2010

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Abstract

It is our opinion that existing research is not sufficient to support the design of a warehouse. As a result, facility designers that work in practice are left to face the design process with their own methods. These methods are in stark contrast to the analytical models developed in academia in that they are highly based on empirical observations. Supported by a collection of empirical observations, facility designers who work in practice employ an *ad hoc* design process. We present a design process based on empirical observations and then formalize it so that it can be taught and used. We illustrate the process with an example and discuss ways in which analytical methods can be used to supplement the process and improve the design. We conclude by describing additional work that is required if the design process is to be realized.

1   Introduction

Warehouse design is often described as being part art and part science [7]. The science component of the design process involves the application of data analysis, analytical models for particular aspects of the design, and simulation modeling for evaluation of design alternatives. In many ways this follows the standard engineering design process of define the problem, analyze the problem, generate alternatives, evaluate alternatives, select the alternative, and implement the design [10]. The acknowledged most difficult task of the engineering design process, and the one referred to as the art component above, is

the generation of alternatives. Many researchers have attempted to aid the generation of alternatives by providing an approach for doing so; most recently, Baker and Canessa [2].

It is our opinion that existing research [5, 6] is not sufficient to support the design of a warehouse. This opinion is based on our (nearly 100) collective years in designing facilities. We find the research literature to be very uneven, with many papers treating several very small aspects of the problem while other necessary areas have received no attention. Even when there are multiple models that can support a design effort, the basis and assumptions upon which the models are based are inconsistent, which further complicates this task.

As a result, facility designers who work in practice are left to face this design process with their own methods. These methods, in stark contrast to the analytical models developed in academia, are heavily dependent on empirical observations. Supported by a collection of empirical observations, the facility designers who work in practice employ an *ad hoc* design process. Although it is *ad hoc*, the necessity of project requirements means it is performed hundreds of times a year (and we would argue, typically, with success). It is worth noting that because the designs result from different sets of empirical experience (and possible biases), they are often quite different from one another. This is not a desirable state of affairs. On the other hand, there is potential to change this as the research community is producing good research and appears eager to produce research that could also be applied.

The purpose of this paper is to pose a philosophical question: Is academia ready to meet the practice world half way? That is, can academia in warehouse design accept an empirical basis for modeling a facility (the strength of those working on these problems in practice) and improve that process through a systematic, repeatable adaption of what is currently practiced, and the ability to develop models that complement and extend the empirical basis for the models? (We note that other engineering disciplines commonly integrate material from handbooks with the results from mathematical models.)

To assist warehouse design academics in answering this question, our paper presents an initial attempt to produce a systematic, empirically-based approach to warehouse design. We focus the paper most closely on facilities that receive pallet loads of products packed in cases and fulfill orders for case quantities. Our approach will combine elements like the functional flow network presented in [7], which itself was inspired by designers working in practice, with comparison tables like those of Fortna Inc. that appear in [10]. It is intended in our approach that both elements would be refined for particular sections of the warehouse with empirical data. For the paper, data are supplied by the lead author, a practicing consultant (but the focus of evaluating the work should be on the thoughts contained in the paper and not the data in the tables). We also note that the focus of our approach is on a "high-level" or "first-cut" design, which we realize in practice would be improved by optimizing sub-systems within the overall high-level design.

After presenting our empirically-based approach, we apply it to an example problem for a warehouse that receives pallet loads of cases and fulfills outgoing case orders. A standard size pallet is assumed throughout the warehouse. The example problem is derived

from a consulting project led by the lead author, covering a 100,000 square foot addition to an existing manufacturing facility.

We believe the paper will be of interest to academics for use in teaching and in research. In terms of the latter, we expect many opportunities will exist to improve the design process andto use sophisticated modeling in refining and extending the empirical observations. Moreover, an examination of the process will reveal multiple opportunities for existing research to answer specific questions that are raised as part of the design process (e.g., the forward-reserve problem, lane depth specification, etc.).

2   Related Research

A comprehensive review of the warehouse design research literature may be found in [6]. In [6] the authors categorize the warehouse design research literature into: overall structure, department layout, operation strategy selection, equipment selection, and sizing and dimensioning. Along with its companion survey article on warehouse operations [5], the authors examined over 250 research articles and benefited from prior surveys in the field [3, 11, 9].

The category of research that aligns most closely with our work is that of *overall structure*. Notably, in [6], only three papers fall into this category. From [6]:

> Park and Webster [8] assume the functions are given, and select equipment types, storage rules, and order picking policies to minimize total costs. The initial investment cost and annual operations cost for each alternative [are] estimated using simple analytical equations. Gray *et al.* [4] address a similar problem, and propose a multi-stage heuristical approach that uses simple calculations to evaluate the tradeoffs and prune the design space to a few superior alternatives. Simulation is then used to provide detailed performance evaluation of the resulting alternatives. Yoon and Sharp [12] propose a structured approach for exploring the design space for order picking systems, which includes stages such as design information collection, design alternative development, and performance evaluation.

More recently, two published papers directly relate to our work. The first paper, Baker and Canessa [2] presents a, "general framework of steps, with specific tools and techniques that can be used for each step." The framework is based on looking at prior frameworks for similarities, with an attempt to be more comprehensive. The steps of the Baker and Canessa framework are as follows: (1) Define system requirement; (2) Define and obtain data; (3) Analyse data; (4) Establish unit loads to be used; (5) Determine operating procedures and methods; (6) Consider possible equipment types and characteristics; (7) Calculate equipment capacities and quantities; (8) Define services and ancillary operations; (9) Prepare possible layouts; (10) Evaluate and assess; and (11) Identify the preferred design. For each step in the framework, the authors identify research literature that can be used to assist the
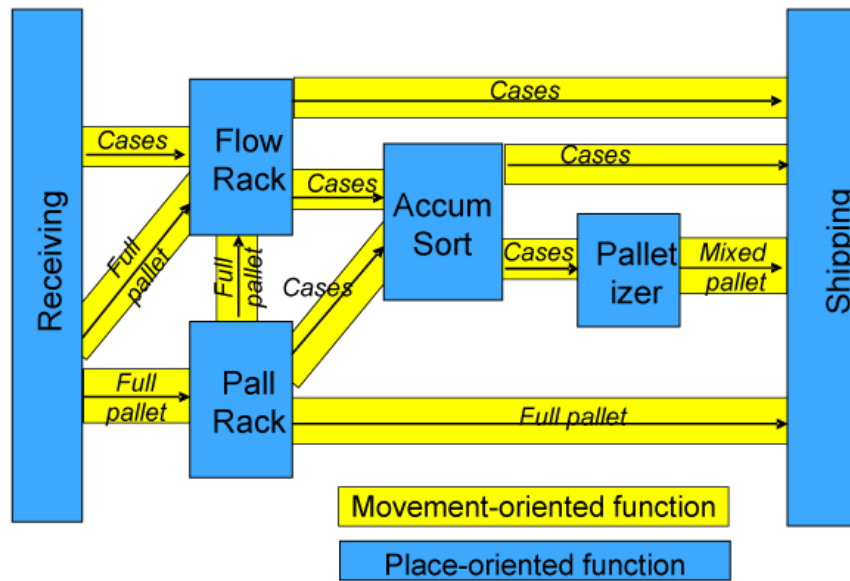
Figure 1: An Example Functional Flow Network.

designer (e.g., for "define system requirements," the authors identify two checklists that may be of interest to the designer; for "calculate equipment capacities and quantities," the authors refer to papers that provide analytical models to assist for one or more specific equipment types).

The second paper is that of McGinnis, *et al.* [7]. Whereas the authors of [2] attempt to synthesize prior approaches, gleaned mostly from descriptions of the facility design process in industry, McGinnis *et al.* have,over the past ten years, attempted to move beyond checklists and simple spreadsheet models (like those cited in [2]) to a new paradigm of warehouse design, which is also based in practice. This paradigm is based on the *functional flow network* (FFN) [7], which is defined to be a network of nodes, where each node corresponds to a specific warehouse function (e.g., receiving, storage, etc.). Arcs connect each node and represent the aggregate flow of materials between the functions. See Figure 1 for an example FFN, where nodes are denoted as "place-oriented functions," and arcs are denoted as "movement-oriented functions." The premise of McGinnis *et al.* is that designers attempt to specify the simplest FFN to represent their conceptual design and then, in turn, size the nodes and the arcs so as to "evaluate" their design. Based on that evaluation, the designers may then modify the FFN by adding nodes or arcs in a search for an improved design.

It is our view that Baker and Canessa [2] have admirably summarized the collected wisdom of numerous attempts to capture the sequence of steps required for warehouse design. However, we still are left without a standardized methodology for performing each step, especially steps 5 and 6 in which one must identify and select process alternatives. The goal of an "empirical approach" is to provide a framework for identifying process alternatives based on professional experience with a wide range of actual warehouse design solutions,

and further to provide a framework for selecting a starting point based on standardized definition and metrics for problem and process descriptions. As will be shown, our approach is most in line with the approach taken by McGinnis *et al.* [7], but with additions to their approach.

In the next section (Section 3) we present the basis for our approach and in Section 4 we discuss the tools or our approach. Our approach is presented in Section 5. Then in Section 6 we provide an abbreviated example of applying our approach. We conclude the paper in Section 7 with iscussion of "where to go from here?"

3   A Basis for an Empirically-Based Warehouse Design Approach

The empirically-based warehouse design approach that we propose is based on two partial methodologies presented in textbooks. The first are lists of "factors to be considered," and the second are matrix solution guides. They are presented next as the basis for our approach.

3.1   The Literal, "Factors to be Considered"

It has long been a hope that because we believe that warehouse and material handling system design should be data driven, that it should be possible to identify and gather the relevant data and then follow a logical process through a defined series of analytical steps that will lead to a good, if not optimal solution. So far, this dream has proven elusive.. There seems to be so many factors to consider and so many process and technology combinations (i.e., a large number of degrees of freedom) that even in very simple warehouse design projects we exhaust ourselves and, in frustration, fall back on experience and "proven designs" for similar situations.

The "Factors to be Considered" in designing a warehouse facility and operation are daunting. See Table 9.2 in [1], which covers two pages with lists of things not to forget. Many of these factors are applicable across a broad range of warehousing problems, but a great number are related to one very specific warehousing environment or another.

In practice, professional designers have created solutions that address the factors important to a particular industry. These historic solutions become the starting point for creating a design for a new facility having characteristics similar to an existing design. Of course, logically, if previous solutions were good and the problems are truly similar, then we might believe this is the best methodology.

After the lead author's almost 40 years of working on warehouse design projects, and spending at least 20 of them trying to develop a repeatable step-by-step process, we have hypothesized that a frequently-used approach is to match the current project with the metrics and processes of former projects. Using this hypothesis as the foundation for our process, we begin by challenging the fit and re-evaluate alternatives for individual pro-

Scale of facility	Retail apparel	Consumer direct apparel	Packaged foods manufacturing	Grocery distribution	Service parts
Small					
Medium					
Large			• Order pick with cart to shipping carton • Pick multiple orders per pick trip • Pick products for groups of orders in several zones and sort and pack centrally		

Figure 2: Industry Solution Matrix (Alternatives Displayed in Each Cell).

cesses. The difficulty arises when the current designer does not have a relevant collection of solutions at his or her disposal.

3.2 Matrix Solution Guides

The long list of factors to be considered, as in [1] are rarely quantitative. A matrix solution guide on the other hand, would be very quantitative in that it would ask the designer to determine key parameters and then use a matrix lookup to specify which material handling solution would be best for that combination of parameters. This would then be repeated for all subsystems in the warehouse.

The key in such an approach is the development of a catalog of reference solutions that is large enough and sufficiently current in equipment technology and its performance so that the matrix defines each solution in terms that permit an accurate comparison with the current design project.

This was attempted 10–15 years ago in a simplified way in an effort with *Modern Materials Handling* to suggest appropriate starting points for designing warehouses with different sizes and missions (the issues were called, *Design Plans and Ideas*). Based on the proposition that the mission within an industry, or in a segment of its supply chain would be the same for a range of business sizes, a simple matrix might reference solutions in each cell as shown in Figure 2.

The processes within a warehouse are a function of the requirements to convert the handling units of the products; e.g., pallet in/pallet out or cases in/units out. That is, identifying through the FFN when handling units change. Because today's warehouses are likely to include more than one such conversion, the total flow may be divided into several different conversions based on the network (see Figure 3).

The difficulty indeveloping a design process that leads to the "one, right solution" is due to the fact that two solutions to the same problem can have very different processes, investment and labor costs, but can be equal in economic terms. That is, a low capital/labor-intensive solution can be equivalent to a higher cost automated system with less labor. Even

Handling unit conversion	Retail apparel	Consumer direct apparel	Packaged foods manufacturing	Grocery distribution	Service parts
Pallet in/pallet out			100%	10%	
Pallet in/cartons out	20%			80%	
Pallet in/units out	70%	5%			
Cartons in/cartons out					
Carton in/units out	10%	90%	• Batch pick for multiple orders in each zone, convey to packing and "put" to order pigeonholes • Wave pick for 1000-2500 orders in each zone, convey through buffer and induct pieces onto unit sorter and pack at chute		
Units in/units out		5%			
Scale of facility					
Small					
Medium					
Large					

Figure 3: Industry Handling Unit Matrix (Alternatives Displayed in Each Cell).

though they can each produce an acceptable result, a serial myopic is unlikely to lead to the two design alternatives. The matrix approach permits us to identify several different solutions within the same industry/size cell for evaluation.

4 Tools for Defining Warehouse Processes

The purpose of this section is to provide "tools" for defining warehouse process options for later evaluation. The tools we present combine Pareto analyses and prior experiences to identify alternatives for individual processes within the warehouse. The end result is that the nodes in a FFN can then be defined so that a system may be created and later explored via evaluation mechanisms. We cover, in turn, the pallet, case and piece-level fulfillment areas of the warehouse.

4.1 Pallet Storage and Retrieval

Among the most useful analyses are those that are based on simple Pareto charts, the results of which suggest alternative solutions based on fast- and slow-moving products (hereafter we define a unique product as its more common name of stock keeping unit, or SKU). In Figure 4 SKUs are ranked from the product with the largest to the product with the fewest number of pallets in storage. Plotted cumulatively, the Pareto curve points to appropriate storage methods for each section of the curve for facilities of varying size. Figure 5 further describes operating characteristics of those options with cost estimates. An ABC rating is noted for each factor.

How the pallets reside in storage is only half of the equation. They must also be placed there and then retrieved. The characteristics of the alternative vehicle types are tabulated in Figure 6. To assist in the selection of a truck for a particular situation, ABC ratings have been assigned to the non-quantitative characteristics. Some of the storage modes may
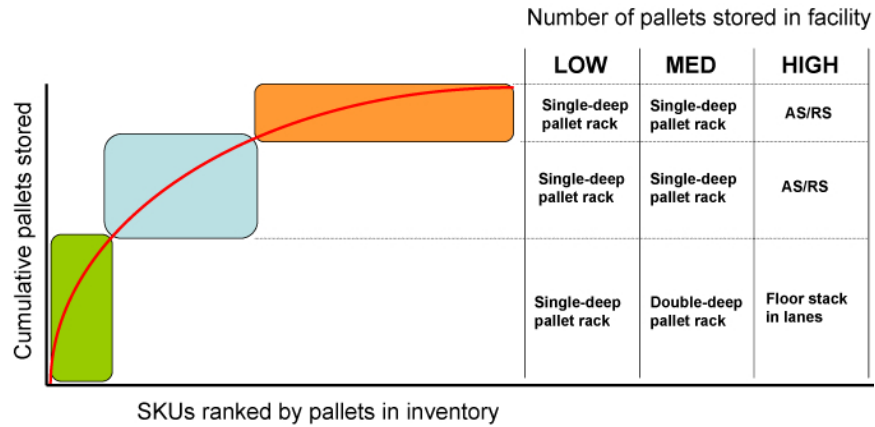
Figure 4: Pallet Storage Alternatives by SKU Activity.

	Floor storage	Stacking frames	Single deep	Double deep	Drive-in	Drive-thru	Flow rack	Push back	Mobile rack	Canti-lever
Cost per position	n.a.	$50	$40	$45	$65	$65	$200	$150	$250	n.a.
Storage density	A	C	C	B	B	B	B	A	A	B
Load access	B	C	A	B	B	B	B	B	C	A
Throughput capacity	A	B	A	B	C	C	A	A	C	B
Inv. and loc. control	C	C	A	A	B	B	A	A	A	B
FIFO control	C	C	A	B	C	C	A	B	A	A
Load size flexibility	A	B	B	B	C	C	C	B	B	A

Figure 5: Pallet Storage Options Comparison.

	Walkie stacker	Counter balance	Straddle	Single-deep reach	Double-deep reach	Turret	AS/RS
Vehicle cost	$12K	$30K	$35K	$40K	$45K	$95K	$250K
Lift height	18	28	22	24	24	35	100
Aisle width	8	12	9	8.5	9	5.5	4.5
Weight capacity	2-4K	2-10K	2-5K	2-5K	2-5K	2-4K	2-5K
Lift speed	50 fpm	80 fpm	60 fpm	50 fpm	50 fpm	75 fpm	100 fpm
Travel speed	200 fpm	550 fpm	450 fpm	450 fpm	450 fpm	490 fpm	500 fpm
Load size flexibility	C	A	B	B	B	B	C
Storage density	C	B	B	B	A	B	A
Throughput capacity	C	A	C	B	B	C	B

Figure 6: Pallet Retrieval Options Comparison.

be accessed by more than one vehicle type while others may require a specific vehicle, as shown in Figure 7.

In a more quantitative comparison, Figure 8, pallet storage configurations are compared for square feet/pallet position provided. The number of storage levels is dependent on the building height, truck type, load height and stacking strength. Each rack type also has a different utilization factor. So, even a simple comparison is highly dependent on a specific situation (i.e., pallet size, facility layout, etc.).

In thinking about the best storage mode for each SKU, the Pareto diagram from Figure 4 is used, along with a measure of product activity to further expand the choices for consideration, as shown in Figure 9.

The vision of our research approach is to motivate the development of numerical equivalencies for the ABC ratings of tables and numerical axes for figures under various conditions (related to labor, space and capital investment). This would be the final stage in "empiricalizing" our approach.

	Floor Stack	Drive-In / Drive-Thru	Single Deep	Double Deep	Push Back	Flow Rack	Canti-lever		Height Limits
Walkie Stacker	X		X						12-15'
Counterbalanced	X	X	X		X	X	X		15-18'
Straddle/Reach	X	X	X	X	X	X			20-25'
Turret (Swing reach)			X						35-40'
Turret (Swing mast)			X				X		35-40'
Sideloader			X	X		X	X		40-50'
Hybrid S/R Truck			X			X			40-60'
AS/RS			X	X		X	X		40-100'

Figure 7: Storage Mode/Retrieval Mode Pairings.
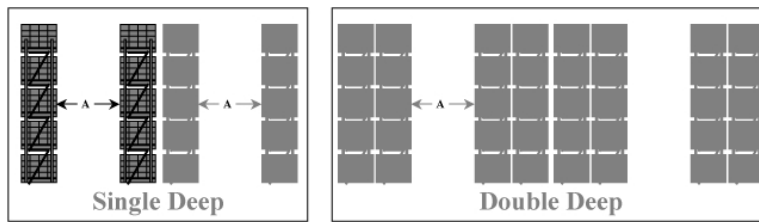
Rack	Truck	Aisle Width (ft)	No. Levels High	Sq. Ft. Per Pallet
Single Deep	Counterbalance	12	4	10.3
	Straddle	9	5	7.0
	Reach	8.5	5	6.8
	Turret	5.5	5	5.8
Double Deep	DD Reach	9.5	5	5.2
Floor Stack	Counterbalance	12	3h x 3d	8.3
	Counterbalance	12	3h x 5d	7.2
	Reach	9	3h x 5d	6.8

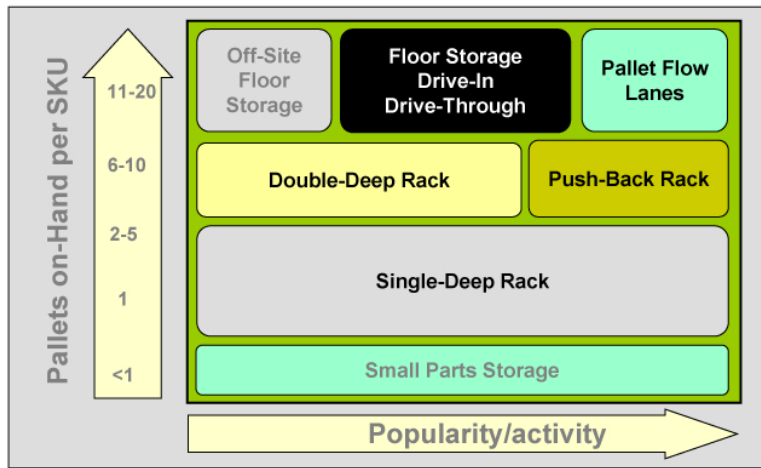Figure 8: Impact of Pallet Storage Options on Aisle Width.

Figure 9: Example Pallet Design as a Combination of Storage Modes by SKU Activity.

4.2 Case Picking

Case picking represents a tradeoff between labor and mechanization, as a function of facility case activity and the relative importance of SKUs (much in the same way as was described earlier with pallet storage and retrieval). That is, as the facility's case activity level increases, there is more of a reason to deploy mechanization. For example, as illustrated in Figure 10, the fast movers in a warehouse, in a low level of activity, storing the pallets and picking cases off of pallets at the floor level will be sufficient. However, as the activity level of the facility increases, then pick-to-belt is justified as the technology (represented by the conveyor and its associated control software) provides a higher level of throughput in an economical fashion. For even higher levels of activity, it may be economical to pick pallets, taking them to a de-palletizing operation that feeds a sorting operation.
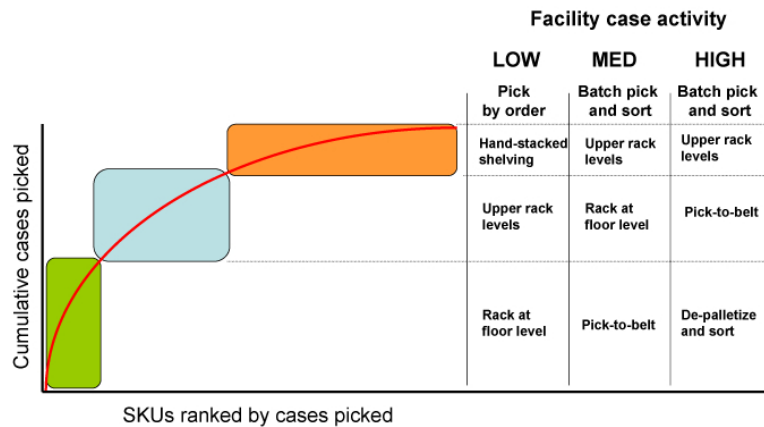

Figure 10: Case Storage Alternatives by SKU Activity.

Furthermore, the boundaries between low and medium levels of activity can be determined with an argument based on economics. Namely, the three basic fulfillment methods for case picking fast movers according to Figure 10 are: manual belt, pick-to-belt (which requires an investment in a conveyor, typically a belt conveyor), and a sorting operation (which typically precedes floor loading of cases in a truck or a palletizing operation as these are typically employed for higher volumes). Note that we present some typical rates for these three fulfillment methods in Figure 11, along with the staffing requirements for various total throughput levels (presented in total case picks per hour). Note that for these data and a throughput level of 5,000 cases per hour, the investment in the mechanization must be justified with the savings of (only) five workers.

As noted for pallet storage and retrieval, the vision of our research approach is to motivate the development of the empirical results related to labor, space and capital investment needed for our approach.

Total case picks/hr		Operator rate per hour					
	Manual pick	100	150	200			
	Pick-to-belt				400	500	500
	Palletize after sort				400	400	500
1,000		10	7	5	5	4.5	4
3,000	Staffing requirements	30	21	15	15	13.5	12
5,000		50	35	25	25	22.5	20
10,000		100	70	50	50	45	40

Figure 11: Case Picking Economics.

4.3   Piece Picking

Piece picking is the most complicated form of order fulfillment in a warehouse. Also, because in most situations a significant fraction of the warehouse operating costis directly related to piece-level picking (as well as the service being provided to the warehouse's customers), there has been more attention devoted to developing material handling technologies for piece-level fulfillment. Thus, more alternatives for the designer to consider.

Also, as order volumes for piece-level fulfillment in a facility increase, mechanization and automation become more attractive. Figure 12 illustrates the progression from the simplest process for picking to the most complex. When the chart is applied to a specific industry or to facilities with similar order and product characteristics, then the Order Volume scale can be quantified. It is important to note that there can be significant overlap where two or more methods can work equally well for a specific order volume.

The first step is to partition the orders in terms of order cube (the physical size of an order) and the number of lines per order, as illustrated for a particular example with 2,570 total orders (corresponding to 7,600 total lines) in Figure 13. The number of lines per order is of interest, mainly, because orders consisting of only one item have the potential to be handled more efficiently in a warehouse. On the other hand, the cube of an order will indicate, for example, how many orders can be fulfilled in a single shipping carton (which again, provides an opportunity for more efficient handling).

Figure 14 then takes this partition and assigns picking methods (based on the lead author's experience). This partition defines the scale of each system; assigning rates to each method allows the number of pickers in each process to be calculated.

For example, assume the mix of lines/order and cube/order remain about the same and assume there are 10,000 active SKUs. At a very conservative 100 lines/hr (based on the lead author's experience) about 8 pickers are requird. Such a combination of processes typically requires very little capital investment. To improve the pick rate per picker (and thus reduce their number), improve the slotting to reduce walking distances and/or group orders by trip to match the slotting. Implementing an RF terminal and/or voice-directed
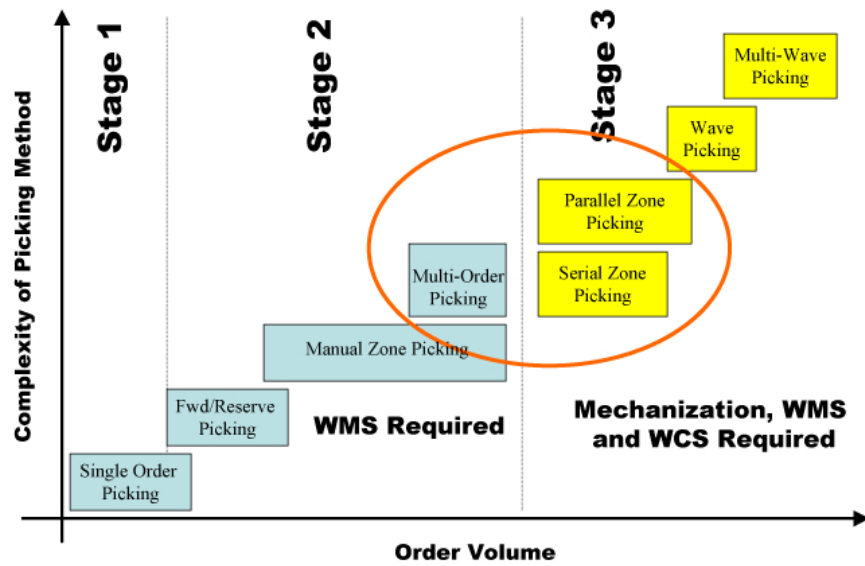
Figure 12: The Evolution of Order Picking Solutions.

Figure 13: Piece-Level Fulfillment Matrix Based on Lines and Cube per Order.

Order cube / Lines/order	<.5	<2	<5	<10	>10	Total
1	1000	100	10			1110
2	300	100				400
3-5	100	200	200			500
6-10		50	100	100	50	300
11-20		10	50	100	100	260
Total	1400	460	360	200	150	2570

Batch pick 50 and station pack

Cartonize and treat each shipping carton like an order

Pick 10 orders/trip into shipping cartons
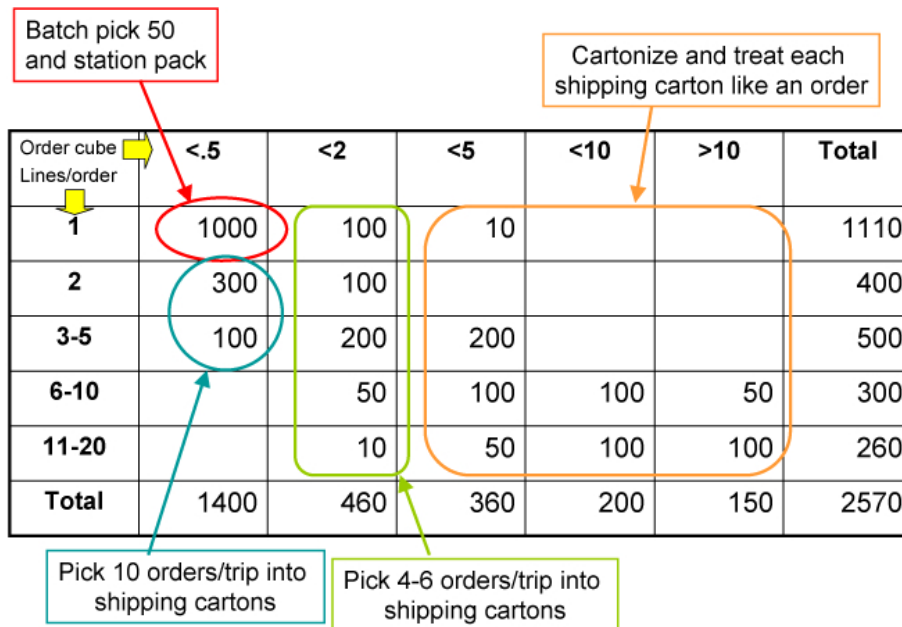
Pick 4-6 orders/trip into shipping cartons

Figure 14: Piece-Level Fulfillment Methods Based on Lines and Cube per Order.

picking also improves the pick rate. However, we can see that at least a 12% improvement in this example would be required to have an impact on the number of full-time workers required (note that, by definition, with a larger number of workers required in a system it becomes easier for a capital investment to reduce the number of full-time workers by at least one).

When order volume doubles (i.e., increases to 5,000/day), it may be time to consider some simple mechanization to reduce congestion in the picking area (which artificially inflates the number of workers needed). At 10,000 orders/day, or with a large increase in SKUs, additional mechanization may be warranted.

Now consider an international client with multiple facilities having the same overall mission, but with different annual volumes and local labor rates.A matrix was developed to guide the local designers in the selection of technologies for each of the processes. Figure 15 shows the matrix for lines of high-speed picking stations. Green squares indicate the expected application. Adjacent yellow squares indicate that a higher or lower technology might be appropriate depending on trends in volume and labor cost. Red squares are used to caution a user from inappropriate technology applications; e.g., if a facility has an annual volume in excess of 2 million orders, then the lowest level of technology will not be sufficient to satisfy the demand.

As noted at the pallet and case level, the vision of our research approach is to motivate the development of the empirical results related to labor, space and capital investment needed for our approach.
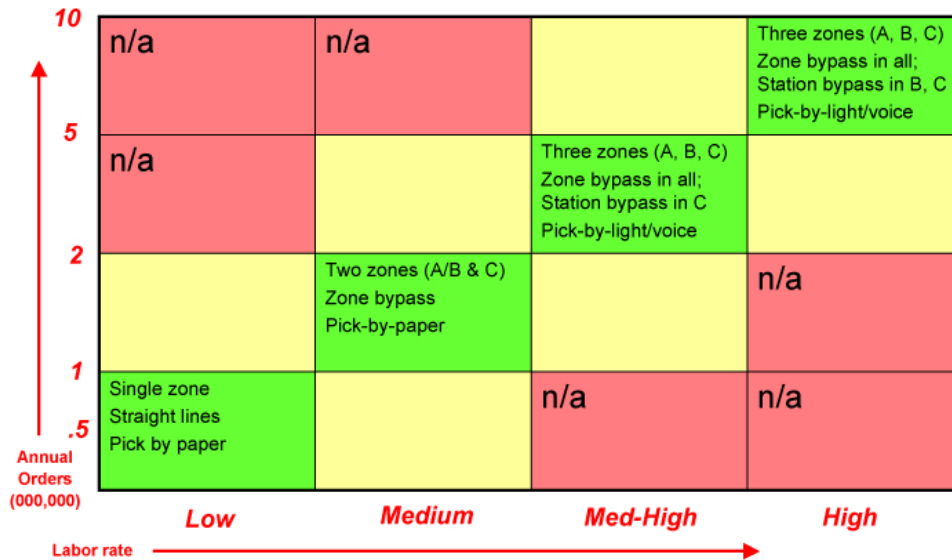
Figure 15: Choosing Technology Based on Activity and Labor Cost.

5   Our Empirically-Based Methodology

From the above, our empirically-based methodology emerges,

1. Define the facility mission:
   - industry;
   - size; and
   - unit load conversion %.

2. Use matrices to identify technologies/solutions to similar problems.

3. Use Pareto charts to divide the problem into logical activity components (e.g., in storage, less than a pallet, 1 pallet, 2 pallets, etc.; for activity level, less than a case, less than a pallet, more than a pallet, etc.).

4. Develop a FFN (Functional Flow Network) represent the conceptual design so as to establish relationships and handling characteristics.

5. Size each of the functional components using charts and available tools:
   - receiving;
   - reserve storage;
   - forward picking;
   - packing; and
   - shipping.

6. Develop trial block layouts with the goal of minimizing manual handling distance within the constraints of a specified building.

7. Develop:
   - connecting processes (aisles/conveyors);
   - pick paths and slotting;
   - flow synchronization; and
   - work structure (zones, smart batches, etc.),

   so as to estimate material handling investment and labor costs.

Note that in the above we mention "manual handling distance," which implies manual material handling. This results from a solution development philosophy to which we adhere:begin with a solution that is based on manual processes and then substitute mechanization/automation as the volume pushes the capability of that solution. Generally, a solution's capability is exceeded when one or more of the following systems occur:

- reserve storage expands to the point of resulting in long travel distances (which indicates that increasing the height of the storage area would be preferred);

- the number of active SKUs expands to require substantially larger pick faces (making picking inefficient);

- activity creates congestion in aisles and pick faces (making picking inefficient); and/or

- total labor requirements challenge hiring, training and turnover capacity.

When this situation occurs, the following are examples of mechanized/automated solutions that should be considered:

- For pallet and case reserve storage, consider automated storage/retrieval (AS/RS) alternatives (unit-load and mini-load end-of-aisle systems).

- For case picking, consider pick-to-belt, layer picking, or automated carousel technologies.

- For piece picking, first break the order into individual shipping cartons (cartonization), then consider:

  - conveyorized "serial zone" picking by order;
  - parallel zone picking by order with buffers before packing;
  - parallel zone picking for a batch of orders with buffers and manual sortation at packing;
  - wave picking, buffers and high-speed unit sortation;

- pick-to-light or voice-directed technology; and

- "put-to-order" at pack stations from reserve carton and batch-picked units (which may be stored in various AS/RS technologies like carousel and vertical lift modules).

In moving from the functional flow network to the block layout, because carton flow can be more easily mechanized via conveyor travel and pallet flow is more likely to be accomplished via lift truck, the overall layout should place more emphasis on the pallet flow distances (and then work the other processes around this). Also note that except for reserve storage, some bulk picking activities, and receiving/shipping, many activities in the warehouse can be performed effectively on a second, or third, level, reducing their footprint on the warehouse floor. They may be located on structural mezzanines, or for picking, or rack-supported flooring. Normally, these operations are served with conveyors.

As noted earlier in the paper, the paper is meant to illustrate a methodology to develop a high-level design of a facility that can further be improved via optimization of the subsystems. The next section provides an example.

6   Example

In this section we present an example of how the empirical design process may be used. The example is based on a project with Rayloc, the remanufacturing division of Genuine Parts. Rayloc supplies remanufactured parts to Genuine Parts retail locations (via a national distribution center (DC) network) and to Genuine Parts customers direct via Internet sales (these customers are referred to as "jobbers"). The jobbers are served by weekly orders of minimum order quantities.

The company proposed a 100,000 square foot facility to replace its current warehouse. Products were such that pallets were made up of cases and the cases were not broken down to the item level in the warehouse (i.e., orders were fulfilled with a set of cases).

A Pareto analysis of the products indicated that the top-80 products account for 23% of the unit throughput and 34% of the order cube. Of these top-80 products, only the top-40 ship more than one pallet per week. The jobber orders represent 40% of the business and this percentage is trending upward (e.g., for a particular month, the DC orders cubed out at 55.6 pallets per day whereas the jobber orders were 22.7). The DC orders tended to be larger (more than 45% of the DC orders were more than 100 lines/order, whereas approximately the same percentage of the jobber orders were more than 10 lines/order). Almost 5% of the DC orders were over 1,000 lines/order (and only 6% of the jobber orders were over 100 lines/order). The smaller jobber orders result in a lower picking productivity as compared to the retail orders.

Products were grouped based on the on-hand inventory to determine requirements by storage mode. This exercise indicated that 5,920 of the 8,756 SKUs had less than a pallet of on-hand inventory and could be stored in hand-stacked shelving. Another 1,839 SKUs had one pallet of inventory on-hand, whereas only 285 SKUs had more than 5 pallets of
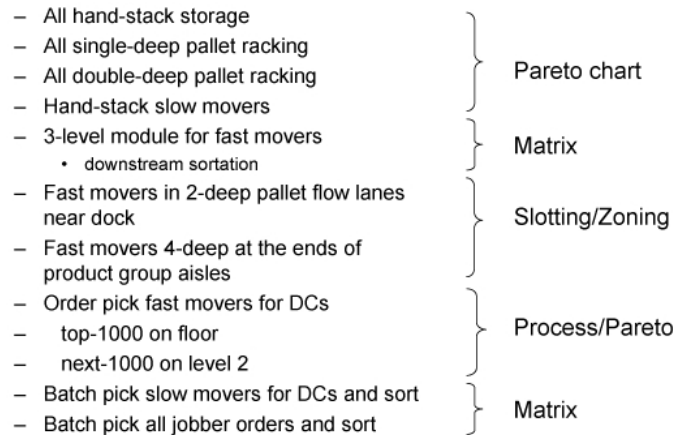
Figure 16: Problem Example Alternatives and Empirical Sources.

inventory on-hand. The pallet reserve inventory may be estimated as the total number of pallets for those products with more than one pallet of inventory, minus the pallets that are in the picking face. Doing so yields approximately 4,250 pallets.

In terms of growth, the company has estimated that the number of SKUs will grow by about 500/year, unit throughput will grow 7–8% per year, and the inventory is expected to increase approximately 10% per year. This implies that the current reserve inventory of approximately 4,250 pallets will double in seven years. These projections indicate that storage alternatives with high density will be required to achieve the objective of housing the entire inventory in the proposed 100,000 square foot facility.

Based on prior projects and experience, the storage/handling alternatives presented in Figure 16 were considered. Also shown in Figure 16 are the empirical sources that were used to help generate alternatives and to consider relevant numerical cutoffs (e.g., the "top-1000" in Figure 16).

According to the presented methodology, the next step is to consider the industry handling unit matrix for this example problem. As can be seen in Figure 17, the overall strategy revolved around fast and slow movers, with fast movers on the floor and slow movers in the rack.

We then turn to the pallet storage and case picking process determination (see Figures 18–19, respectively). The Pareto analysis and facility case activity are used to determine the appropriate methods. After which, rates are used to determine labor and other parameters of interest.

The recommended layout is presented in Figure 20. Note that a sorter was implemented as part of the layout. The sorter schematic is presented in Figure 21.

6.1   Issues not Addressed in the Example Problem

In applying the presented methodology to the example above, it became apparent that there are still a number of open issues. That is, there are many decisions made in the design

Handling unit conversion	Retail	Consumer	Packaged foods	Grocery distribution	Mfg. hard goods
Pallet in/ pallet out				10%	5%
Pallet in/ cartons out				80%	85%
Pallet in/ units out					
Cartons in/ cartons out					10%
Carton in/ units out	10%	90%			
Units in/ units out					
Scale of facility					
Small					
Medium					
Large					

• Single- or double-deep pallet reserve
• High-rise racks and order picking trucks for slow movers
• Pick fast movers by order from floor-level positions
• Batch pick slow movers and induct cases onto sorter and palletize at spur

• Single- or double-deep pallet reserve
• High-rise racks and order picking trucks for slow movers
• 3-level pick module for fast movers and convey to sorter at dock
• Batch pick slow movers and induct cases onto sorter

Figure 17: Problem Example and Industry Handling Unit Matrix.

Number of pallets stored in facility

Cumulative pallets stored

SKUs ranked by pallets in inventory

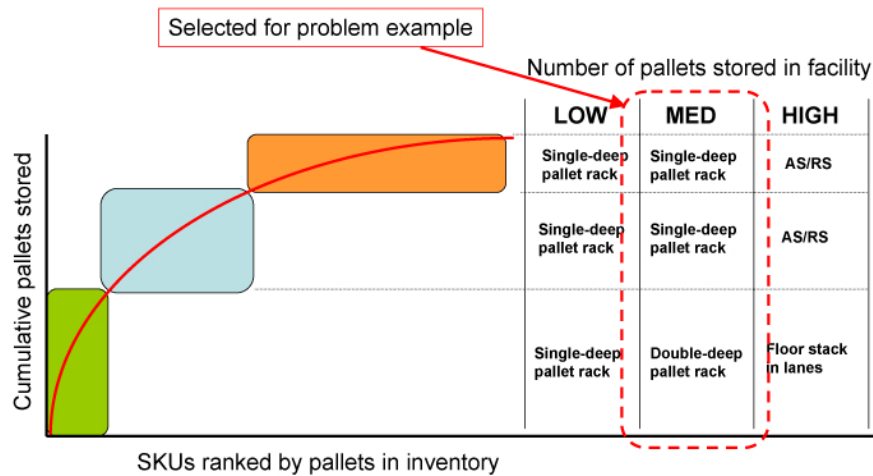|	LOW	MED	HIGH
	Single-deep pallet rack	Single-deep pallet rack	AS/RS
	Single-deep pallet rack	Single-deep pallet rack	AS/RS
	Single-deep pallet rack	Double-deep pallet rack	Floor stack in lanes

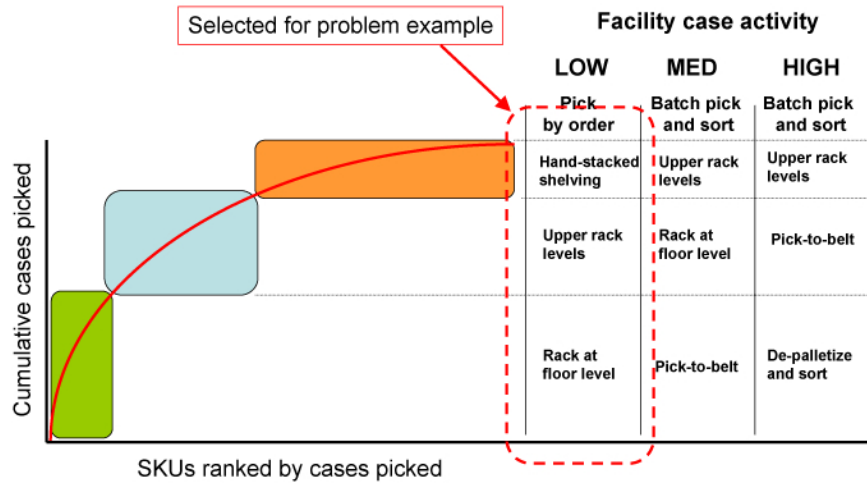Figure 18: Pallet Storage Alternatives by SKU Activity.

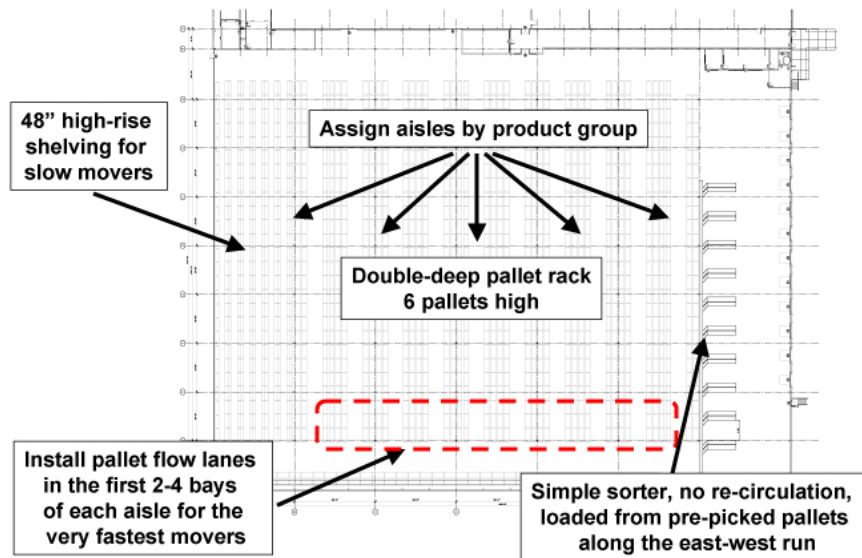Figure 19: Case Storage Alternatives by SKU Activity.

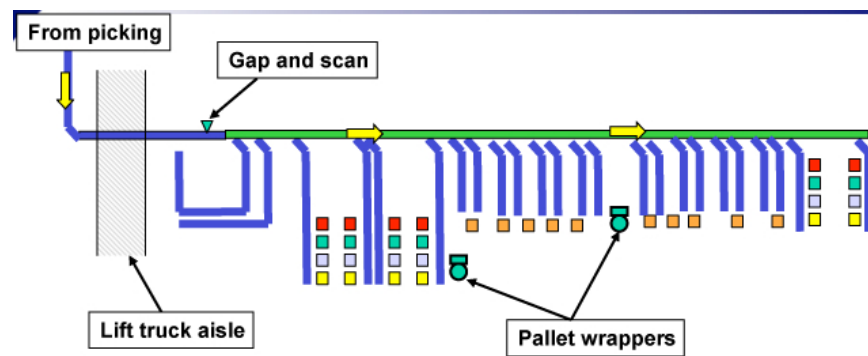Figure 20: Pallet Storage Alternatives by SKU Activity.

Figure 21: Case Storage Alternatives by SKU Activity.

process that are not derived using an analytical process, bt can be supported as a preferred method by analytical comparison. It would be interesting to study these decision processes in more detail to see if they fit within a methodology like that presented here. Some examples within this project include:

- vertical spacing of the shelves for hand stacking slow-moving SKUs;

- slotting the fastest of the slow-moving SKUs close to the floor;

- orientation of the pallet racking;

- long loading conveyor for inducting batch-picked cases;

- number of orders per batch;

- number of spurs on a sorter; and

- re-circulation for the sorter vs. "dump" lanes.

7   Conclusions and Where to go from Here?

In Section 2 we noted that an empirically-based methodology is founded on a "a wide range of reference design solutions from the commercial world," and this certainly defines the most obvious need in terms of further work in this area (we have only populated a subset of the necessary tables needed for this methodology to be fully implemented and tested). There are many research issues involved beyond the collection, representation, and presentation of these designs. There is also the important task of developing standardized definitions for process descriptions and characterizing the performance of such facilities so that the tables that we have presented in this paper can be populated and maintained. In particular, how can we sufficiently evaluate solutions that meet the same needs, but represent a different collection of processes? Also, are there analytical models that can

be developed that will generate the entries in the tables and re-evaluated with updated parameters as time and technology progress?

For example, within serial zone picking, should we:

- Pick (or not) and pass through all zones?

- Bypass zones without activity for an order?

- Provide recirculation or provide long accumulation within each zone?

Or, when is case pick-to-belt (typically a 3-level module) most effective?

- High total case volume?

- Big cases vs. little cases?

- Steep Pareto distribution of SKU activity?

- Big orders vs. many small orders?

- Direct load truck vs. sort to pallet?

And, for high-volume piece picking, how do we choose between wave picking with high-speed unit sortation and batch picking for "putting" to order cartons?

- Total unit and order activity?

- Number of SKUs and activity distribution?

- Size and handling characteristics of products?

- Order sizes?

And, we conclude in the manner in which we began . . . is Academia ready for an empirically-based warehouse design approach? Would you teach your students this approach, use the tables it was based on, accept solutions generated from it as the starting point of a good "engineering" process? Would you be willing to help populate the various tables and figures? Do you believe such an approach would motivate new research? We welcome your comments.

Acknowledgements

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