Warehouse Design and Product Assignment and Allocation: a mathematical programming model

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ABSTRACT

Warehouses can be considered one of the most important nodes in supply chains. The dynamic nature of today's markets compels organizations to an incessant reassessment in an effort to respond to continuous challenges. Therefore warehouses must be continually re-evaluated to ensure that they are consistent with both market's demands and management's strategies. In this paper we discuss a mathematical programming model aiming to support product assignment and allocation to the functional areas as well as the size of each area. In particular a large mixed-integer programming model (MILP) is presented to capture the trade-offs among the different warehouse costs in order to achieve global optimal design satisfying throughput requirements.

INTRODUCTION

A supply chain can be considered as a network of entities whose efficiency and effectiveness is highly determined by the performance of the overall network (see Figure 1).

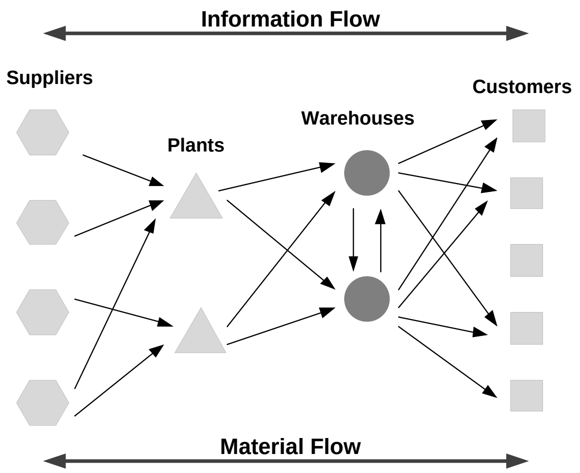

Figure 1: A typical supply chain network

In a supply chain network, products need to be physically moved. During this process, they may be buffered or stored at warehouses for a certain period of time for tactical or strategic reasons. Within this context warehouses play an important role in supply chains and may be considered a key aspect in a very demanding and uncertain market.

Warehousing is concerned with all the material handling activities that take place within the warehouse. They include the receiving of goods, storage, order-picking, accumulation and sorting and shipping. Basically, one can distinguish two types of warehouses: *distribution warehouses* and *production warehouses*. According to Van den Berg and Zjim (1999), a distribution warehouse is a warehouse in which products from different suppliers are collected, and sometimes assembled for delivery to a number of customers. On the other hand, a production warehouse is used for the storage of raw materials, semi-finished products and finished products in a production facility.

According to Bartholdi and Hackman (2006) there are four main reasons why warehouses are useful:

1. To consolidate products in order to reduce transportation costs and provide customer service;
2. To take advantage of economies of scale;
3. To provide value-added processing services and
4. To reduce response time.

Thus, these facilities will continue to be important nodes in the logistic network by the fact that if a warehouse cannot process the customers' orders quickly, effectively, and accurately, then all the supply chain optimization efforts will suffer (see Tompkins, 2003).

The primary functions of a warehouse include: (i) temporary storage of products; and (ii) providing value-added services such as packaging of products, after sales services; inspections and assembly. To perform these functions warehouses are generally divided into different functional areas, i.e. receiving, storage reserve and forward areas, accumulation and shipping (see Figure 2). At the receiving area products – Stock Keeping Units (SKUs) – are unloaded and inspected to verify any quantity and quality inconsistency. Afterwards, items are transferred to a storage zone or are directly placed to the shipping area (this is called a cross-docking operation). We can distinguish two types of storage areas: reserve storage area and forward or picking area. The reserve area is the place where the products stay until they are required by costumers' orders. The picking area is a relatively small area, typically used to store fast moving products. Most of the flows between these areas are the result of replenishment processes. Order picking is one of the most important functions in most warehouses. SKUs are retrieved from their storage positions based on customers' orders and moved to the accumulation and sorting area or directly to the shipment area. The picked units are then grouped by customer order, packaged and stacked on the right unit load and transferred to the shipping area.

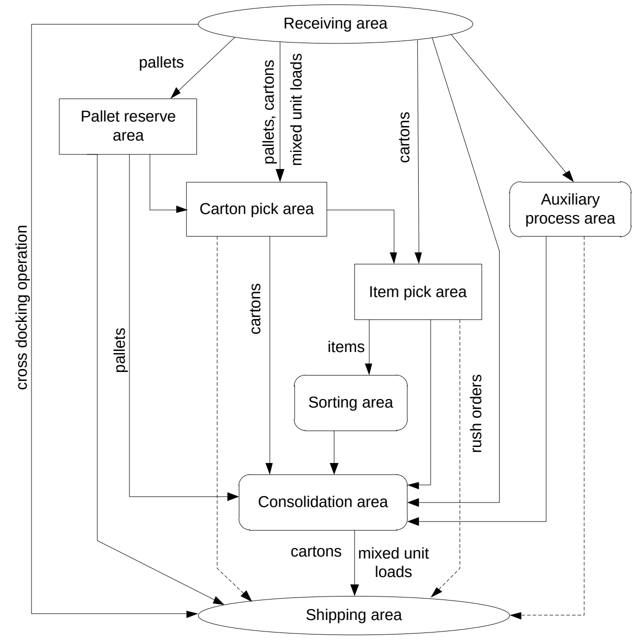

Figure 2: Functional structure of a warehouse (adapted from Salvendy, 2001)

The design of a warehouse is a very complex problem due to the large number of interrelated decisions. Some major decisions involved in the warehouse design and operational problems are illustrated in Figure 3 (see Gu et al., 2007).

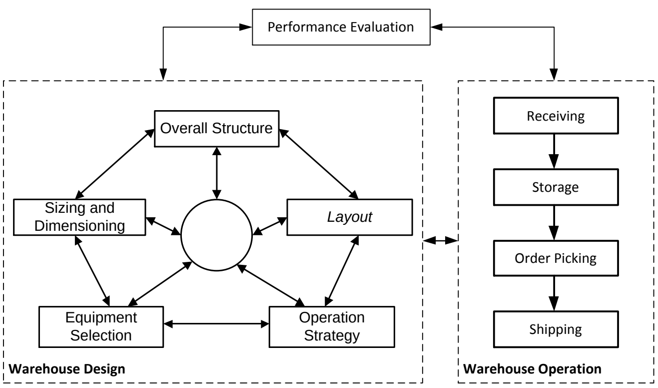

Figure 3: A framework for design and operation problems (adapted from Gu et al., 2007)

Warehouse design and planning typically runs from a functional description, through a technical specification, to equipment selection and determination of the layout. The overall structure decision determines the material flow patterns within the warehouse, the specification of functional areas and the flows between areas. Sizing and dimensioning decisions determine the total size of the warehouse as well as the space allocation among functional areas. Layout definition is the detailed configuration within a functional area and equipment decisions define an automation level for the warehouse and identify equipment types. Finally operating policies refer to storage, picking and routing decisions.

In distribution logistics where market competition requires higher performances from warehouses, companies are compelled to continuously improve the design and planning of warehouse operations. Furthermore, the ever-increasing variety of products, the constant changes in customer demands and the adoption of management philosophies also bring new challenges to reach flexible structures that provide quality, efficiency and effectiveness of the logistics operations. In practice, warehouses must be modular, adaptable, compact, accessible and flexible, and must be capable to respond to changing conditions, to improve space utilization and to reduce congestion and movement.

Despite the importance of warehousing there is not a comprehensive systematic method for the warehouse design problem (see Baker and Canessa, 2009). In this paper the authors explored the literature on the overall methodology of warehouse design, together with the literature on tools and techniques used for specific areas of analysis. The output was a general framework of steps, with tools and techniques that can be of value to warehouse practitioners.

Also Hassan (2002) presented a framework for the design of warehouse layout. The proposed framework accounts for several factors and operations of warehousing such as:

1. Specification of warehouse type and purpose;
2. Analysis and forecasting demand;
3. Definition of operating policies;
4. Establishment of inventory levels;
5. Class formation;
6. Definition of functional areas and general layout;
7. Storage partition;
8. Selection of equipment for handling and storage;
9. Design of aisles;
10. Determination of space requirements;
11. Location and number of I/O points;
12. Location and number of docks;
13. Arrangement of storage;
14. Zone formation.

Once warehouse decisions are strongly interrelated, warehouse design is a highly complex task where frequently conflicting objectives impose specific trade-offs.

Despite the various decision models available in scientific literature, the majority addresses isolated problems in a pyramidal top-down approach in order to provide the best solution. Strategic decisions create limits to decisions taken at the tactical and operational levels and tactical decisions limits operational decisions (see Van den Berg, 1999). However, most of the real problems are unfortunately not well-defined and often cannot be reduced to multiple isolated sub-problems. Therefore, warehouse design often requires a mixture of analytical skills and creativity. Anyhow, research aiming an integration of various decisions models and methods is badly needed in order to develop a methodology for systematic warehouse design (see Rouwenhorst et al. 2000).

In this paper we present a mathematical programming model that integrates issues concerning:

- The size of the warehouse functional areas;
- The assignment and allocation of SKUs to storage areas;
- The external storage additional capacity, if needed.

Our aim is to test an integrated approach that takes into account some warehouse decisions.

The section 2 of this paper will present a small literature review on warehouse design and planning problems including the most relevant modelling contributions. In section 3 we discuss the mathematical model, state some assumptions in our approach and mention the methodology used to solve the model. Computational results will be presented and summarized in section 4. Finally some conclusions and future work directions are reported in section 5.

LITERATURE REVIEW

According to Rouwenhorst et al. (2000) the warehouse design problem is a "coherent cluster of decisions" and they define decisions to be coherent when a sequential optimization does not guarantee a globally optimal solution. Thus, warehouse design can be defined as a structured approach of decision making at distinct levels in an attempt to meet a number of well-defined performance criteria.

The design of a warehouse is a highly complex problem. It includes a large number of interrelated decisions involving warehouses processes, warehouse resources and warehouses organizations (see Heragu, 2005). Rouwenhorst et al. (2000) classify management decisions concerning warehousing into strategic decisions, tactical decisions and operational decisions. Strategic decisions are long term decisions and always mean high investments. The two main issues are concerned with the design of the process flow and with the selection of the types of warehousing systems. Tactical management decisions are medium term decisions based on the outcomes of the strategic decisions. The tactical decisions have a lower impact than the strategic decisions, but still require some investments and should therefore not be reconsidered too often. At the operational level, processes have to be carried out within the constraints set by the strategic and tactical decisions made at the higher levels. At this level, the concern includes the operational policies such as storage policies and picking and routing operations.

Gray et al. (1992) propose a multi-stage hierarchical design method for the design and operation of a typical order-consolidation warehouse. This approach included warehouse layout, equipment and technology selection, item location, zoning, picker routing, pick generation list and order batching. The hierarchical approach used a sequence of coordinated mathematical models to evaluate the major economic trade-offs and to reduce the decision space to a few alternatives. They also used simulation technique for validation and fine tuning of the resulting design and operating policies.

Van den Berg et al. (1998) proposed a binary programming model to solve de forward-reserve problem (FRP) in the case of unit load replenishment and presented efficient heuristics that provide tight performances guaranties. Those replenishments can occur during busy or idle picking periods. The objective was to minimize the number of urgent or concurrent replenishments of the forward area during the busy periods.

Heragu et al. (2005) developed a mathematical model and a heuristic algorithm that jointly determines the functional areas size and the product allocation in a way that minimizes the total material handling and storage costs. The proposed model uses real data readily available to a warehouse manager and considers realistic constraints.

Geraldes et al. (2008a) adapted the mixed-integer programming model proposed by Heragu et al. (2005) to tackle the storage allocation and assignment problems during the redesign process of a Portuguese company warehouse.

Liu (1999) applied clustering techniques to extract the correlated information from customer orders, and then stock locations were optimized. The author proposed a binary programming model to group products or customers. An exact primal-dual type algorithm was explored and implemented using real data collected from a distribution centre. Simulation results also demonstrated the potential benefits of the clustering technique to solve the stock location problem. Geraldes et al. (2008b) adapt Liu (1999) linear programming model to a case study and its performance was assessed through the use of real data.

Strack and Pochet (2010) presented a robust approach that integrates aspects such as: (i) the size of the functional areas; (ii) the assignment and allocation of products to storage locations in the warehouse; and (iii) the replenishment decision in the inventory management. This is probably the most integrated model found in this area, nevertheless still assumes fixed and known capacity for the warehouse.

More recently Geraldes et al. (2012) discussed a mathematical programming model that jointly integrates the total size of the warehouse, the external storage additional capacity if needed and the replenishment quantities and reorder points of the products to be stored. Although the model was a mixed-integer nonlinear programming model with a large number of variables it was possible to solve it to optimality, using a general optimization package, in very satisfactory times.

The model discussed in Geraldes et al. (2012) does not include some important warehouse design and planning decisions. For example: the size of the warehouse functional areas, and the assignment and allocation problem of the products.

In the next section a programming model will be discussed aiming to tackle these warehouse decisions. For that purpose the flow patter of the products and the size of the warehouse functional areas will be optimised taking into account the global storage capacity

MATHEMATICAL MODEL

Model assumptions

Temporary storage of products may be considered one of the major warehouse functions. The model presented by Strack and Pochet (2010) assumed fixed and known capacities for both forward and reserve areas. Our approach will then try to have a model capable of obtaining optimal sizes for the functional areas.

In this paper we consider a warehouse composed of four functional areas: receiving, reserve storage, forward or picking storage, and shipping. Thus, the following material flows are possible (see Figure 4):

1. Flow 1: Receiving → Reserve → Shipping
2. Flow 2: Receiving → Reserve → Forward → Shipping
3. Flow 3: Receiving → Forward → Shipping

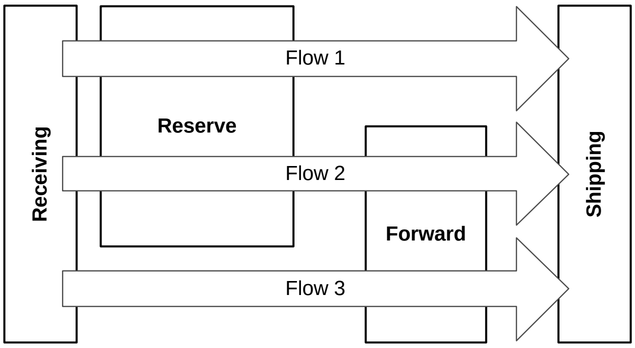

Figure 4: Typical product flows in the warehouse

Flow 1 refers to a pattern that characterises a typical warehouse operation. Products are stored in a reserve area and picking operation is performed as required. Usually it is assumed that only those products that remain for long periods of time or product quantities used for replenishment will be allocated in this area. Flow 2 is also a typical warehouse operation. Products with this pattern flow are initially stored in the reserve area and then moved to the forward area. This pattern flow is considered for fast picking operations, order consolidation or even to perform value-added operations. Flow 3 refers to products that go directly to the forward area. This pattern flow is usually seen when where there is a need to consolidate large orders.

In the next section, we present a mathematical model that determines the flow to which each product must be assigned and as result the size of the functional areas within the warehouse. It assumes the following:

- The available total storage capacity is known;
- It is possible to rent external storage space if necessary;
- The forward storage area will be handled through a dedicate storage policy;
- The reserve storage area will assume a random storage policy;
- The warehouse operation costs are known;
- The product demand rates and order quantities are known and based on continuous review policy (reorder point system).

Model formulation

In formulating the model, the following notation, adapted from Strack and Pochet (2010), is used:

Parameters:

i	: Product number ($i = 1, \dots, I$)
j	: Number of locations in the forward area ($j = 1, \dots, J$)
$CapW$	: Total storage capacity of the warehouse
$CostRepA$	: Cost of advanced replenishment
$CostRepC$	: Cost of concurrent replenishment
$CostR$	: Reception cost for the reserve area
$CostF$	: Reception cost for the forward area
$PickF$	: Picking cost in the forward area
$PickR$	: Picking cost in the reserve area
$CostCapS$	: External capacity cost
u_{ij}	: The increase in the expected number of replenishment if we allocate an additional location in the forward area to product i
α_i	: Number of units of product i that can be stored in a single location of the forward area
$E(U_i)$	: Expected value of the demand of product i
$E(p_i)$	: Expected value of the number of picks of product i
L	: Supply lead time
d_i^L	: Demand of product i during L
μ_i^L	: Average demand of product i during L
σ_i^L	: Standard deviation of demand of product i during L
Q_i	: Order quantity for product i
r_i:	: Reorder point of product i

Decision variables:

$$x_{ij} = \begin{cases} 1 & \begin{array}{c} if\ product\ i\ has\ a\ Flow\ 2\ pattern\ with\ \ at \\ least\ j\ locations\ allocated\ in\ the\ forward\ area \end{array} \\ 0 & otherwise \end{cases}$$

$$y_i = \begin{cases} 1 & if\ product\ i\ has\ a\ Flow\ 3\ pattern \\ 0 & otherwise \end{cases}$$

$$z_i = \begin{cases} 1 & if\ product\ i\ has\ a\ Flow\ 1\ pattern \\ 0 & otherwise \end{cases}$$

$CapR$: Capacity of the reserve area

$CapF$: Capacity of the forward area

$CapS$: External storage capacity

The general formulation of the model can be stated as:

$$min \sum_{i=1}^{I} CostRepA \times x_{i1} + \sum_{i=1}^{I}\sum_{j=1}^{J} CostRepC \times u_{ij} \times x_{ij}$$
$$+ \sum_{i=1}^{I} CostR \times \frac{E(U_i)}{Q_i} \times (z_i + x_{i1}) + \sum_{i=1}^{I} CostF \times \frac{E(U_i)}{Q_i} \times y_i$$
$$+ \sum_{i=1}^{I} PickF \times E(p_i) \times (x_{i1} + y_i) + \sum_{i=1}^{I} PickR \times E(p_i) \times z_i$$
$$+ CostCapS \times CapS \qquad (1)$$

Subject to:

$$x_{ij} \le x_{ij-1} \quad \forall_{i,j} : j \ge 2 \qquad (2)$$

$$x_{i1} + y_i + z_i = 1 \quad \forall_i \qquad (3)$$

$$\sum_{i=1}^{I}\left[\left(\sum_{j=1}^{J} x_{ij}\right) + \left(\frac{Q_i + r_i - \mu_i^L}{\alpha_i}\right) y_i\right] \le CapF \qquad (4)$$

$$\sum_{i=1}^{I}\left[\left(\frac{Q_i}{2} + r_i - \mu_i^L\right)(z_i + x_{i1}) - \sum_{j=1}^{J} \alpha_i x_{ij}\right] \le CapR + CapS \qquad (5)$$

$$CapF + CapR \le CapW \qquad (6)$$

$$LL_R \le CapR \le UL_R \qquad (7)$$

$$LL_F \le CapF \le UL_F \qquad (8)$$

$$CapF, CapR, CapS \ge 0 \qquad (9)$$

$$x_{ij}, y_i, z_i \in \{0, 1\}\ \forall_{i,j} \qquad (10)$$

The objective function (1) minimizes the warehouse operating costs per period. We have taken into account: (i) costs of advance and concurrent replenishments of the forward area; (ii) reception costs for both reserve and forward areas; (iii) picking costs for the forward and reserve areas; and (iv) rental cost of the external storage capacity. Constraints (2) are sequencing constraints that specify that a j^{th} location can only be assigned to the product i if $j-1$ locations have already been assigned. In addition, constraint (3) ensures that each product is assigned to only one flow pattern in the warehouse. Constraints (4)-(5) ensure that the space constraints for the forward and reserve areas are met, and constraint (6) guarantees that the total available capacity in the warehouse is not exceeded. Constraints (7)-(8) serve to enforce upper and lower limits on the space that can be allocated to forward and reserve areas. Finally, a set of variables must be nonnegative (9) and another set is considered binary (10).

Comparatively to the original model this formulation add two new decision variables, since the size of the reserve are forward areas are now unknown, and three new constraints (6)-(7)-(8).

Mathematical model analysis and methodology

The above optimisation problem was modelled as a mixed-integer objective function with linear inequality constraints. This type of mathematical models can be solved directly using a branch-and-bound algorithm.

To evaluate the computational performance involved in solving the proposed model, experimental tests were performed using LINGO 12.0 solver which uses a branch-and-bound algorithm for mixed-integer linear problems. All tests were performed on an Intel Core 2Duo 1.4 GHz CPU and 3GB RAM.

COMPUTATIONAL RESULTS

In this section, numerical results of a preliminary study are presented and discussed. Instances for different scenarios were randomly generated to assess the behaviour of the model when the number of products increases (see Table 1). Table 2 shows parameter values used to generate the testing problems.

Table 1: Analysed scenarios

	Scenario			
	I	II	III	IV
SKU [units]	10	100	1000	5000
$CapaW$ [no. locations]	7	70	600	3000

Table 2: Parameter values for the numerical examples

Parameter	Value
$CostRepA$	5
$CostRepC$	20
$CostR$	5
$CostF$	8
$PickF$	3
$PickR$	10
$CostCapS$	30
$E(U_i)$	Uniform [1, 50]
$E(p_i)$	Uniform [1, 5]
d_i^L	$N(\mu_i^L, \sigma_i^L)$

Table 3 shows some solutions details (CPU time, binary variables, and number of constraints) explored by the branch-and-bound algorithm in LINGO 12.0 solver.

Table 3: Solution details for four scenarios

	Scenario I	Scenario II	Scenario III	Scenario IV
Total variables	93	3203	62003	3760003
Binary variables	90	3200	62000	3760000
No. of constraints	74	3004	60004	3750004
Iterations	6	183	26767	-
CPU time [mm:ss]	00:01	00:05	11:03	-
State	Global Opt.	Global Opt.	Global Opt.	**

** Due to the size of the generator matrix, the computer did not have sufficient memory.

It was possible to analytically solve to optimality tree of the four test scenarios in a very satisfactory computational time. Thus, it may be concluded that, in general the branch-and-bound algorithm is very efficient and converge to the global optimal solution in a very short time. However, as the problem size increases the computational time of LINGO rises. For large instances (see scenario IV) the number of variables and constraints of the model increased considerably. Consequently solving the model takes significant computational time and computer memory. It was not possible to obtain the solution details for this scenario due to the insufficient memory of the used computer.

CONCLUSIONS AND FUTURE WORK

Having a single decision model capable of integrate several decisions concerning warehouse design is a very complex task due the enormous amount of existing alternatives, and to the existence of various and often conflicting objectives through and out of the warehouses.

In this paper the product assignment and allocation problem and the functional area size determination problem in the design of a warehouse were considered. The presented mathematical model jointly integrates: (i) the size of both functional areas (reserve and forward); (ii) the assignment and allocation of SKUs to the storage areas; and (iii) the external storage additional capacity, if needed. The aim was to have a single model that jointly determine the flow pattern for each product, the dimensions of the functional areas and the eventual need of rent some external storage area minimizing the warehouse costs.

Although the model is a mixed-integer linear programming model with a large number of variables, computational results of the preliminary study, show that it was possible to solve the model to optimality in very satisfactory times using a branch-and-bound algorithm.

Even though the presented model integrates some important decisions, many other decisions concerning the design and planning of a warehouse were not included. For example: the storage policy, the picking and routing strategies, etc. However gathering several decisions in a single model leads us to complex models difficult to treat and analytically solve. For that reason we believe that simulation technique can be used to validate the models and to incorporate dynamic aspects not yet included. For example, we can use the solution obtained by solving the mathematical model and then simulation can be used to introduce operational decisions related with storage, picking and routing strategies.

Given the prevalence of warehouses in the supply chain networks and despite some advances in integrated models we believe that further research is still required and may have significant impact in the supply chain performance.

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