful to the design practitioner community, the obvious answer is to create a formalized warehouse design methodology that incorporates both types of research results. This is a formidable objective. An alternative approach is to understand and formalize the process of design as it is practiced by industry experts, and then link this formalization with existing and new research to form a design methodology. This paper explores this second approach to the problem. As a starting point, we know that the results published in the research literature are well understood, because they are based on mathematical formalisms. What is not so well understood, however, is the process used by industry practitioners to perform design. Hence, we seek to understand this process by observing expert designers in action. In addition to formalizing this type of design process and linking it to existing research, our goal is to create computational tools to aid industry designers.

The remainder of this paper is organized as follows. Section 2 discusses perspectives on expertise and design of industrial facilities, with a focus on warehouse systems. Section 3 describes our methodology, as well as our model to date of the expert design process. Section 4 outlines computational tools based on this model to aid the design process. Finally, Section 5 provides conclusions and a discussion of future research.

2. Perspectives on Expert Design

In this section, we discuss the warehouse design problem, followed by engineering design expertise in general. We then describe a strawperson model of the expert design process based on interaction with industry experts.

2.1 The Warehouse Design Problem

A warehouse receives inbound shipments from a variety of suppliers and prepares outbound shipments to a variety of customers. These shipments consist of varying numbers and quantities of products, commonly referred to as stock keeping units (SKUs). A warehouse stores SKUs in various quantities to offset mismatches in the quantities of SKUs received vs. SKUs shipped at any given time. The warehouse design problem is to specify the layout and material flow network of the facility, the processes to be used in storing and handling material, and the systems that implement these processes. The underlying objective is to provide functionality that meets the requirements of the facility as expressed in terms of capacity (ability to handle orders) and cost (budget, return on investment, etc.). To be sure, the type of warehouse has a significant impact on the functions to be supported and the processes and systems to be designed and implemented. In addition, there is the issue of greenfield design vs. redesign of an existing facility. These must be factored into formulations of the design problem, as well as models of design processes.

2.2 Design Expertise

Design is a fundamental process in engineering and has been studied extensively. Citing the full extent of the literature is outside the scope of this paper. Instead, we discuss expertise in design as it is found among industry practitioners. Clearly, decision-making is critical to design, and information is key to the decision-making process [8]. In our definition of expertise, the expert designer has considerable knowledge and expertise based on experience from a number of design efforts. This knowledge and expertise can be applied in new situations to improve the quality of a design or reduce the time needed to generate a design. Expertise may be institutionalized in some sense within an organization consisting of multiple designers. Typically, though, expertise is not explicit and consists of knowledge held by the expert. An expert may not be fully able to articulate a precise mathematical reason for a particular design decision. However, the expert makes such decisions on the basis of past experience (e.g., what has worked before in similar situations). In novel situations, the expert is able to extract the situation and design decisions made so that they become part of his or her experience base, and hence future expertise. In one instance with which we are familiar, an expert designer encounters a client who uses a very unusual storage mode for warehouse inventory (truck trailers). While the designer would never have thought to design a warehouse using this storage mode, he does include this storage mode in the final design (modified from the way in which the client originally used it). This storage mode now becomes part of his expertise. Vincente [20] synthesizes a model of how engineers accumulate design knowledge in the aerospace domain that it is quite relevant to the notion of design expertise.

2.3 A Strawperson Design Process

Based on preliminary research and several one-day brainstorming sessions with a industry partners, we have formulated a description of how the expert design process works, at least in many instances. A warehouse is designed for a client or owner. We use the term client in the generic sense to represent the person or organization for whom a design is done. The designer(s) may be consultants, third-party logistics providers, or an internal corporate design group.

The designer requests four major types of data: (i) all SKUs to be handled by the warehouse, (ii) vendor shipment history, (iii) inventory history, and (iv) customer order history. If these items are not available, the client is asked to provide estimates. In addition, the client is asked to project future growth over a time horizon. The process begins with the computing of routine statistics (i.e., Pareto analysis of order history by SKU, by product family, by cube shipped, etc.). This activity is called profiling. The designer may concentrate on the pick frequency or on the cube movement rate of the SKUs. Through the process of profiling, a designer determines what high-level functionalities are required from the warehouse in terms of product handling and storage. At present, this is based on the designer's expertise, and is not captured in an explicit model. The output of this process is what we call architectural design (i.e., a high-level specification for the facility, such as whether to have an order sort and accumulate function, or a forward pick area, or automated storage systems). The designer then focuses on specifying and optimizing specific warehouse systems that will implement the desired functions (e.g., particular storage systems). The design process is shown in Figure 1.

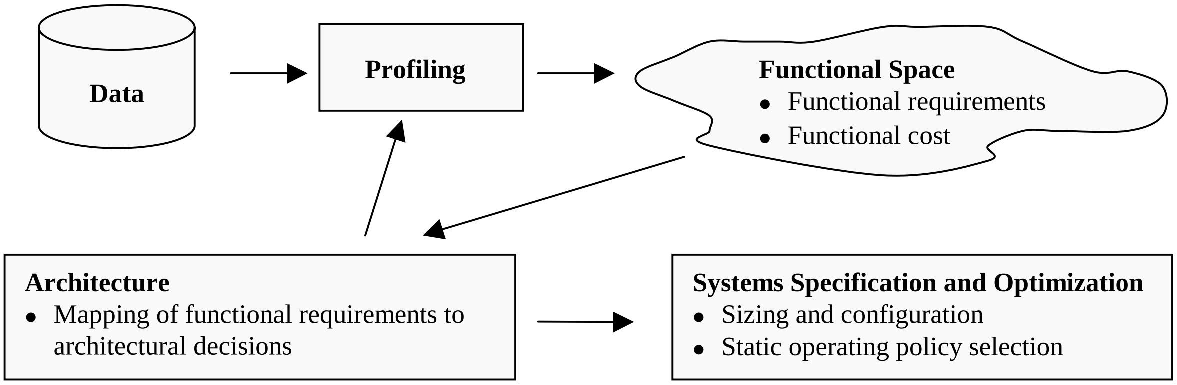

Figure 1. Warehouse Design Process

We can identify complex trade-offs that designers consider. For instance, all things being equal, fewer transactions are preferred to more. However, not all transactions are equally costly. Picking a case or item from reserve pallet storage is an expensive transaction. Having a forward pick area for this transaction reduces its cost, but one incurs costs for establishment of this area and for on-going replenishment from reserve storage. The designer must decide if there is enough SKU volume for these transactions to justify the cost of having a forward pick area. In addition, one must decide if there is enough complexity in the order transactions to justify multiple forward pick areas, each supporting a different purpose (e.g., single-item orders, correlated multi-item orders) and possibly a different storage technology (e.g., flow rack, bin shelving, pallets stored on the floor).

3. Toward a Conceptual Model of the Design Process

Given that there is an expert design process, or that there may be several, how does one understand it and formalize it? In this section, we discuss our methodology, which uses ethnographic studies to catalog the decision-making behavior of expert designers at work. We also discuss our results to date in terms of a conceptual model of an expert design process.

3.1 Ethnographic Studies

The research approach used here differs from most facility design research. In most research, the approach is to model an existing or proposed physical process and propose a solution procedure. Here, our concern is to understand what are the critical decisions in the design process, how they are made by experts, and what criteria are used. In other words, we must study the cognitive processes and behavior of expert designers as they engage in the design process. Thus, rather than use typical methods and tools such as economic, optimization, or analytic models, we employ the methodology of ethnographic studies [3], [5]. Here, experts are studied "in the field," as they perform their work, and observational data are collected. In our case, data include such elements as decisions, decision sequences, information used, etc.

Research on models and theory of design via case studies and ethnographic studies has a long tradition. Hubka and Eder [10] and Hubka *et al.* [9] discuss research intended to develop formal models and theories of design and to assist designers using a collection of examples and cases. Ullman *et al.* [19] and Ullman [18] develop a model of mechanical design from empirical data. Other empirical and ethnographic design studies include [2], [6], [14]. These efforts involve development of computational design decision support systems. A key component of the ethnographic studies performed here is the cognitive systems engineering problem [15] of understanding and characterizing the domain. In performing an ethnographic study of expert warehouse designers, we are concerned with identifying: (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 and organize data, discern client preferences, formulate and solve design problems, and generalize from the experience for the future).

3.2 Model of the Design Process

While we are only in the early stages of this research, our results to date have yielded an initial model of the "expert" design process, based on a case study involving redesign of an apparel distribution center. Obviously, it must be elaborated, refined and probably modified through additional case studies. However, we can outline the generic aspects. It should be noted that this outline serves only as an overview and does not capture the details of the process observed.

The design team starts by assessing the problem so as to formulate the scope of the design. This yields a problem definition, agreed upon by both the client and the design team. This process involves significant interaction with the client to gather data and determine the client's needs, preferences and goals. A simplified overview is shown in Figure 2.

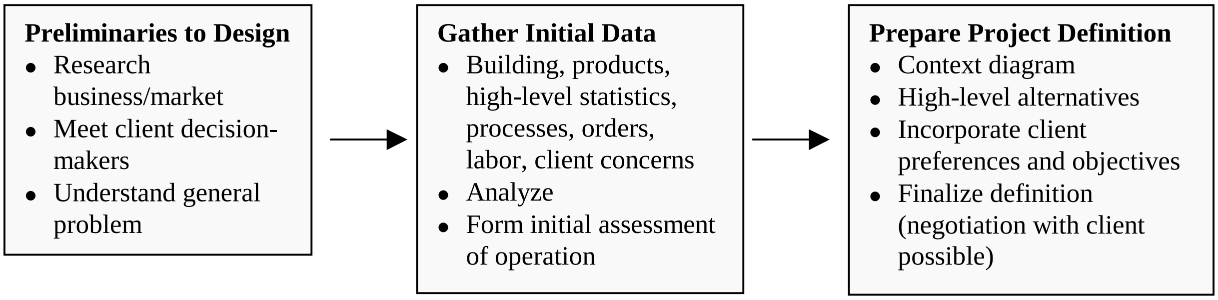

Figure 2. Initial model of preliminary design process

Once the problem has been defined, the design process shifts to more in-depth data requesting, analysis and identification of major alternatives, etc. The expert designer has a pre-specified list of data to be requested. However, depending on circumstances of a particular design, other data may be requested, as well. In the development of the architectural design, considerable brainstorming activity takes place. Constraints are identified (e.g., building expansion constraints in a redesign effort). Relationships between activities are examined, in an effort to develop a high-level design to accommodate, for example, a need for batch-picking by providing an order sort and accumulate system. Alternatives are generated, and often there is opportunistic investigation of alternatives that might not be readily apparent. Once major alternatives are identified, they are evaluated based on whether they meet expected capacity requirements and cost requirements. Continued interaction with the client occurs to gather information on client needs and preferences and refine criteria by which design decisions are made. Once an alternative is selected, sub-systems are specified in detail, and the alternative is presented to the client for review and possible modification. Of course, iteration occurs during this process, which is shown in Figure 3.

4. Computational Tools to Aid in Design

Due to data availability, designers perform increasingly sophisticated analyses. However, due to time constraints, such analysis typically is rather limited, for example, in the number of scenarios evaluated. Improved computational tools would allow more options to be evaluated, for instance, hence potentially improving the final design. In this section, we describe the types of computational tools that we intend to specify and implement. This list may be expanded or modified during the course of on-going research, but it illustrates our approach to date.

- *Order and activity profiling.* Designers need to understand patterns of orders and warehouse activities to support specification of architectural design. A prototype application to perform profiling has been developed using Microsoft® Access [11].
- *Data inaccuracy detection and rectifying.* Often, while one might have an extensive dataset, much of the data simply are incomplete or not accurate. A designer certainly could use a tool to identify inconsistent data (hence highlighting potential inaccuracies), and perhaps perform some type of data rectifying function (e.g., generate representative data to replace inaccurate or missing data). For example, one might sum individual data elements (e.g., sales from entries in the order database) and compare the sum against a known quantity (e.g., total sales) to determine the completeness of the order data.

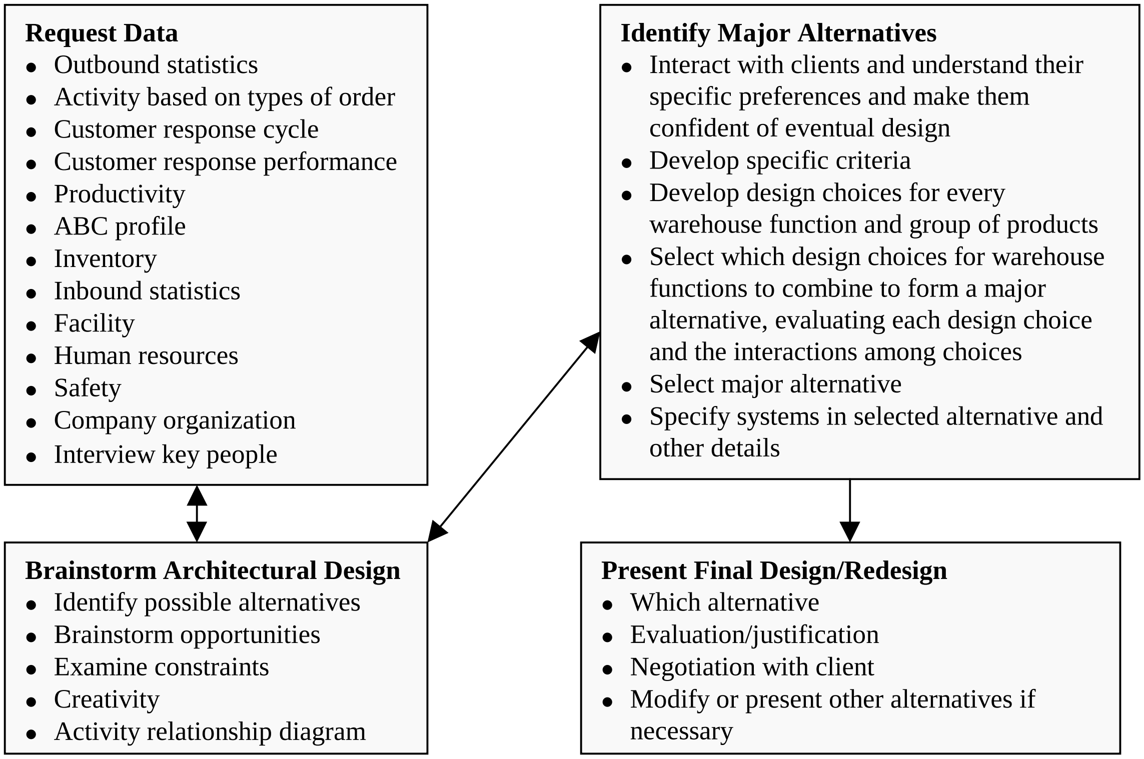

Figure 3. Initial model of main design process

- *Throughput and transaction analysis*. For a given alternative design, tools are needed to support evaluation of throughput capability and distributions of expected transactions.
- *Utilization analysis*. For a given alternative design, tools are needed to support evaluation of the expected utilization of resources such as dock doors, material transport and labor, as well utilization of building cube.

It should be stated that many designers have *ad-hoc* tools using spreadsheets and similar technologies to perform subsets of this list. However, their tools usually have limited functionality and do not incorporate research results that would be of use. To improve this situation, we envision these functionalities for the types of tools that we plan to create, in addition to linking them with research results:

- *Integration*. These tools should be integrated with one another via a common database structure to ensure consistency across tools.
- *Configurability*. The tools should be designed up-front to support specific types of what-if analysis that designers typically use. This type of what-if analysis must be determined from analysis of case studies.
- *Trade-off evaluation*. Tools to help designers evaluate trade-offs in design decision-making would be of use. Often, these trade-offs are not explicit or easily computed. Hence, a goal is to make such trade-offs explicit.
- *Web-enabled for remote use*. Designers often operate in the field, where they may have access to a computer, but not necessarily access to the tools or datasets needed for specific analyses. The increasingly ubiquitous nature of the worldwide web enables powerful applications and databases to be installed on a server and accessed by a "thin-client" machine. In addition, a web-enabled system would allow a designer to use third-party design technology or decision support software hosted by the third party as an application service provider. Finally, a web-enabled system is amenable to eventual use in a collaborative design environment. We are currently using WebObjects™ technology from Apple Computer to investigate design and implementation issues associated with computational tools that support design of industrial systems and database integration.

5. Conclusions and Future Work

This paper has explored formalizing the decision processes used by industry experts in the design of industrial systems. In particular, we have focused on warehouses, and we have used an ethnographic approach. We believe that there is significant potential to improve the state-of-the-practice in industrial system design by (i) understanding how expert designers operate, (ii) linking this understanding to research results, and (iii) specifying computational aids for designers based on the model generated. Future work involves collecting more case study data, further development of our models of expert design, and implementing the desired computational tools.

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References

1. Ashayeri, J. and Gelders, L. F., 1985, "Warehouse Design Optimization," *European Journal of Operational Research*, 21, 285-294.
2. Blessing, L. T. M., 1995, "Using Protocol Analysis for Evaluating a Design Support Tool," *Proceedings of the 10th International Conference in Engineering Design: Design Science for and in Design Practice*, Prague.
3. Blythin, S., Rouncefield, M., and Hughes, J. A., 1997, "Never Mind the Ethno' Stuff, What Does All This Mean and What Do We Do Now: Ethnography in the Commercial World," *Interactions*, 4(3), 38-47.
4. Bozer, Y. A. and White, J. A., 1996, "A Generalized Design and Performance Analysis Model for End-of-Aisle Order-picking Systems," *IIE Transactions*, 28, 271-281.
5. Bucciarelli, L. L., 1987, *An Ethnographic Perspective on Engineering Design*, M.I.T. Press, Cambridge, MA.
6. Court, A. W., Culley, S. J. and McMahon, C. A., 1995, "A Methodology for Analysing the Information Accessing Methods of Engineering Designers," *Proceedings of the 10th International Conference in Engineering Design: Design Science for and in Design Practice*, Prague.
7. Goetschalckx, M., 1992, "An Efficient and Interactive Adjacency Graph Heuristic for Rapid Prototyping of Facilities Design," *European Journal of Operational Research*, 304-321.
8. Hazelrigg, G. A., 1996, *Systems Engineering: An Approach to Information-Based Design*, Prentice Hall, Upper Saddle River, NJ.
9. Hubka, V., Andreasen, M. M. and Eder, W. E., 1987, *Practical Studies in Systematic Design*, Butterworths, London.
10. Hubka, V. and Eder, W. E., 1987, "Scientific Approach to Engineering Design," *Design Studies*, 8(3), 123-137.
11. McGinnis, L. F. and Mulaik, S., 2000, "Your Data and How to Analyze It," *Proceedings of the Industrial Engineering Solutions 2000 Conference*, May, 2000, Cleveland, OH.
12. Muther, R., 1973, *Systematic Layout Planning, 2nd edition*, Cahners Books, Boston.
13. Nadler, G., 1973, *Production Systems Design with the IDEALS Concept*, Industrial and Commercial Techniques, London.
14. Pejtersen, A. M., Sonnenwald, D. H., Buur, J., Govindaraj, T. and Vicente, K. J., 1995, "The Design Explorer Project: Using a Cognitive Framework to Support Knowledge Exploration," *Proceedings of the 10th International Conference in Engineering Design: Design Science for and in Design Practice*, Prague.
15. Rasmussen, J., Pejtersen, A. M. and Goodstein, L. J., 1994, *Cognitive Systems Engineering*, John Wiley, New York.
16. Rosenblatt, M. J., Roll, Y. and Zyser, V., 1993, "A Combined Optimization and Simulation Approach for Designing Automated Storage-Retrieval Systems," *IIE Transactions*, 25(1), 40-50.
17. Rouwenhorst, B., Reuter, B., Stockrahm, V., van Houtum, G. J., Mantel, R. J. and Zijm, W. H. M., 2000, "Warehouse Design and Control: Framework and Literature Review," *European Journal of Operational Research*, 122, 515-533.
18. Ullman, D. G., 1997, *The Mechanical Design Process, 2nd Edition*, McGraw-Hill, New York.
19. Ullman, D. G., Dietterich, T. G. and Stauffer, L. A., 1988, "A Model of the Mechanical Design Process Based on Empirical Data," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 2(1), 33-52.
20. Vincente, W. G., 1990, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*, Johns Hopkins University Press, Baltimore.
21. Yoon, C. S. and Sharp, G., 1996, "A Structured Procedure for Order Pick System Analysis and Design," *IIE Transactions*, 28, 379-389.