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Warehouse design: a structured approach

Abstract:

In spite of the importance of warehousing to the customer service and cost levels of many businesses, there is currently not a comprehensive systematic method for designing warehouses. In this paper, the current literature on the overall methodology of warehouse design is explored, together with the literature on tools and techniques used for specific areas of analysis. The general results from the literature have then been validated and refined with reference to warehouse design companies. The output is a general framework of steps, with specific tools and techniques that can be used for each step. This is intended to be of value to practitioners and to assist further research into the development of a more comprehensive methodology for warehouse design.

Keywords:

Facilities planning and design; Decision support models; Logistics; Warehouse design.

Warehouse design: a structured approach

1. Introduction

Warehouses are a key aspect of modern supply chains and play a vital role in the success, or failure, of businesses today (Frazelle, 2002a). Although many companies have examined the possibilities of synchronised direct supply to customers, there are still many circumstances where this is not appropriate. This may be because the supplier lead times cannot be reduced cost effectively to the short lead times required by customers, and hence these customers need to be served from inventory rather than to order (Harrison and van Hoek, 2005). Similarly, it may be beneficial to hold strategic inventory at decoupling points in the supply chain to separate lean manufacturing activities (which benefit from a smooth flow) from the downstream agile response to volatile market places (Christopher and Towill, 2001). Alternatively, the supply and distribution networks may be of sufficient complexity that there is a need for goods to be consolidated at inventory holding points so that multi-product orders for customers can be delivered together i.e. at break-bulk or make-bulk consolidation centres (Higginson and Bookbinder, 2005). The operations of such warehouses are critical to the provision of high customer service levels. A large proportion of warehouses offer a same-day or next-day lead-time to customers from inventory (Baker, 2004) and they need to achieve this reliably within high tolerances of speed, accuracy and lack of damage.

In addition to these traditional inventory holding roles, warehouses have been evolving to act as cross-docking points (where goods are moved directly from inward to outward vehicles without being put away into inventory), value added service centres (e.g. pricing and labelling goods for customers), production postponement points (configuring or assembling goods specifically to customer demand so that a smaller range of generic products can be held in inventory), returned good centres (for reverse logistics of packaging, faulty goods or end-of-life goods) and many other miscellaneous activities, such as service and repair centres (Maltz and DeHoratius, 2004).

Whilst warehouses are critical to a wide range of customer service activities, they are also significant from a cost perspective. Figures for the USA indicate that the capital and operating costs of warehouses represent about 22% of logistics costs (Establish, 2005), whilst figures for Europe give a similar figure of 25% (ELA/AT Kearney, 2004).

A UK study has shown that the number of new large warehouses has steadily increased during the period from 1995 to 2002 (Baker 2004). These warehouses are significant investments for companies and are often highly complex in nature. Expenditure on warehouse automation has increased steadily in Europe (Frost & Sullivan, 2001) and this trend is reflected globally by figures that show that sales have increased by an average of 5% per annum for the period 2003 to 2005 (Modern Materials Handling, 2004, 2005, 2006).

With this critical impact on customer service levels and logistics costs, as well as the degree of complexity involved, it is thus imperative to the success of businesses that warehouses are designed so that they function cost effectively. This is particularly important as warehousing costs are to a large extent determined at the design phase (Rouwenhorst et al., 2000).

2. Warehouse Design

In spite of the importance of warehouse design, a number of reviews of the literature have concluded that relatively little has been written in academic journals on the systematic approach that should be taken by warehouse designers. Typical conclusions over the years include:

- “A search of the literature shows that very few papers deal with the general warehouse design problem” (Ashayeri and Gelders, 1985, p285);
- “In general, however, there is not a procedure for systematically analysing the requirement and designing a warehouse to meet the operational need using the most economic technology” (Rowley, 2000, p3);
- “a sound theoretical basis for a warehouse design methodology still seems to be lacking” (Rouwenhorst et al., 2000, p515);
- “a comprehensive and science-based methodology for the overall design of warehousing systems does not appear to exist” (Goetschalckx et al., 2002, p1).

On the other hand, these reviews have demonstrated that there is a wealth of material written on analysing particular aspects of warehouse design, such as layout, order picking policies

and equipment choice. It is the synthesis of these techniques that appears to be lacking to act as a basis for the overall warehouse design (Rouwenhorst et al., 2000).

In the absence of a defined and accepted methodology, most warehouse designers have developed their own approach (Oxley, 1994). In research with warehouse designers undertaken by Govindaraj et al. (2000), the very complex trade-offs made by the designers are described. Terms such as “eye-ball the data”, and “makes some initial design decisions...based on intuition, experience and judgement” are typical of the process described. It therefore appears that a more formalised process would be of great assistance to practitioners.

3. Approach

The scope for the research is the design phase from the time a specific need is identified for a warehouse (for example, following a distribution strategy review) through to an operational specification being produced, detailing for example, operating methods, equipment, staffing levels, layout and costs. This would be up to the point where capital approval could be given for the warehouse project. The subsequent steps, such as equipment tendering (if that route is selected), construction, installation and project management are not covered in this research.

An initial research of the literature was undertaken using library facilities and searching a range of electronic databases, including EBSCO Business, Emerald, ProQuest, and Science Direct. These databases were searched using relevant keywords, such as “distribution centre”, “facility”, “material handling”, “plant”, and “warehouse”, combined with “design”, “layout” and “operations”. Relevant papers were then selected in accordance with the titles and abstracts. From these publications, the search was then extended by accessing the relevant books and papers that were cited.

The literature was then classified into two groups: those that addressed the overall steps used in warehouse design and those that examined particular tools and techniques. A chronological classification was conducted of the former to identify whether, and how, the steps have developed over time. The steps proposed by the different authors were compared to identify whether there was common agreement and thus whether some basic warehouse design steps could be used with some confidence as an overall framework.

As a validation exercise to identify whether this framework reflected current practice, twelve warehouse design companies were contacted by telephone or face-to-face. Details were sent out by e-mail for their comments and responses were received from seven of the companies. These responses were used to refine the framework.

The companies contributing to this study ranged from large multi-national materials handling system manufacturers and integrators (namely, Jungheinrich, Savoye Logistics, and Swisslog) to small and medium-sized consultancies (namely, Jigsaw Logistics, LCP Consulting, LPC International, and Total Logistics). In all cases, the UK office of the company was contacted.

The positions of the respondents were: director (2 companies), managing director (1), head of warehouse projects (1), logistics consultant (1), project engineer (1) and proposals engineer (1).

As well as requesting the steps used in the warehouse design process, the companies were asked which tools and techniques were normally used for each step. These tools and techniques were then combined with those mentioned in publications already explored. In addition, further database searches were conducted on these tools and techniques so that a wide span of literature relevant to the subject of warehouse design was covered. The different tools and techniques associated with each step were then identified so as to form a structured approach for warehouse design, combining both literature and practitioner sources.

4. Literature on warehouse design steps

A number of key books and papers on overall warehouse design were identified during the literature search and these are set out in chronological order in Tables 1a and 1b. They generally describe the design process in terms of a series of steps, varying from three to fourteen steps in number.

[Insert Tables 1a and 1b about here]

Over thirty years ago, Heskett et al. (1973) described the main aspects of warehouse design under three broad headings of determining the requirements, designing the material handling systems, and developing the layout. The sequence of these three broad stages can be found in most of the subsequent literature.

Apple (1977) observed that the designer (of facilities) faces a complex task because of the interactions and relationships between each design activity, and suggested a 20-step procedure for facilities design that can be adapted to the 12 steps shown in Table 1a for warehouse design. Firth et al. (1988), Hatton (1990) and Mulcahy (1994) follow a similar approach to the previous authors, but also incorporate features such as the recognition of the warehouse in the overall distribution network, and the comparison of alternative approaches (covering concepts, equipment types and layouts).

Oxley (1994) provides a fairly comprehensive list of steps that incorporates the key features of the previous authors. He starts with defining the overall system requirements of the supply chain, including such factors as service levels and implementation time constraints. Again, data collection and analysis are key steps. He also introduces a new step of establishing the unit loads to be used. The following steps are again concerned with developing alternative operating methods, equipment types and layouts. He stresses that the warehouse design should be centred on the storage and handling requirements and that the building should then be designed around these.

This basic framework of steps is also set out in Rowley (2000) and Rushton et al. (2000), where Oxley was a contributor or co-author. In the former publication, a further step is included, namely the use of computer simulation, to test the impact of different volume throughputs and to identify the consequences on the rest of the supply chain. It is stressed that although the steps are set out in sequence, the overall design process is iterative in nature.

Rouwenhorst et al. (2000) also state that a design process typically runs through a number of consecutive phases. However, they then go on to group the activities within these steps into a hierarchical framework based on a top-down approach, thus identifying strategic, tactical and operational decisions. They propose that these three clusters of decisions should be considered in sequence.

Govindaraj et al. (2000) and Bodner et al. (2002) used ethnographic study techniques to identify how experts actually design warehouses. They focus on the procedures that are used by designers and experts in the field, trying to understand the decisions they make and the processes they follow when developing a design project. They state that the designer must consider some very complex trade-offs. Four to five steps are identified in these papers, plus the need for reiteration of these steps. The authors state their future intention to use these steps to develop computational aids for warehouse design. Govindaraj et al. (2000) propose an object-oriented model comprising five modules: a project module (base data); warehousing module (including unit load and equipment details); flow and control module (encompassing movement within the warehouse); operation module (a specified design); and a cost module. These object modules encapsulate most of the elements described by the previous authors.

Hassan (2002) and Waters (2003) again provide a series of steps which are similar in many ways to the previous authors, although the former is primarily concerned with just one aspect of the design problem, namely the layout design. Waters (2003) concurs with some of the previous authors in that warehouse design steps do not represent a strict sequence.

Rushton et al. (2006) have refined the steps in their earlier edition to recognise the importance of flexibility in warehouse design. The business requirements step includes the concept of scenario planning and this leads to a later specific step of evaluating design flexibility. The iterative nature of the design process is exemplified by the equipment and staffing calculations now being shown after the layout design rather than before, as with most other frameworks. For example, truck numbers cannot be finalised until the distances are known of how far they will need to travel.

There are a number of common themes running through all of these methodologies to warehouse design:

- It is acknowledged that warehouse design is highly complex;
- The authors tackle this complexity by describing step-by-step approaches;
- These steps are interrelated and a degree of reiteration is necessary;
- It may not be possible to identify what is the “optimum” solution, owing to the high number of possibilities that exist at each step.

There are differences in the precise steps within the various approaches described. This is partly caused by the way that activities are grouped together into steps and partly due to some approaches appearing to be more exhaustive than others. However, most of the approaches follow a common pattern, as can be identified by the similar names to the steps in the rows in Table 1. In fact, the steps do not appear to have changed greatly over time.

5. Steps used by warehouse design companies

In order to verify the general steps found in the literature, warehouse design companies were asked to set out the steps that they follow when they design warehouses and then to list the tools that they use for each step. The steps listed by Oxley (1994) were provided as a template for the latter, for convenience or for where no formal design steps are used. The Oxley (1994) steps were used for this purpose as they encompass the key features of the various approaches found in the literature. Three companies adopted the template as a good representation of their steps and four provided their own steps. The steps used by the four latter companies are as set out in Table 2.

[Insert Table 2 about here]

For the four companies that described different steps to those provided on the template, it should be noted that a similar number of steps are used (i.e. either eight or nine, compared to eleven on the template) and these can be related reasonably closely to the template steps (i.e. those of Oxley, 1994). Across the seven warehouse design companies, the steps used by practitioners are thus not dissimilar to those described in much of the literature. It is therefore proposed that the steps used for the template in this research represent a way forward for the development of a more comprehensive warehouse design methodology, as they are well grounded in the literature and are recognisable to design practitioners.

6. Individual tools and techniques

The research into the individual tools and techniques used within each of the steps was undertaken both from the literature and from the warehouse design companies. It was found that the literature provides useful tools for some steps but does not appear to cover all of the steps involved. This is supported by Rouwenhorst et al. (2000) who concluded that the

existing literature tends to concentrate on a small numbers of specific areas within the total warehouse design problem, with areas such as conventional equipment solutions and staffing calculations being largely neglected.

The various tools used by the warehouse design companies were set out in their responses and are summarised in Table 3.

[Insert Table 3 about here]

The results show that warehouse designers use a variety of tools during the design process. The main areas of commonality (i.e. used by more than half the respondents) were the use of:

- database and spreadsheet models for data analysis;
- spreadsheet models for considering equipment types;
- formal spreadsheet models to calculate equipment capacities and quantities;
- computer-aided design (CAD) software for drawing up the layouts;
- simulation software and formal spreadsheet models for evaluation and assessment.

By combining the results from the literature review and the warehouse design companies, an overall framework can be developed, summarising the main tools used and the key references in the literature where these are described in more detail. This is shown in Table 4.

[Insert Table 4 about here]

These tools and techniques are described below for each of the steps.

Define system requirements

Oxley (1994) refers here to the overall system within which the warehouse operates, and therefore includes business strategy requirements and relevant constraints, such as planning and environmental issues. Approaches described in business and supply chain strategy literature, such as on competitive advantage and consumer value (Christopher, 2005) are relevant, as is the use of scenario planning (e.g. Sodhi, 2003). A framework to identify the role of warehousing within supply chains is given in Baker (2007a) and there are some

checklists on warehouse roles (e.g. cross-docking) and functions (e.g. storage) within warehousing literature, for example in Higginson and Bookbinder (2005).

Define and obtain data

Bodner et al. (2002) state the expert designer has a pre-specified list of data to be requested, to which they may add depending on the precise nature of the project. The warehouse design companies surveyed support that checklists are often used by practitioners, normally formalised into database or spreadsheet models, ready for analysis. Flow charts may also be used to obtain information.

Such checklists of data are given in various publications, including Rowley (2000), McGinnis and Mulaik (2000), and Frazelle (2002b) and Rushton et al. (2006). These lists include product details, order profiles, goods arrival and despatch patterns, cost data and site information (where a site has already been identified).

Hatton (1990) mentions the use of specially written software by some design companies to extract data from company computer systems and summarise it in a useful way. After the extraction of historic data, Hatton (1990) goes on to explain the need to consult with various business departments (e.g. marketing) to then develop these numbers to the required planning horizon (e.g. 5 years hence).

Analyse data

Database and spreadsheet models are normally used by practitioners to analyse data. Govindaraj et al. (2000) state that this process normally involves an analyst computing a number of routine statistics from the order database and then the designer uses his experience to interpret these statistics.

Frazelle (2002b) presents a set of such routine statistics in a section on warehouse activity profiling. These include:

- Customer order profiling (e.g. pallet / carton / item mix profiles and lines per order distribution);

- Item activity profiling (e.g. item popularity distribution and demand variability distribution);
- Inventory profiling (e.g. inventory distribution by Pareto group or handling unit);
- Calendar-clock profiling (e.g. seasonality and daily activity distributions);
- Activity relationship profiling (i.e. importance of certain functions being located nears other functions);
- Investment profiling (e.g. wage rates and required Return On Investment).

Benchmarking is also seen as a critical part of this process (Frazelle, 2002b), although Hackman et al. (2001) warn of the dangers of normal ratio comparisons for comparing warehouse performances. They state that a more comprehensive approach is needed that can consider several dimensions of performance simultaneously and explore the use of data envelopment analysis (DEA) for this purpose.

Bodner et al. (2002) describe the general use of *ad hoc* spreadsheet and database tools developed during the course of previous design projects. The results of these may be brought together into comprehensive planning bases for a number of planning horizons (e.g. a 1-year horizon for the initial staffing level and a 5-year horizon for the building design), as described by Rushton et al. (2006).

The respondents did not identify the use of any advanced mathematical techniques (e.g. linear programming), although some techniques may of course be contained in the spreadsheet models that are used at many stages of the design process.

Establish unit loads to be used

There are few tools listed in the literature for this step, although Roll et al. (1989) do describe a systematic approach that develops a mathematical relationship between container size and storage cost and then proceed to describe a simulation approach that can be used where average values are not appropriate. Rushton et al. (2000) go on to explain that the choice of unit load cannot be taken in isolation but must take into account the whole supply chain (i.e. supplier and customer considerations).

It is evident from the responses that there is considerable reliance placed on the expertise of the individual warehouse designers. For example, one respondent stated that unit loads were established by “design experience and expertise, combined with iterative discussions with the client”.

Determine operating procedures and methods

These are the high-level procedures and methods for each function of the warehouse. A wide variety of techniques are used by the respondents, including checklists, warehouse zoning, technology assessment charts, concept library, and standard work procedures.

Hatton (1990) stresses the role of the experienced designer in this process, and this is supported by the ethnographic studies by Bodner et al. (2002) who describe this process as implicit based on the designer’s expertise.

Rouwenhorst et al. (2000) propose a framework for making these high-level decisions. They determine two clusters of problem areas at what they describe as “strategic” level decisions: centred around system selection on the basis of technical and economic capabilities. The first cluster (i.e. based on technical capabilities) relates to this step. They identify decision areas and state that these are highly interrelated, but found no literature to assist with these decisions.

An important part of this step is the decision as to the zones into which the warehouse should be divided (e.g. zones for different product groups, temperature regimes, or Pareto classifications). Again, this appears to be left to the experience of the warehouse designer. Based on the adopted zones, Rushton et al. (2006) describe warehouse flow diagrams that represent the daily flows passing through the various zones of a warehouse as a basis for the subsequent steps.

Gu et al. (2007) identified many papers that covered the operational design of particular aspects of a warehouse, although some aspects have been researched far more than others. The reader can refer to that paper for techniques that may be useful in determining the operating methods for specific activities within the warehouse. Another paper that is useful in this regard is the review of warehouse models by Cormier and Gunn (1992).

Frameworks of how to incorporate flexibility into warehouse design are provided in Baker (2006 and 2007b). These frameworks include the consideration of which resources to adapt for flexibility (e.g. buildings, equipment, staffing, processes or systems) and how to accommodate potential change (e.g. by extra capacity, additional resources when needed or the use of flexible resources).

Consider equipment types and characteristics

In contrast to some of the previous steps, there are many tools available in the literature that may assist with the evaluation of equipment types. This is also reflected in the wide range of techniques used by the warehouse design companies, such as decision trees, matrices, SCOR assessments and factor analysis.

Ashayeri and Gelders (1985) identify three generic methods that assist chiefly, although not solely, with this step:

- Heuristic methods (which are based on a close examination of different design alternatives through intuitive rules, based on experience);
- Analytic methods (which are used to calculate an optimum solution);
- Simulation methods (which conduct “what if” analyses).

Naish and Baker (2004) describe a step-by-step approach to equipment evaluation, comprising:

- High-level technology assessment, based on such general factors as the scale of the operation and the flexibility required;
- Equipment attributes, to identify whether each equipment type is suitable for the application;
- Decision trees, which act as representations of “expert systems”. Examples are also given in Rowley (2000) and Rushton et al. (2006);
- Full costing comparison, to calculate all the costs associated with the remaining options;
- Sensitivity analyses, to identify whether the preferred systems still perform well under alternative business scenarios;

- Computer simulation, to test the effectiveness of the preferred system under different conditions (e.g. crane breakdown).

This heuristic method encompasses a number of the tools described in the literature and overcomes one of the disadvantages of analytic and simulation approaches whereby it is difficult to evaluate by these means the full range of options. This narrowing down of options is supported by Hatton (1990), who recognises that the experience of the designer is important in discarding inappropriate options and thus simplifying the design task. Once the infeasible options have been eliminated then analytic and simulation methods can be used to evaluate specific alternatives.

Calculate equipment capacities and quantities

This is generally a matter of calculation and formal spreadsheet models tend to be used, based on warehouse flows (as per Rushton et al., 2006) and performance standards (e.g. from historic KPIs or rated activity sampling). Many of the analytic and simulation methods, mentioned in the previous step, in fact address equipment capacities and quantities as well as the wider equipment selection question. For example, Ashayeri and Gelders (1985) list a number of papers that use a range of analytic methods, including such techniques as non-linear mixed integer programming and dynamic programming, as well as simulation methods. The types of question they address include the development of optimum rack lengths and space utilisation, although some do examine cost minimisation between specific options. Similarly, Cormier and Gunn (1992) provide a good overview of a range of warehouse models that have been developed to analyse specific aspects, such as performance evaluation of automated storage and retrieval systems (AS/RS).

Define services and ancillary operations

There are no real methodologies described in the literature for this step. It appears to be derived from the experience of the warehouse designers, sometimes formalised into checklists of requirements.

Prepare possible layouts

All of the respondents use computer-aided design (CAD) software to assist in drawing up the layouts. Canen and Williamson (1996) provide a review the literature on computer-based layout packages and conclude that there is considerable software available. However, their research concluded that specialist warehouse layout software appeared to be little used by companies, who tend instead to use non-specialist software, such as AutoCAD. Such software tends to be an aid for an experienced designer to help draw the layout, as exemplified by one respondent who stated that layouts are prepared “by experience and use of AutoCAD to draft layouts”.

This is recognised as a key step and some approaches are proposed in the literature as to how to formulate draft layouts. Some of these refer to plant layout tools, such as route sheets, operation schedules, and movable templates drawn to scale to represent freight and equipment, as mentioned by Heskett et al. (1973).

Mulcahy (1994) explains the complexity of the warehouse layout problem by listing ten different objectives that need to be maximised, including for example space minimisation, access to products, efficient flows, safe working environment and expansion potential. He goes on to explain four methods to help design and present the layout:

- Block layout;
- Layout board and standard templates;
- Conventional or computer-produced drawing;
- Model method (e.g. a three-dimensional model, often built for presentational purposes, but particularly useful to provide an insight into the relationships between different floor levels of a warehouse).

Hudock (1998) demonstrates techniques for space planning of receiving / shipping and storage areas, before proceeding to explain how experienced layout planners generate alternative layouts and then evaluate these. Rowley (2000) takes a high-level view, describing the four most common layouts based on the location of the receiving and shipping docks that are used in warehousing operations and lists the advantages and disadvantages of using them. However, he does not propose a precise methodology.

Frazelle (2002b) presents a five-step methodology for warehouse layout, which combines some of the above techniques:

- Space requirements planning: This involves determining the space required for each zone (as in the block layout technique described earlier);
- Material flow planning: The determination of the overall flow pattern (e.g. U-shape or flow-through);
- Adjacency planning: This uses a warehouse activity relationship chart, which may form the input for computer-aided facility layout tools.
- Process location: The split of areas by low-bay and high-bay usage.
- Expansion / contraction planning: Consideration of how the facility may be changed in the future.

There are thus a number of techniques available to assist warehouse designers in formulating the layout of a warehouse, but these are generally designed to assist an experienced warehouse designer, rather than provide an optimal layout solution *per se*. As noted by Canen and Williamson (1996) there are many qualitative factors, such as safety and aesthetics, to consider as well as the purely quantitative factors, such as the flows of goods.

As regards the external areas, some authors, such as Napolitano (1994) and Rowley (2000), mention certain criteria that designers need to bear in mind, but no specific tools are proposed.

Evaluate and assess

Oxley (1994) states that this step is largely concerned with validating the operational and technical feasibility of the proposed solutions, checking that it meets the requirements of step one (i.e. the initial requirements), and undertaking capital and operational cost evaluations.

Simulation is used by most of the respondents and this technique is mentioned by several authors, such as Ottjes et al. (1988), Brito (1992), Smith and Nixon (1994), Kosfeld (1998) and Queirolo et al. (2002). This tool can be used to analyse individual sections of the facility, or the facility as a whole.

Scenarios can be built, either by simulation or other modelling, to consider a series of different situations in which the flexibility of the design can be tested. These scenarios may

include for example alternative growth forecasts, changes in order profiles, and abnormal peak requirements.

There are a number of simulation tools available, including general simulation packages that can be adapted for warehousing, as well as specific warehousing simulation packages. Some of these can be bought directly from suppliers, whilst others are available through consultancies, equipment suppliers and warehouse management system suppliers. However, it should be noted that not all of these tools are used on every occasion. For example, one warehouse design company stated that: “Dynamic simulation is added for proof-of-concept for specific projects where the client is undergoing fundamental business change. Dynamic simulation is used only where database modelling will not provide accurate answers”.

Identify the preferred design

This step is basically the drawing together of all of the above elements into a coherent design, identifying, for example, the unit loads to be used, the operations and flows, the information systems, the equipment types and quantities, the internal and external layouts, the staffing requirements and the costs (Oxley, 1994). No specific process is described in the literature for this step, but the warehouse design companies gave some examples of both quantitative (e.g. financial business case) and qualitative (e.g. SWOT analysis) methods.

7. Discussion

Based on the literature and the responses from the warehouse design companies, there appears to be some consensus on the overall approach that needs to be followed for warehouse design. There can be some debate on the precise steps, as the activities in the design process can be grouped together in various combinations. Similarly, there can be a further debate concerning the sequence of these steps, as warehouse design tends to be an iterative, rather than a sequential, process. However, whilst there appears to be general consensus on the overall structure of the approach, there is less consensus on the exact nature of the tools to be used for each step. It is evident that there is considerable reliance on the experience of individual warehouse designers in deciding the tools to be used and in making judgements between various alternative solutions. A comprehensive warehouse design methodology thus appears to be a goal that is far from being achieved.

There appear to be no optimisation or “black box” solutions for the whole design process whereby the planning base can be fed into a tool and an optimum design is produced. Also, in spite of the reliance on the experience of individuals, there appears to be limited use of “expert systems”. A study by Kurokawa (2005) identified some decision tree techniques that could form the basis for such systems within steps 5, 6 and 9 of the framework described above but these were rather limited in nature. Based on the expert system analysis methodology set out by Turban and Aronson (1998), he went on to conclude that parts of steps 1, 2, 5, 6, 8 and 9 may be suitable for the further development of expert systems.

Ashayeri and Gelders (1985) identified heuristic, analytic (i.e. optimisation) and simulation techniques and it appears that these all have their place. Rouwenhorst et al. (2000) grouped the different decisions that need to be made into strategic, tactical and operational levels, with the first two decision areas being particularly relevant to the scope of this research. Whilst the interrelationship between the different decisions was stressed, no method for bringing these together was identified.

The findings of this paper are important to academics and practitioners. The structured review of the literature summarises the warehouse design steps that have been put forward and the general approach that can be drawn from this has been validated with practitioners. The contribution to theory is thus a structured approach to warehouse design, whilst the contribution to practitioners is a validated framework, plus tools for each step, that can be used in practice. In addition, an agenda for research can be developed from this framework, as it forms a reasonably sound basis for further reflection, study and development.

8. Further research areas

As identified by previous literature reviews of warehouse design, relatively little has been written about the total design process. Owing to the high cost of such facilities and the significant consequences of any deficiencies in this area (Emmett, 2005), a more comprehensive and systematic methodology is needed. It is proposed that this framework can act as a research agenda for this area. Existing tools that address the general warehouse design problem have been brought together in this framework. These need to be integrated more fully and further tools developed to address gaps, such as those identified by Kurokawa

(2005). In this way, an overall methodology can be established that builds on previous academic research as well as on the current techniques used by practitioners.

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Table 1a
Warehouse design steps in the literature (1973-2000)

Heskett et al. 1973	Apple 1977	Firth et al. 1988	Hatton 1990	Mulcahy 1994	Oxley 1994	Govindaraj et al. 2000
		Identify the warehouse functions	Determine the task (inc. data collection)		Define system requirements	
Determine warehouse requirements	Procure data Analyse data	Gather data and make projections	Analyse product quantity Analyse product movement	Collect data Analyse data	Define and obtain data Analyse data	Assemble and analyse data
Design material handling systems and facility design	Design processes Plan material flow pattern Calculate equipment requirements Plan individual work areas	Develop alternative methods Combine functional alternatives into single system	Develop alternative concepts	Establish design year parameters Consider alternative material handling equipment and concepts	Determine operating procedures and methods Calculate equipment capacities and quantities Define services & ancillary operations	Determine functional requirements Make high-level ("architecture") decisions
Develop the facility layout	Select material handling equipment Determine storage requirements Plan service and auxiliary activities Determine space requirements Allocate activity areas to total space Construct the master layout	Select the total system	Develop the management system (methods, procedures and systems)	Develop alternative layouts	Evaluate and assess Identify the preferred design	Undertake detailed system specification and optimization Reiterate above steps

Table 1b
Warehouse design steps in the literature (2000-2006)

Rouwenhorst et al. 2000	Rowley 2000	Rushton et al. 2000	Bodner et al. 2002	Hassan 2002	Waters 2003	Rushton et al. 2006
Define concept	Define system requirement and design constraints	Define system requirements and design constraints		Specify type and purpose of warehouse		Define business requirements and design constraints
Acquire data	Define and obtain relevant data	Define and obtain data	Assemble data	Forecast and analyse expected demand	Estimate future demand	Define and obtain data
	Analyse data	Analyse data	Undertake data profiling	Establish operating policies	Forecast movements through warehouse	Formulate a planning base
	Establish unit loads to be used	Establish unit loads to be used		Determine inventory levels		Define the operational principles
Produce functional specification	Postulate operating procedures and systems	Postulate basic operations and methods	Determine high-level functionalities	Form classes (of products)	Compare available handling equipment	Evaluate equipment types
Produce technical specification	Consider equipment types and characteristics	Consider possible equipment types	Produce high-level specification ("architecture")	Departmentalize (into areas) and establish general layout	Calculate the space needed for storage and movement	Prepare internal and external layouts
Select the means and equipment	Calculate equipment quantities	Calculate equipment quantities		Partition into storage areas	Identify which materials should be close to each other	Draw up high-level procedures and IS requirements
	Define other facilities and services	Calculate staffing levels		Design material handling, storage and sortation systems		Evaluate design flexibility
Develop layout	Draft possible layouts	Prepare possible building and site layouts		Design aisles	Develop outline plans	Calculate equipment quantities
Select planning and control policies	Select the preferred design	Evaluate the design against requirements	Undertake detailed system specification/ optimization	Determine space requirements		Calculate staffing levels
	Evaluate and assess expected performance	Identify the preferred design	Reiterate above steps	Determine input / output points	Finalise plan	Calculate capital and operating costs
	Conduct computer simulations			Determine docks		Evaluate the design against requirements
					Determine the storage arrangement	Finalise the preferred design
				Form picking zones		

Table 2
Alternative steps used by warehouse design companies

Step	Company A	Company B	Company C	Company D
1	Develop material flows (including unit load formats) [1,2,3,4]	Define and collect data [1,2]	Data acquisition [1,2]	Define operation requirements [1]
2	Technology evaluation [5,6]	Analyse data [3]	Data analysis [3]	Define and obtain data [2]
3	Refinement of preferred options [5,6]	Establish design parameters [3]	Material flow diagrams [4,5]	Define operational constraints [1,4]
4	Manning levels [7,10]	Establish operating procedures [4,5]	Operating principles [4,5]	Consider equipment types and characteristics [5,6,7]
5	CAD layout [9]	Initial design [6,7,8,9]	Develop alternative designs [6,7,8,9]	Design layouts [8,9]
6	Functionality definition (i.e. processes and systems functionality) [5,10]	Evaluate initial design [10]	Outline costing [10]	Evaluate and assess design layouts [10]
7	Detailed design (including ancillaries) [8,10,11]	Refine design [10]	Design evaluation [10]	Identify preferred design [11]
8	Simulation [10]	Simulation of solution [10]	Development of preferred option [11]	Prepare final proposal and detailed specification [11]
9	Equipment specification [11]	Evaluate final design [10,11]	Submit design proposal [11]	

Note: The figures in square brackets relate to the corresponding steps set out by Oxley (1994) in Table 1a.

Table 3
Tools used by warehouse design companies for each step

Step	Tools used (the number of companies using each tool is shown in brackets)
1. Define system requirement	Checklists (2) Distribution network software (1)
2. Define and obtain data	Checklists (3) Database models (3) Formal spreadsheet model (2) Informal spreadsheet models (2) Flow charts (1)
3. Analyse data	Database models (5) Formal spreadsheet models (3) Informal spreadsheet models (2) Flow charts (1)
4. Establish unit loads to be used	Checklists (2) Survey existing operations (1) Formal spreadsheet model (1) Database model (1)
5. Determine operating procedures and methods	Checklists (2) Warehouse zoning (1) Technology level assessment chart (1) Picking method assessment chart (1) Concept library (1) Standard work procedures (1) Informal spreadsheet model (1)
6. Consider possible equipment types and characteristics	Formal spreadsheet models (2) Informal spreadsheet models (2) Decision trees (2) Two-by-two matrix (1) Equipment attribute matrix (1) Concept library (1) Supplier bespoke tools (1) SCOR assessments (1) Factor analysis (1)
7. Calculate equipment capacities and quantities	Formal spreadsheet models (4) Informal spreadsheet model (1) Formal database model (1) Historical KPI and performance standards (1) Rated activity sampling (1)
8. Define services and ancillary operations	Checklists (2) Formal spreadsheet model (1) Formal database model (1) From equipment specification tools (1)
9. Prepare possible layouts	CAD software (7) Process flow software (1) Simulation software (1) Standard rack modules (1)
10. Evaluate and assess	Simulation software (6) Formal spreadsheet models (4) Formal database models (3) Two by two matrices (1) Financial models (1) Checklists (1) Factor analysis (1) SCOR (1)
11. Identify the preferred design	Simulation software (2) Two by two matrices (1) SWOT analysis (1) Business case (1) Formal spreadsheet models (1) Process flow templates (1)

System functionality checklists (1)
Standard equipment specification proforma (1)
Factor analysis (1)
SCOR (1)

Abbreviations:

CAD Computer-aided design
KPI Key performance indicator
SCOR Supply-Chain Operations Reference model (Supply-Chain Council)
SWOT Strengths, weaknesses, opportunities, threats

Note:

Formal models are defined as those designed and quality controlled for use on multiple projects, whilst informal models are those developed previously for other projects and modified for use on subsequent projects.

Table 4
Proposed framework, tools and key references

Step	Tools and key references
1. Define system requirement	Refer to literature on business and supply chain strategy literature (e.g. Christopher, 2005) and scenario planning (e.g. Sodhi, 2003). Warehouse role framework is provided in Baker (2007a) and role checklist in Higginson and Bookbinder (2005).
2. Define and obtain data	Checklists and spreadsheet, or database, models are used. Useful checklists appear in Rowley (2000), McGinnis and Mulaik (2000), Bodner et al. (2002), Frazelle (2002b) and Rushton et al. (2006).
3. Analyse data	Database and spreadsheet models are used. Activity profiling techniques are given in Frazelle (2002b). Planning base, planning horizon and warehouse flow charts are described in Rushton et al. (2006).
4. Establish unit loads to be used	Analytic and simulation approaches are described in Roll et al. (1989).
5. Determine operating procedures and methods	A wide variety of techniques are used. Rouwenhorst et al. (2000) set out a framework of the cluster of decisions that need to be considered. Rushton et al. (2006) describe warehouse zoning. Flexibility frameworks are set out in Baker (2006 and 2007b).
6. Consider possible equipment types and characteristics	Spreadsheet models and decision trees tend to be used. Heuristic, analytic and simulation methods are described in Ashayeri and Gelders (1985). A heuristic approach is set out in Naish and Baker (2004). Decision tree examples are given in Rowley (2000) and Rushton et al. (2006).
7. Calculate equipment capacities and quantities	Spreadsheet models, as well as historic performance measures, are used. The analytic and simulation methods described by Ashayeri and Gelders (1985) are also relevant for this step.
8. Define services and ancillary operations	Checklists are used by some practitioners.
9. Prepare possible layouts	CAD software is generally used by practitioners. Outline steps and methods are provided by Mulcahy (1994), Hudock (1998) and Frazelle (2002b). A warehouse relationship activity chart is described in Frazelle (2002b).
10. Evaluate and assess	Simulation software is useful at this step (e.g. see Kosfeld, 1998) and is commonly used by practitioners. Analytic models are also used by practitioners.
11. Identify the preferred design	Quantitative (e.g. financial business case) and qualitative (e.g. SWOT analysis) methods are used. No specific process is described in the literature.

Warehouse design: A structured approach.

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