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# A Supporting Decisions Platform for the Design and Optimization of a Storage Industrial System

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## 1. Introduction

In a recent survey the consulting company AT Kearney (ELA/AT Kearney survey 2004) states that there are more than 900,000 warehouse facilities worldwide from retail to service parts distribution centers, including state-of-art, professionally managed warehouses, as well as company stockrooms and self-store facilities. Warehouses frequently involve large expenses such as investments for land and facility equipments (storage and handling activities), costs connected to labour intensive activities and to information systems. Lambert et al. (1998) identify the following missions:

- Achieve transportation economies (e.g. combine shipment, full-container load).
- Achieve production economies (e.g. make-to-stock production policy).
- Take advantage of quantity purchase discounts and forward buys.
- Maintain a source of supply.
- Support the firm's customer service policies.
- Meet changing market conditions and again uncertainties (e.g. seasonality, demand fluctuations, competition).
- Overcome the time and space differences that exist between producers and customers.
- Accomplish least total cost logistics commensurate with a desired level of customer service.
- Support the just-in-time programs of suppliers and customers.
- Provide customers with a mix of products instead of a single product on each order (i.e. consolidation).
- Provide temporary storage of material to be disposed or recycled (i.e. reverse logistics).
- Provide a buffer location for trans-shipments (i.e. direct delivery, cross-docking).

Bartholdi and Hackman (2003) conversely recognize three main uses:

- *Better matching the supply with customer demands*

Nowadays there is a move to smaller lot-sizes, point-of-use delivery, high level of order and product customization, and cycle time reductions. In distribution logistics, in order to serve customers, companies tend to accept late orders while providing rapid and timely delivery within tight time windows. Consequently the time available for order picking becomes shorter.

- *Consolidating products*

The reason to consolidate products is to better fill the carrier to capacity and to amortize fixed costs due to transportation. These costs are extremely high when the transportation mode is ship, plane or train. As a consequence a distributor may consolidate shipments from vendors into larger shipments for downstream customers by an intermediate warehouse.

- *Providing Value-added processing*

Pricing, labelling and light assembly are simple examples of value added processing. In particular the assembly process is due for a manufacturing company adopting the postponement policy. According to this policy products are configured as close to customers as possible.

As a result warehousing systems are necessary and play a significant role in the companies' logistics success.

## 2. Classification and notation

A classification of warehouse design and operation planning problems is illustrated in Figure 1 (Gu et al., 2007).

A more detailed description of each problem category previously identified is given in Table 1. This paper will focus mostly on both warehouse design issues and the operation planning problems.

Table 1 reports a large number of problems whose literature presents many studies, models and supporting decision methods and tools. A limited number of studies present integrated approaches to face simultaneously a few of these problems which are significantly correlated. The performance of the generic operation usually depends on design decisions (see Table 1). As a consequence the authors of this chapter decides to develop, test and apply an original DSS based on an integrated approach to best design and manage a warehousing system. It takes inspiration from literature models and algorithms developed during last two decades.

Main operations and functional areas within a general warehousing system are: receiving, transfer and put away, order picking/selection, accumulation/sorting, cross-docking, and shipping.

Fig. 2. Typical warehouse operations (Inspired by: Tompkins et al., 2003) show the flows of product and identifies the typical storage areas and relative logistic movements.

In particular, the *receiving activity* includes the unloading of products from the transport carrier, updating the inventory record, inspection to find if there is any quantity or quality inconsistency. The *transfer* and *put away* involves the transfer of incoming products to storage locations. It may also include repackaging (e.g. full pallets to cases, standardized containers), and physical movements (from the receiving docks to different functional areas, between these areas, from these areas to the shipping docks). The *order picking/selection* involves the process of obtaining a right amount of the right products for a set of customer orders. It is the major activity in most warehouses. The *accumulation/sorting* of picked orders into individual (customer) orders is a necessary activity if the orders have been picked in batches. The *cross-docking* activity is performed when the received products are transferred directly to the shipping docks (short stays or services may be required but no order picking is needed). The storage function is the physical containment of products while they are awaiting customer demands. The form of storage will depend on the size, quantity of the products stored, and the handling characteristic of products or their product carriers (Tompkins et al., 2003).

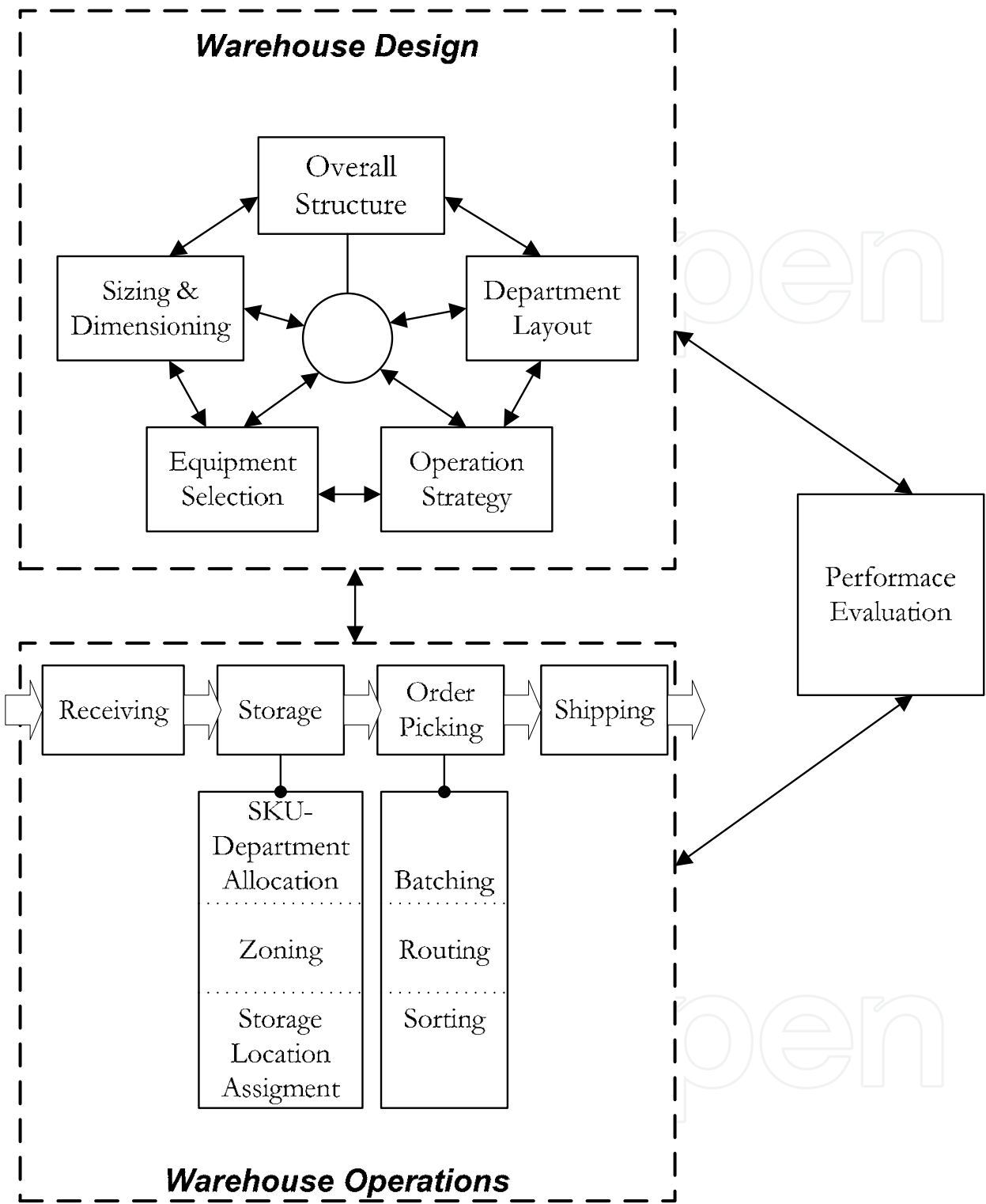


Fig. 1. Framework for warehouse design and operation problems, (Gu et al., 2007).

### 2.1 Order picking systems

Order picking (*OP*) can be defined as the retrieval of items from their warehouse locations in order to satisfy demands from internal or external customers (Petersen, 1999). In order picking systems (OPSs) incoming items are received and stored in (large-volume) unit pallet

loads while customers order small volumes (less than unit loads) of different products as simply shown in Figure 3. Typically, hundreds of customer orders, each made of many requests (orderlines), have to be processed in a distribution warehousing system per day.

| Design and operation problems         |                         |  | Decisions  |
|---------------------------------------|-------------------------|--|--|
| Warehouse design                      | Overall structure       |  | • Material flow  |
|                                       |                         |  | • Department identification                                  |
|                                       |                         |  | • Relative location of departments                           |
|                                       | Sizing and dimensioning |  | • Size of the warehouse                                      |
|                                       |                         |  | • Size and dimension of departments                          |
|                                       |                         |  | • Pallet block-stacking pattern (for pallet storage)         |
|                                       | Department layout       |  | • Aisle orientation  |
| • Number, length, and width of aisles |                         |  |  |
| • Door locations                      |                         |  |  |
| Equipment selection                   |                         | • Level of automation  |  |
|                                       |                         | • Storage equipment selection                                    |  |
|                                       |                         | • Material handling equipment selection (order picking, sorting) |  |
| Operation strategy                    |                         | • Storage strategy selection (e.g., random vs. dedicated)        |  |
|                                       |                         | • Order picking method selection                                 |  |
|                                       |                         |  |  |
| Warehouse operation                   | Receiving and shipping  |  | • Truck-dock assignment                                      |
|                                       |                         |  | • Order-truck assignment                                     |
|                                       |                         |  | • Truck dispatch schedule                                    |
|                                       | Storage                 | SKU-department assignment  | • Assignment of items to different warehouse departments     |
|                                       |                         |  | • Space allocation   |
|                                       |                         | Zoning   | • Assignment of SKUs to zones                                |
|                                       |                         |  | • Assignment of pickers to zones                             |
|                                       |                         | Storage location assignment                                      | • Storage location assignment                                |
|                                       |                         |  | • Specification of storage classes (for class-based storage) |
| Order picking                         | Batching                | • Batch size   |  |
|                                       |                         | • Order-batch assignment   |  |
|                                       | Routing and sequencing  | • Routing and sequencing of order picking tours                  |  |
|                                       |                         | • Dwell point selection (for AS/RS)                              |  |
|                                       | Sorting                 | • Order-lane assignment  |  |

Table 1. Description of warehouse design (Gu et al. 2007)

Even though there have been various attempts to automate the picking process, automatic systems are rarely found in practice. Order picking, like many other material handling activities, still is a repetitive and labour-intensive activity. Order picking systems, which involve human operators can be generally organized in two ways, namely as a *part-to-picker* system in which the requested products are delivered automatically to a person at an input/output (I/O) point, or as a *picker-to-parts* system in which the order picker travels to storage locations in order to bring together the required products. Figure 4 gives a comprehensive classification of OPSs (De Koster 2004).

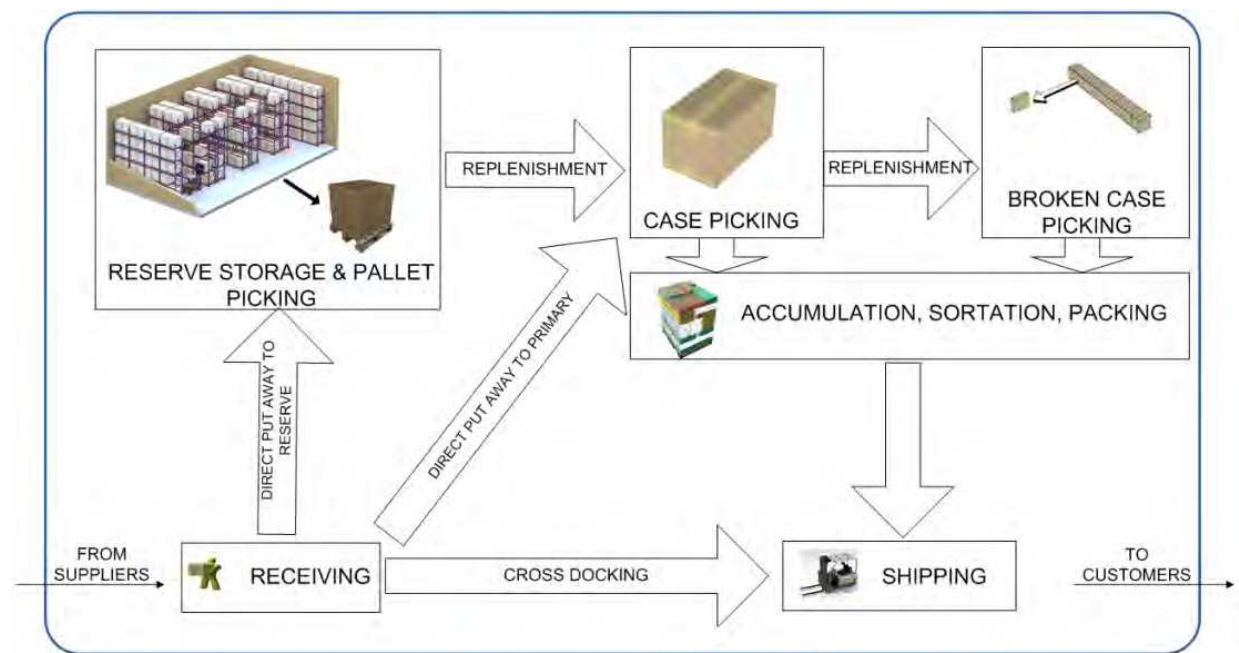


Fig. 2. Typical warehouse operations (Inspired by: Tompkins et al., 2003)

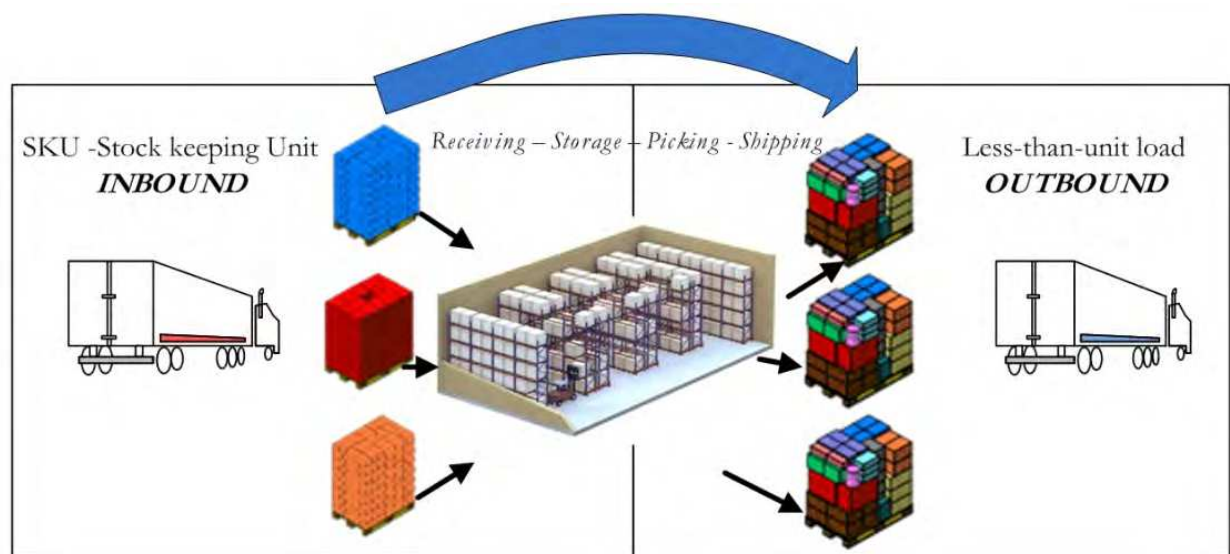


Fig. 3. From stock keeping units (skus) to customer orders

It can be distinguished two types of picker-to-parts systems: *low-level* systems and *high-level* systems. In low-level OPSs the picker picks requested items from storage racks or bins. Due to the labour intensity, low level systems often are called manual OPSs. Some other order picking systems have high storage racks; order pickers travel to the pick locations on board of a stacker or order-pick truck, or a crane. The crane mechanically stops in front of the correct pick location and waits for the order picker to execute the pick. This type of system is called high-level or *man-aboard* system. Parts-to-picker systems include *automated storage and retrieval systems* (AS/RS), using mostly aisle-bound cranes that retrieve one or more unit loads (e.g. of bins: mini-load system, or pallets) and carry the loads to a pick station (i.e. I/O point). At this station the order picker picks the right quantity requested by the customer



order, after which the residual stock quantity is stored again. This type of system is also called *unit-load OPS*. The automated crane can work under different functional modes: single, dual and multiple *command cycles*. The *single-command* cycle means that either a load is moved from the I/O point to a rack location or from a rack location to the I/O point. In the *dual-command* mode, first a load is moved from the I/O point to the rack location and next another load is retrieved from the rack. In multiple command cycles, the S/R machines have more than one shuttle and can pick up several loads in one cycle, at the I/O point or retrieve them from rack locations.

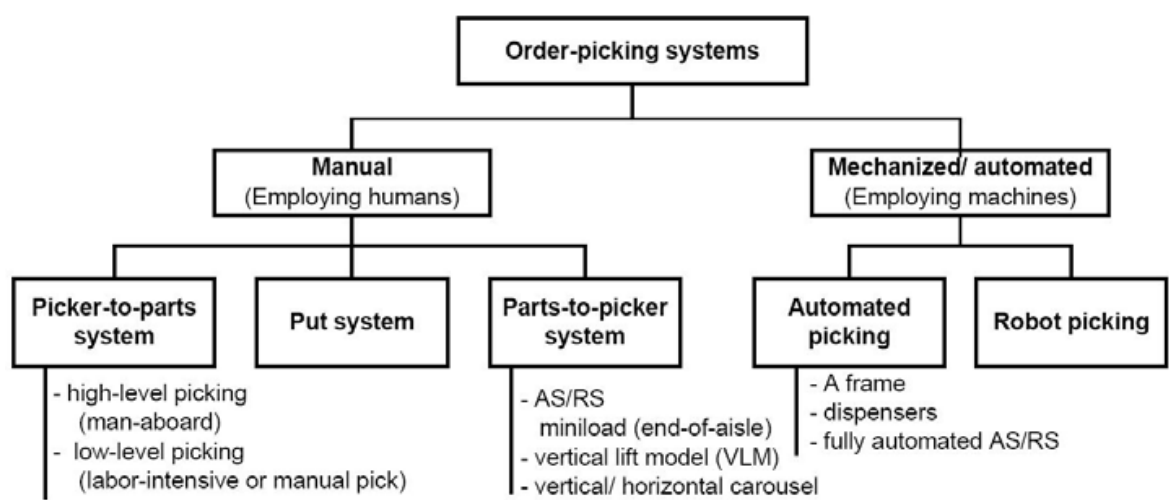


Fig. 4. Classification of order-picking systems (based on De Koster 2004)

Manual-pick picker-to-parts systems are the most common (De Koster, 2004). The basic variants include picking by article (*batch picking*) or pick by order (*discrete picking*). In the case of picking by article, multiple customer orders (the batch) are picked at the same time by an order picker. Many in-between variants exist, such as picking multiple orders followed by immediate sorting (on the pick cart) by the order picker (sortwhile-pick), or the sorting takes place after the pick process has finished (pick-and-sort).

Another basic variant is *zoning*, which means that a logical storage area (this might be a pallet storage area, but also the entire warehouse) is split in multiple parts, each with different order pickers. Depending on the picking strategy, zoning may be further classified into two types: *progressive zoning* and *synchronized zoning*. Under the progressive (or sequential) zoning strategy, each batch (possibly of one order) is processed only in one zone at a time; at any particular point in time each zone processes a batch that is dissimilar from the others. Hence, the batch is finished only after it sequentially visits all the zones containing its line items. Under the synchronized zoning strategy, all zone pickers can work on the same batch at the same time.

3. Conceptual framework and DSS for warehousing systems

Figure 5 illustrates a conceptual framework for the design, control and optimization of an industrial storage system. This framework is the result of the integration of different models and supporting decision methods & tools by the adoption of a systematic multi-step approach. The proposed approach involves several decisions which rarely are faced

simultaneously by the decision maker. As a consequence he/she has to accept local optima and sub optimizations.

Main decisions deal with the determination of (1) the *system type*, e.g. automatic or manual warehousing system, parts-to-picker or picker-to-parts, unit-load or less than unit-load, forward-reserve or forward only, etc.; (2) the best *storage capacity* of the system in terms of number of pallet locations for each sku; (3) the *structure of the system*, i.e. the layout and configuration of the system in terms of racks, bins, aisles, etc.; (4) the *allocation of product volumes* to the storage area in agreement with the whole capacity defined by (1) and in presence/absence of a reserve area; (5) the *assignment of products* to the storage area; (6) the *evaluation of the performance* of the adopted system configuration by the simulation of vehicles' routes.

A brief and not exhaustive classification of storage systems types has been introduced in previously illustrated Figure 4 (as proposed by De Koster 2004). The generic form of the proposed DSS is made of active tables for data entry, reports, graphs and tables of results, etc. A "Quick report" section reports all necessary information for the user: for example it is possible to show the sequence of picking in an order according to a given picking list and to collect a set of performance indices. Next subsections illustrate main data entry forms and decision steps for the design of a storage system.

This chapter adopts the following terms many times: fast-pick, reserve, bulk, sku, etc.. *Which is the difference between the fast-pick area and the reserve one?* The *fast-pick area* is a site inside the warehouse where the most popular skus are stored in rather small amounts so that a large part of daily picking operations can be carried out in a relatively small area with fast searching process and short travelled routes. The items most frequently requested by customers are grouped in this storage area, which is often located in an easily accessible area so that the time of picking and handling is minimized. The location of the items in the fast pick area is better than any other in the warehouse and related operations, e.g. stocking, travelling, searching, picking, and restocking, are faster.

### 3.1 Storage capacity evaluation

The proposed DSS adopts two alternative approaches for the so-called *stock capacity evaluation* (step 2): *historical inventory* (2/HI) based approach and *demand profile* (2/DP) based approach. 2/HI identifies a storage capacity of a warehousing system in agreement with a set of historical, e.g. monthly, stock levels and a specified *risk of stockout*, as a measure of probability a generic stockout occurs in a period of time, such a year. The generic value of inventory level usually refers to the global storage quantity (volume) level of products including both the level for picking and the level for reserve: companies rarely collect historical data on their storage quantities and very rarely they distinguish the storage levels in fast pick area from corresponding levels in bulk area.

The proposed platform supports the determination of the storage level constructing a non parametric *class based frequency analysis* and/or a non parametric continuous *frequency based analysis*. These are non parametric statistical analyses because they do not identify statistical distributions, e.g. Normal, Lognormal, Weibull, etc., as a result of best fitting available data (Manzini et. al 2010). These analyses are the basis for estimating percentiles of historical variation of inventory, i.e. the expected *risk of stockout* adopting a specific level of storage capacity and assuming future movements of products into/out of the system similar to the historical ones.



The so-called class based analysis of historical storage quantities generates a histogram of frequency values of storage levels collected in the adopted historical period of time by the preliminary definition of a number of histogram classes of values. The histogram of cumulative values identifies the probability of "stockin", i.e. the probability of the complementary event of the stockout (the probability that stockout would not occur).

The *continuous frequency based* analysis generates a similar set of graphs without the preliminary definition of a number of classes of values (historical measures).

The so called DP approach identifies the best level of storage capacity by the analysis of historical demand profiles. Given a period of time, e.g. one year, and a set of values of demand quantities for each product within this period, DP quantifies the expected demand during an assumed subperiod of time  $t$ , called *time supply* (e.g. 3 weeks). As a consequence this approach assumes to store an *equal time supply* of each sku. This is a frequently adopted strategy in industrial applications and is widely discussed by Bartholdy and Hackman (2003): the equal time strategy - EQT. By this strategy the storage system should supply the expected demand orders for the period of time  $t$  without stockouts. Obviously this depends on the adopted *fulfilment system*, which relates with *inventory management decisions* significantly correlated to the storage/warehousing decisions object of this chapter.

The output of a storage capacity evaluation is the storage volume of products in the fast pick area (adopting a forward-reserve configuration system) and the whole storage capacity (including the bulk area when forward-reserve configuration is adopted). In presence of fast picking, it usually refers to the lowest level of storage: the so-called 0 level.

This capacity is usually expressed in terms of cubic meter, litres, number of pallets, cases, carton, pieces of products, etc.

Figure 6 presents the form of the proposed DSS for data entry and evaluation of historical storage levels given an admissible risk of stockout. This figure also shows a curve "risk of stockout" as a result of the statistical analysis of historical observations: this is the *stockout probability plot*. Obviously given a greater storage capacity this risk decreases.

### 3.2 Structure of the system: layout & configuration

This section deals with the determination of the layout and configuration of the storage system as the result of warehouse type (see previous discussion and classification) selection including the existence/absence of the forward-reserve strategy, picking at low/high levels, etc.; pallet/unit load dimensions; racks and shelves dimensions; adopted vehicles for material handling. It is important to underline that the layout of the storage area significantly depends on the width of the aisles which have to host different kinds of vehicles:

- vehicles for the *pallet-loading/put-away* process, which usually involves unit loads;
- vehicles for *restocking* (generally unit loads) in presence of a forward-reserve system;
- vehicles for *picking* (unit loads and less than unit loads) at low/high levels.

Figure 7 and 8 present the forms for data entry of *unit load parameters* and *warehouse setting* respectively. All vehicles are characterized in terms of *routing strategies*, distinguishing *traversal* from *return* (Manzini et al. 2006). It is possible to distinguish the vehicle parameters for put-away, restocking and picking. The *shape factor* of a storage system is the ratio between the frontal length and longitudinal length of system layout: this value can be optimized in presence of pallet-loading of unit loads, given the location of the I/O depot area and adopting a shared, i.e. randomized, storage allocation of products. In any different hypotheses, e.g. in presence of less than unit load picking activities, there is not an optimal value of this ratio and the user can arbitrary choose it.

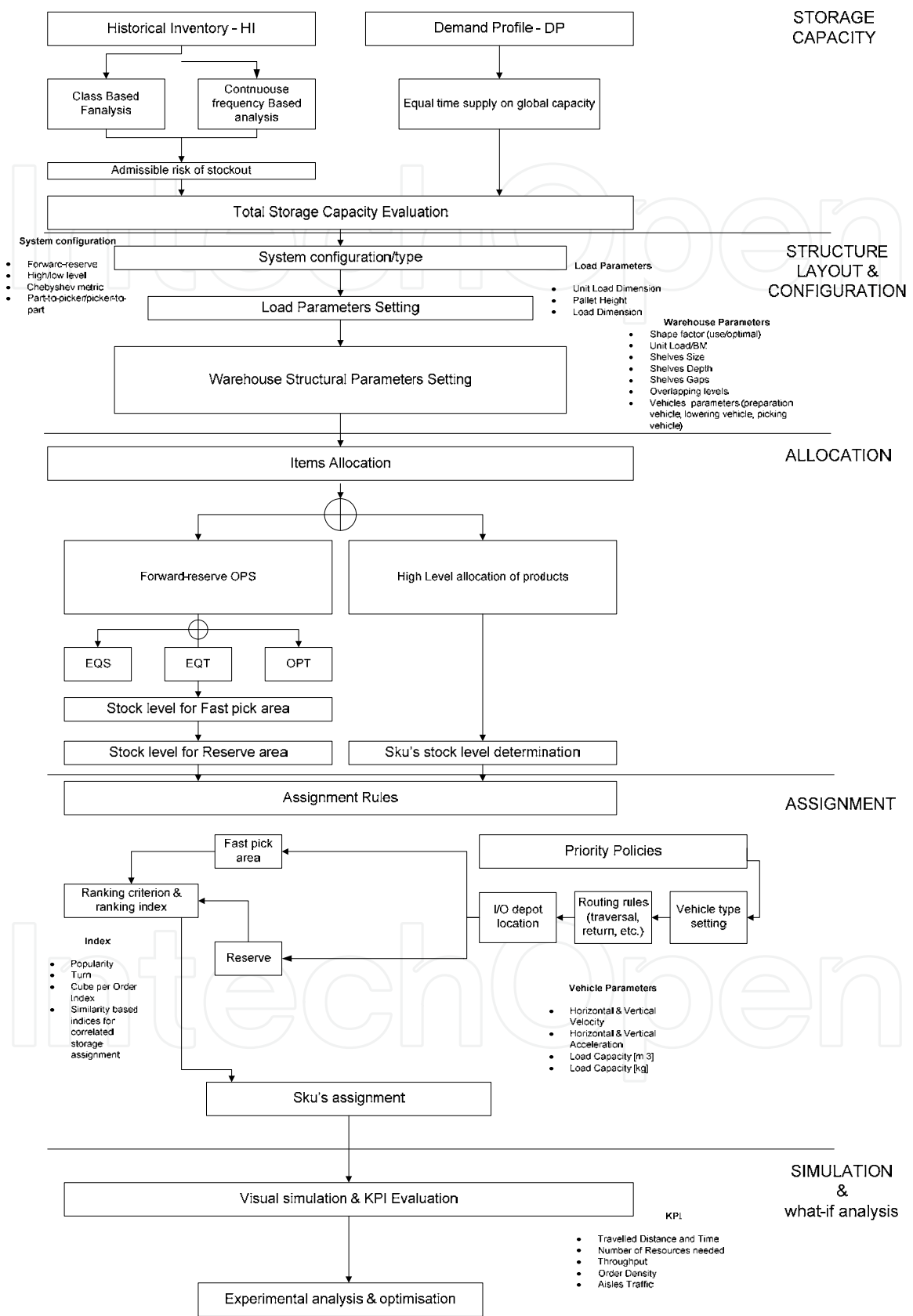


Fig. 5. Conceptual framework

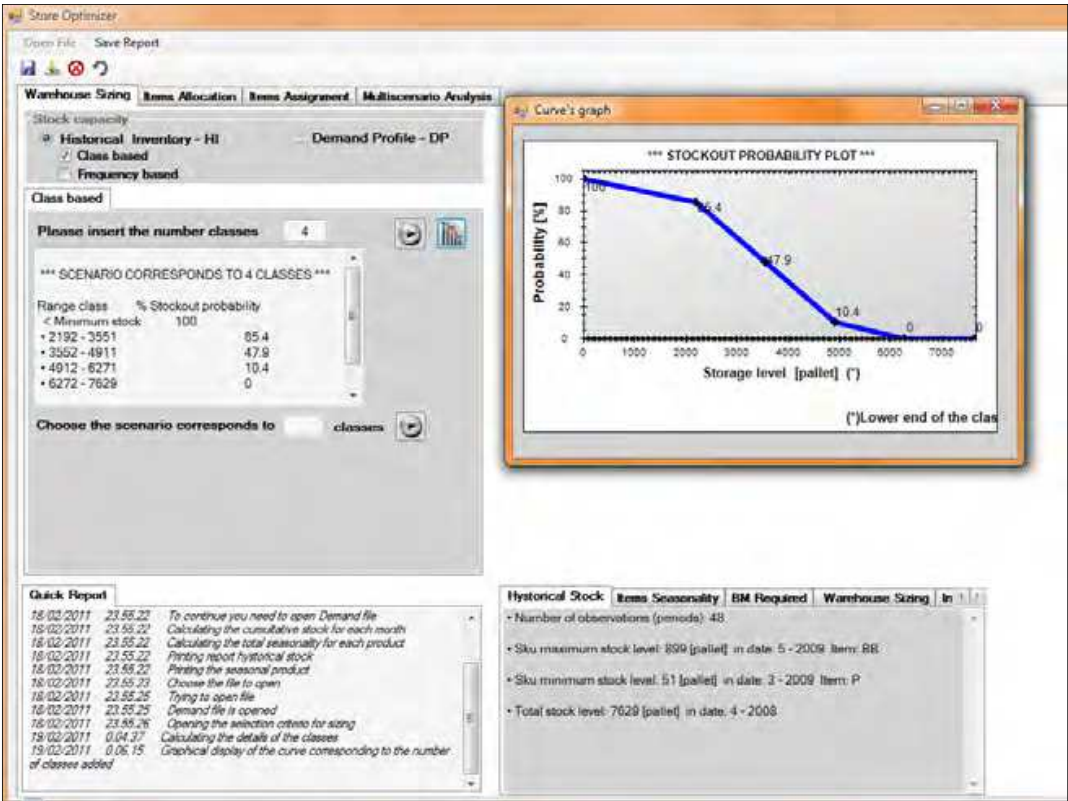


Fig. 6. Historical storage levels analysis and capacity evaluation.

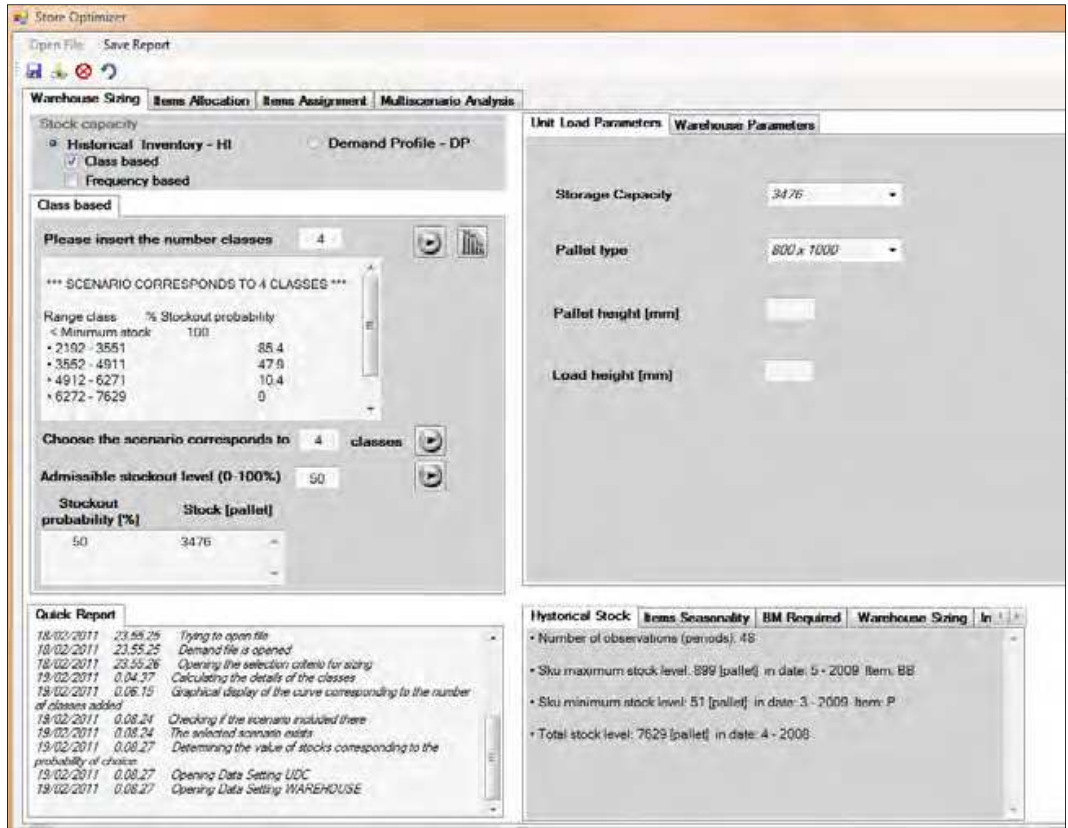


Fig. 7. Data entry, unit load parameters.

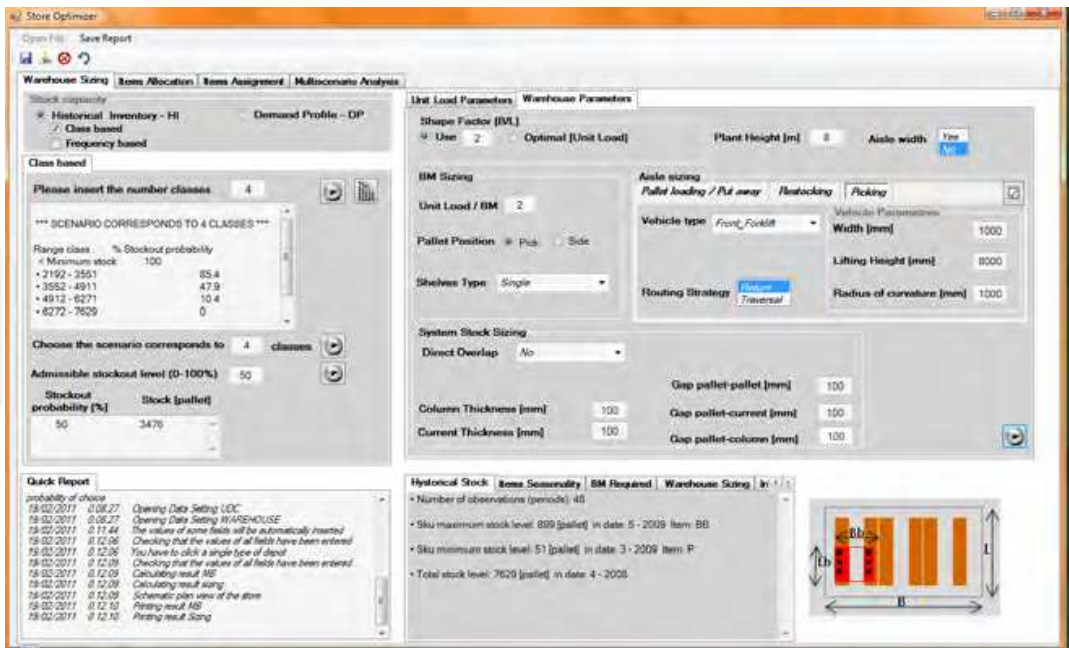


Fig. 8. Data entry, warehouse parameters.

Many other parameters are not described in this brief illustration of the proposed DSS. Figure 9 shows an exemplifying set of reports collecting the results as output of layout & configuration design. They are grouped in different sections: historical stock, BM required, warehouse sizing, etc. A few exemplifying results are: number of historical observations, storage volume available, number of levels, number of bays, number of aisles, etc.

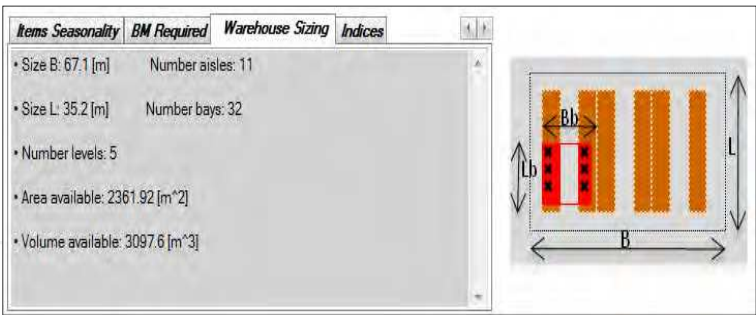


Fig. 9. Warehouse sizing reports

### 3.3 Items allocation

This sections deal with the application of the so called *allocation strategy*, i.e. the determination of the fraction of storage volume for each sku that is a product (also called item). In particular the manager is interested in the following critical question: *which is the best amount of space to assign to any skus?* This question refers to the fast pick area in presence of a forward-reserve storage system and adopting a *dedicated storage*, which adopts *fixed storage locations* for the generic sku.

Bartholdi and Hackman (2003) discuss this issue in order to reduce the number of restocks in a fast pick (forward) and bulk storage (reserve) picking system. The fast pick area cannot contain the right volume of each item required to satisfy the total customer demand in a



specific supply period of time e.g. a month or a year. Consequently, it is necessary to ensure replenishment of picked goods from a bulk storage area, known as *reserve area*.

Therefore, consideration has to be given to an appropriate choice between the space allocated for an item in the fast pick area and its restock frequency (Bartholdi and Hackman, 2003). They discuss three different allocation strategies for calculating the volume to be assigned to each sku assuming it incompressible, continuously divisible fluid. The models proposed for determining the sku level of stock are based on the following notation:

- let  $f_i$  be the rate of material flow through the warehouse for the sku<sub>i</sub>;
- let the physical volume of available storage be normalized to one.  $v_i$  represents the fraction of space allocated to sku<sub>i</sub> so that:

$$\sum_i v_i = 1 \quad (1)$$

Three different levels of stock for sku<sub>i</sub> are defined as follows:

- Equal Space Strategy* (EQS). This strategy identifies the same amount of space for each sku. The fraction of storage volume to be dedicated to the sku<sub>i</sub> under EQS is:

$$EQS_i = \frac{1}{n} \quad (2)$$

- Equal Time Strategy* (EQT). In this strategy each sku  $i$  is replenished an equal number of times according to the demand quantities during the period of time considered. Let  $K$  be the common number of restocks during a planning period so that:

$$\frac{f_i}{v_i} = K \quad (3)$$

From equations (1) and (3):

$$K = \sum_i f_i \quad (4)$$

The fraction of storage volume to be dedicated to the sku<sub>i</sub> under EQT is:

$$EQT_i = \frac{f_i}{K} = \frac{f_i}{\sum_i f_i} \quad (5)$$

- Optimal Strategy* (OPT). Bartholdi and Hackman (2003) demonstrate that this strategy minimizes the number of restocks from the reserve area. The fraction of available space devoted to sku<sub>i</sub> is:

$$OPT_i = \frac{\sqrt{f_i}}{\sum_i \sqrt{f_i}} \quad (6)$$

A critical issue supported by the what-if multi-scenario analysis, which can be effectively conducted by the proposed DSS, is the best determination of the fraction of storage volume for the generic sku as the result of the minimization of pickers travelling time and distance in a forward – reserve picker to part order picking system.

Equations (2), (5), and (6) are fractions of fast pick volume to be assigned to the generic item  $i$ . As a consequence it is necessary to preliminary know the level of storage to be assigned to the fast pick area in order to properly defined each dedicated storage size. A company usually traces and knows the historical picking orders with a high level of detail (date of order, pickers, picked skus and quantities, visited locations, pickers id, restocking movements, etc.) thanks to traceability tools and devices (barcode, RFID, etc.), but it rarely



has "photographs" of the storage systems, i.e. historical values of storage levels. In presence of forward-reserve systems and a few (or many) photographs of storage levels, the generic inventory level, made available by the warehouse management system, does not distinguish the contribution due to fast pick area and that stored in bulk area as discussed in section 3.1. The proposed DSS supports the user to define the whole level of storage for fast picking, the level of storage for bulk area and those to be assigned to each sku in both areas.

Items allocations affect system performance in all main activities previously discussed: pallet-loading (L), restocking/replenishment (R) and picking (P). This is one of the main significant contributions of the proposed DSS to knowledge and warehousing system optimization. The following questions are still open: *Which is the effect of storage allocation to travel time and distances due to L, R and P activities? Given a level of storage assigned to the fast pick area, is the OPT the best allocation storage for travel distance and time minimization?*

We know that the OPT rule, equation (6), supports the reduction of the number of restocks (R) but the logistic cost of material handling is also due to (I) and (P) activities. The multi-scenarios what-if analysis supported by the proposed DSS helps the user to find the most profitable problem setting which significantly varies for different applications.

Figure 10 presents exemplifying results of the item allocation for an industrial application. This is a low level forward-reserve OPS: for each sku the number of products in fast pick and reserve areas is determined.

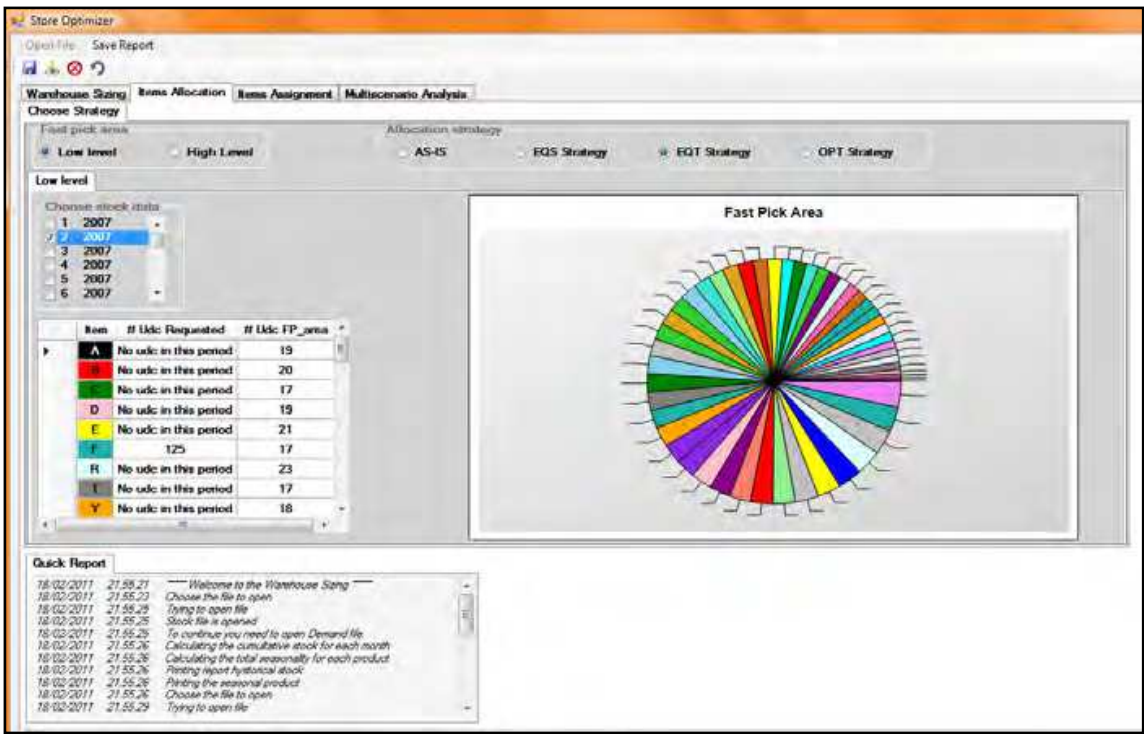


Fig. 10. Allocation of products, fast-pick area.

3.4 Skus assignment

The *storage assignment problem* deals with the assignment of products to storage locations in order to identify which is the best location for the generic product (Cahn, 1948). Decisions on storage assignment affect both time and costs due to I, R and P activities. The assignment problem has been formalized by Frazelle and Sharp (1989) and classified as a Non - Polynomial (NP) hard problem.

A list of typical indices adopted to rank the skus for the assignment of storage locations follows:

- *Popularity (P)*. This is defined as the number of times an item belongs to an order in a given set of picking orders which refer to a period of time  $T$ :

$$P_{i,T} = \sum_{\substack{\text{order } j \\ \text{in period } T}} x_{ij} \quad (7)$$

where

$$x_{ij} = \begin{cases} 1 & \text{if item } i \text{ occurs in order } j \\ 0 & \text{Otherwise} \end{cases}$$

$(x_{ij})$  product-order incidence matrix.

- *Cube per Order Index (COI)* can be defined as the ratio of volume storage to inventory for the generic sku to the average number of occurrences of sku in the order picking list for a given period of time (Haskett, 1963). Given an sku  $i$ , COI is defined as the ratio of the volume of the stocks to the value of its popularity in the period of interest  $T$ . Formally:

$$COI_{i,T} = \frac{v_{i,T}}{\sum_{\substack{\text{order } j \\ \text{in period } T}} x_{ij}} \quad (8)$$

where

$v_{i,T}$  average storage level of sku  $i$  in time period  $T$ .

- *Order Closing Index (OC)*. Order Completion (OC) assignment is based on the OC principle introduced by Bartholdi and Hackman (2003). Bindi (2010) introduced the Order Completion rule based on an index called *OC index* that evaluates the probability of a generic item being part of the completion of an order, composed of multiple orderlines of different products (items). The OC index is the sum of the fractions of orders the generic item performs. For a generic sku and a time period  $T$ , OC is defined as follows:

$$OC_{i,T} = \sum_j f_{ij,T} \quad (9)$$

where

$$f_{ij,T} = \frac{x_{ij}}{\sum_{\substack{\text{order } j \text{ in} \\ \text{period } T}} x_{ij}} \quad (10)$$

$m(j)$  number of orderlines for picking order  $j$ .

According to the previous hypotheses the OC index for a certain item can assume the following special values:

- *Minimum value* =  $1 / \text{Total Number of Items}$ , when the item belongs to all the customer orders.
- *Maximum value* = number of orders, when the item belongs to all customers orders and there are no other items.

- *Turn Index (T)*. Given an sku  $i$ , it is defined as the ratio of the picked volume during a specific period of time  $T$  to the average stock stored in  $T$ . The index can be written as:

$$T_{i,T} = \frac{\sum_j p_{ij}}{v_{i,T}} \quad (11)$$

order  $j$  in  
period  $T$

where

$p_{ij}$  picked volume of product  $i$  in the order  $j$ . The unit of measurement is the same as  $v_{i,T}$ .

The literature presents several storage assignment policies that can be classified in one of the following main categories (Van der Berg and Zijm 1999, Manzini et al. 2006 and 2007):

- *Randomized Storage*  
This policy provides for skus randomly assigned to the first available space in the warehouse. The random storage policy is widely adopted in the warehousing industry because it is easy to use, often requires less space than other storage methods, and uses all the picking aisles intensively.
- *Dedicated Storage*  
This policy reserves specific locations for each sku within the warehouse. It requires more space in the pick area for storage but allows the pickers to memorize fixed locations of skus producing time labour saving. The choice of dedicated location to assign a generic item follows one of the following rules:
  - *class based storage rule*. This rule defines several classes as groups of skus located in storage areas more or less favorable to satisfying particular criteria. Frazelle (2002) punctually states the two most frequently used criteria used to assign a class of products to storage locations are popularity and the cube per order index (COI) as defined by Haskett (1963).
  - *ranked index based rules*. They are based on the ascending or descending values of one of the previously introduced indices e.g. P, COI, OC, or T defined for each sku. The P-based assignment rule considers a list of items sorted by decreasing value of popularity and assigns the highest of them to the nearest location from the depot area (I/O point) i.e. the most favourable location. The COI-based assignment rule considers a list of items sorted by increasing value of COI and assigns the lowest of them to the most favourable location. The OC-based assignment rule arranges items in a similar way to the P-based rule: it considers a list of items sorted by decreasing value of OC index and assigns the highest of them to the most favourable locations. The Turn-based assignment rule assigns items in the same way as for the previous OC rule but uses Turn index instead of OC.
  - *correlated storage policy*. This policy locates items with a high degree of correlation close to each other, which is usually based on the frequency of being in different picking orders. The allocation of products within a storage area can be based on different types of correlation existing between products. Once the correlation has been calculated for all pairs of products, the couples with the highest value of correlation are stored together. For example, customers may usually order a certain item together with another. These products might reasonably have high correlation and it may be useful to locate them close together within the system to reduce the

travelling distance and time during the picking activity. In order to group products, the statistical correlation between them should be known or at least be predictable, as described by Frazelle and Sharp (1989), and by Brynzér and Johansson (1996).

The proposed tool assigns the location to the generic sku by the Cartesian product, as the direct product of two different sets. The first set  $(RANK_{sku})_i$  is made of the list of skus ordered in agreement with the application of a *ranking criterion* (see Figure 10), e.g. the popularity measure based rule or a similarity based & clustering rule (Bindi et al. 2009). The second set is made of available locations ordered in agreement with a priority criterion of locations assignment, e.g. the shortest time to visit the location from the I/O depot area. As a consequence most critical sku are assigned to the nearest available locations. Obviously the generic sku can be assigned to multiple locations in presence of more than one load stored in the system.

This assignment procedure refers to the products quantities subject to picking, e.g. located in the so called fast picking area: this is the so called *low level OPS*. In *high level* systems all locations at different levels can be assignable in agreement with the adopted ranking procedure. Both types of warehouses are supported by the proposed DSS. Figure 10 shows the form for setting the assignment of products within the system.

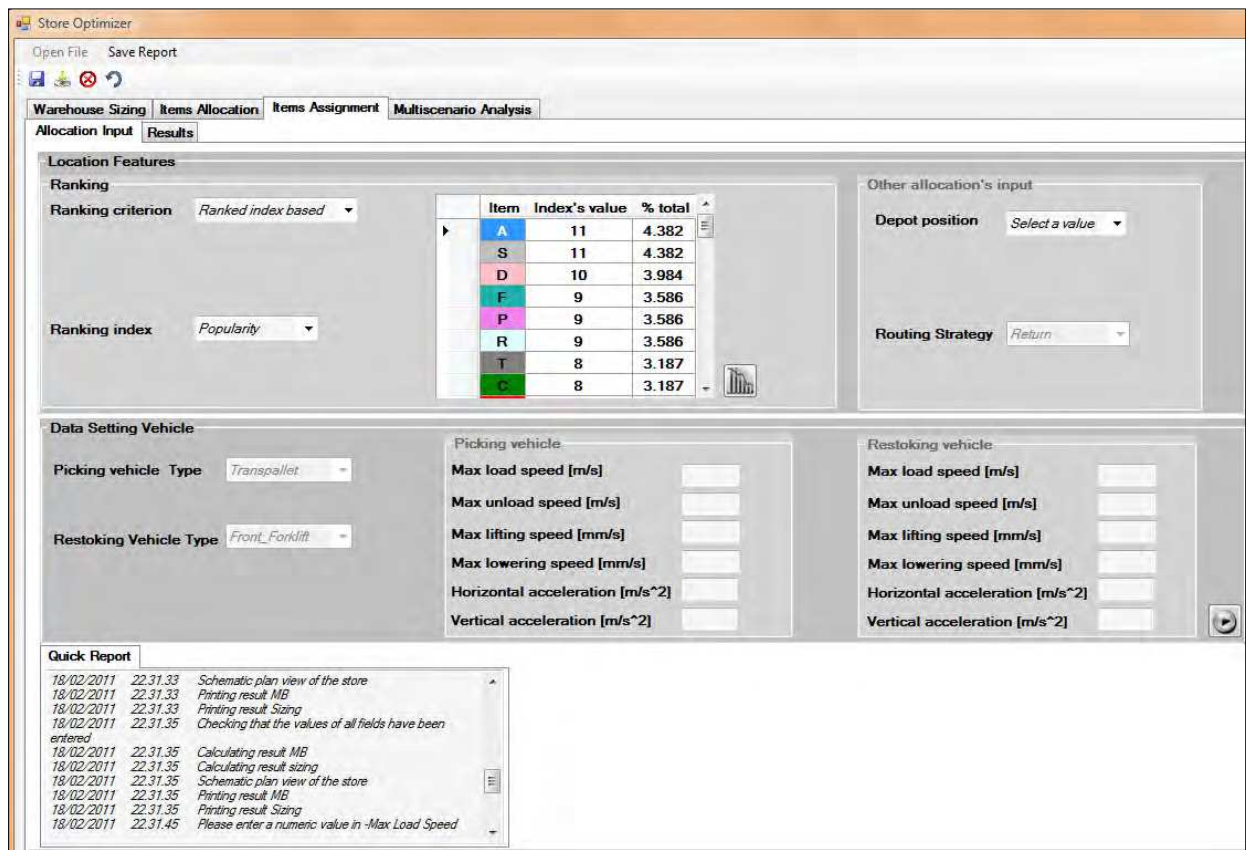


Fig. 10. Storage assignment setting, ranking criterion and ranking index.

Correlated storage assignment rules are supported by the DSS in agreement with the systematic procedure proposed and applied by Bindi et al. (2009 and 2010). Figure 11 exemplifies the result of the assignment of products within the fast pick area by the use of







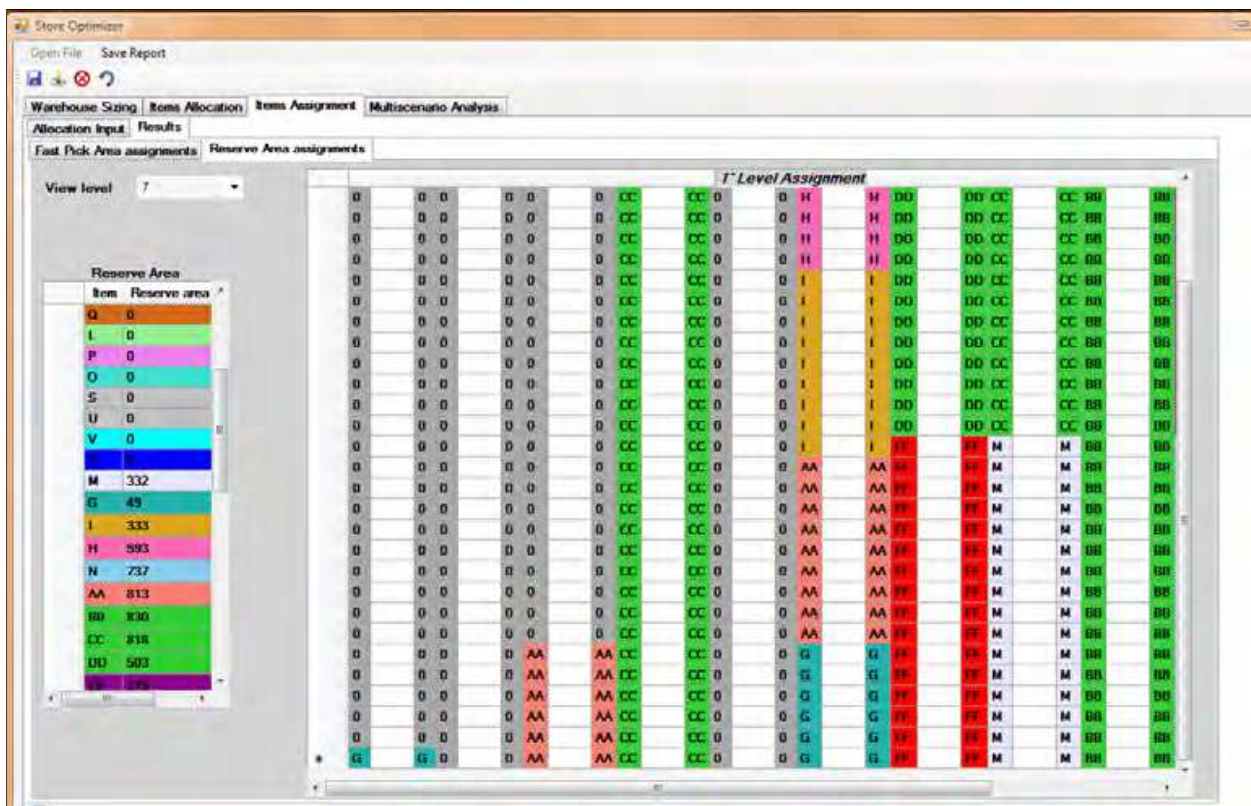


Fig. 12. Storage assignment results, reserve area.

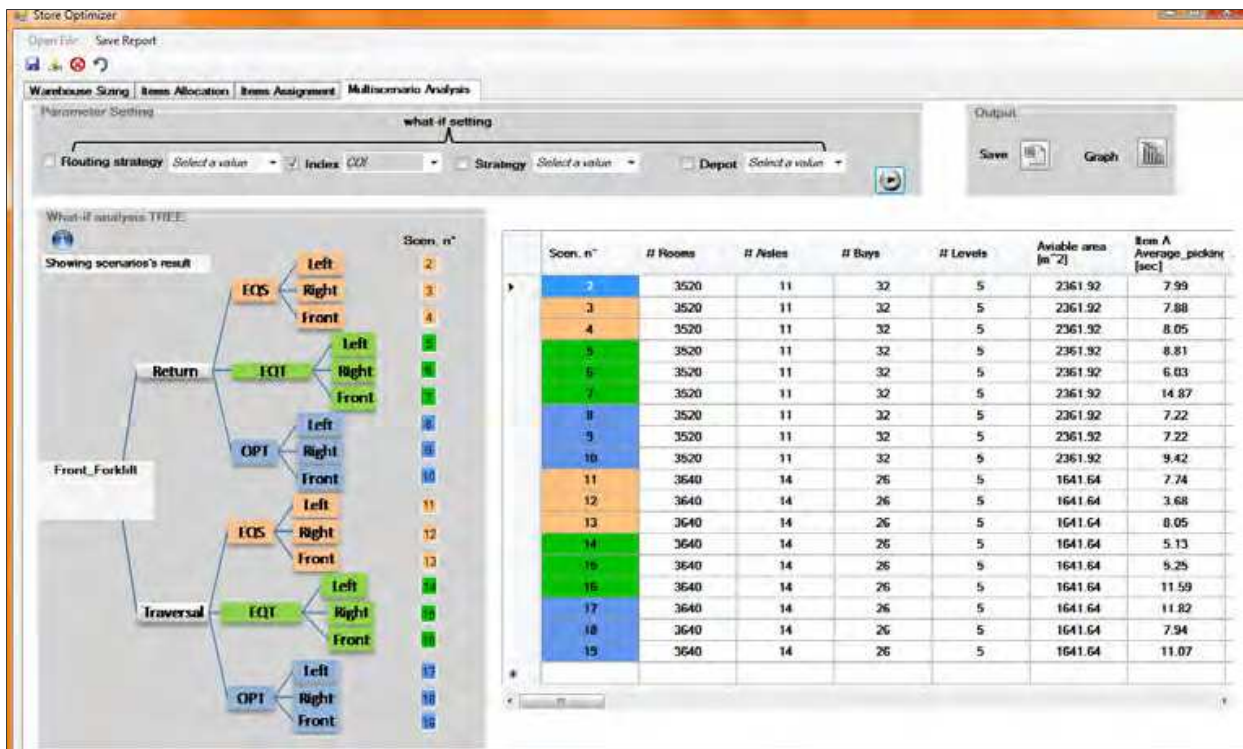


Fig. 13. Multi-scenario what-if analysis.

Figure 14 shows the form for the visual simulation of the picking orders in forward-reserve OPS. This simulation also quantifies the costs due to restocking. Similarly it is possible to simulate the behaviour of the system including *pallet loading* (L) activities, and/or in presence of AS/RS (adopting *Chebyshev* metric), and/or in presence of correlated storage assignment.

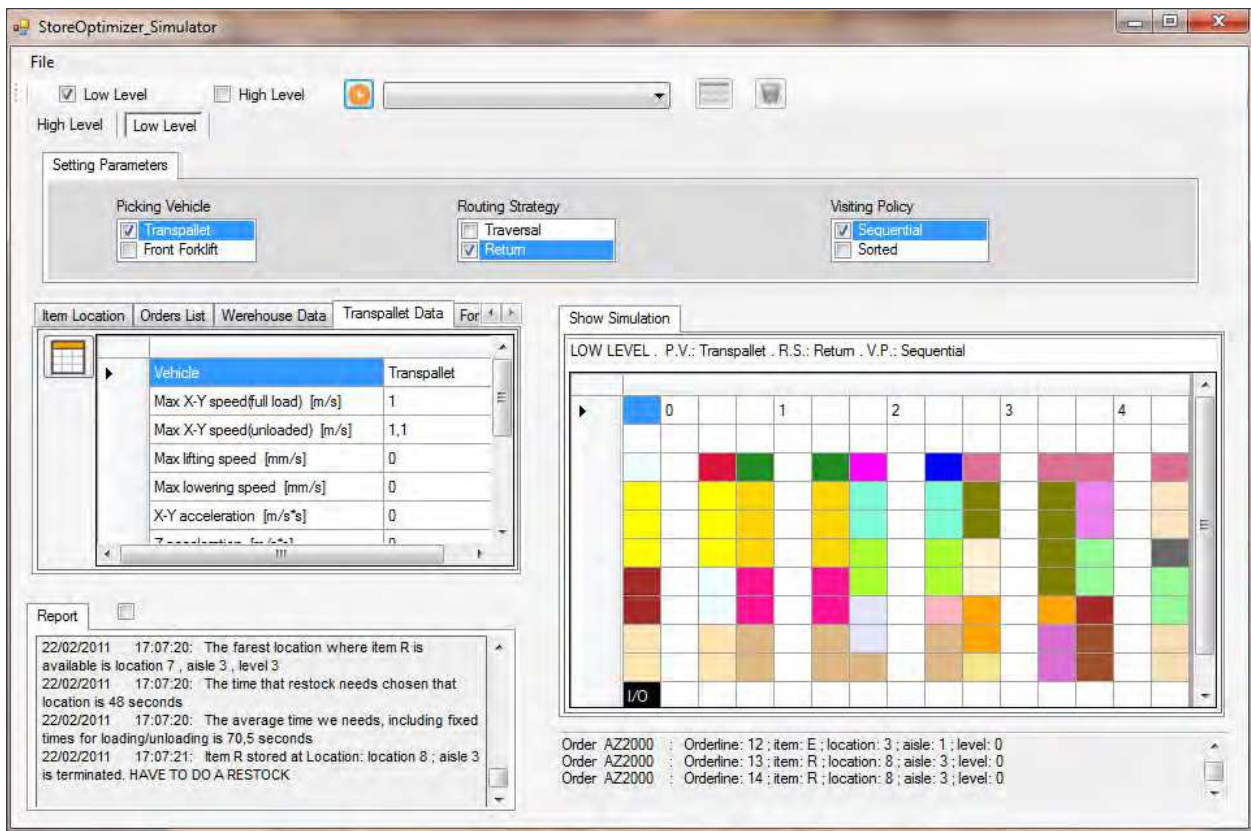


Fig. 14. Visual animation and simulation run.

4. Case study

The proposed DSS has been applied to a low level picker to part OPS for spare parts of heavy equipment and complex machinery in a popular manufacturing company operating worldwide. The total number of items stored and handled is 185,000 but this is continuously growing due to new business acquisitions and above all to engineering changes to address new requirements for pollution control and reduction.

The subject of the analysis is the picking activities concerning medium-sized parts weighing less than 50 pounds per piece. These parts are stored in light racks corresponding to about 89,000 square feet of stocking area. This area contains more than 3,000 different items.

The horizon time for the analysis embraces the order profile data during four historical months. The number of order picking lines is 37,000 that correspond to 6,760 different customer orders. The picking list presents an average of 86 orders fulfilled per day with the average depth varying around 6 items per order.

The result of the design of the order picking system is a 58,400 square foot picking area (350 feet x 170 feet). Table 2 demonstrates that OPT strategy significantly reduces the number of

restocks for the historical period of analysis in agreement with Bartholdi and Hackman (2010). The reduction is about 55% compared to EQS, and about of 62% compared to EQT, thus confirming the effectiveness of OPT strategy.

Table 3 reports the values of traveled distances and aisles crossed in retrieving operations i.e. excluding restocking for different assignment rules and allocation strategies. Table 3 demonstrates that COI and P assignment rules reduce picking activities and cost the most. In particular, the best performance is obtained by adopting the COI assignment rule and the EQS allocation strategy, quite different from the OPT strategy which minimizes the number of restocks (see Table 2).

|                |       |       |              |
|----------------|-------|-------|--------------|
|                | EQS   | EQT   | OPT          |
| Total Restocks | 3,650 | 4,269 | <b>1,635</b> |
| % Reduction    | 55.2% | 61.7% |              |

Table 2. Restocks with different allocation strategies

| Assignment rules | Allocation strategies |                |                   |                |                   |                |
|------------------|-----------------------|----------------|-------------------|----------------|-------------------|----------------|
|                  | EQS                   |                | EQT               |                | OPT               |                |
|                  | Traveled distance     | Aisles crossed | Traveled distance | Aisles crossed | Traveled distance | Aisles crossed |
| COI              | <b>6,314,459</b>      | <b>33,579</b>  | 6,025,585         | 33,659         | 6,706,537         | 34,482         |
| OC               | 6,536,697             | 33,922         | 8,047,296         | 36,210         | 7,241,533         | 35,424         |
| P                | 6,379,887             | 33,713         | 7,254,318         | 35,270         | 6,869,774         | 34,655         |
| T                | 8,015,507             | 35,766         | 8,155,378         | 36,191         | 8,717,042         | 36,497         |

Table 3. What-if analysis results. Traveled distance [feet] and aisle crossed [visits] during a picking period of 4 months

Figure shows where the most frequently visited skus are located in the fast pick area: the size of circles is proportional to the popularity value respectively according to the return and the traversal strategies.

5. Conclusions and further research

This chapter presents an original DSS for the design, management and optimization of a warehousing system. The large amount of decisions is usually faced separately as demonstrated by the literature proposing sub-optimal models and supporting decision methods. The proposed DSS is the result of the integration of different decisions, models and tools by the adoption of a systematic and interactive procedure. It supports the design of the system configuration, the allocation of skus, and their assignment to storage location, the vehicle routing and sequencing within the system. The evaluation of the performance is supported by the dynamic construction of vehicle routes to satisfy material handling needs collected in a period of time, named observation period.

Further research is expected on the following topics of interest:

- 3D computer aided design - CAD of the mechanical structure of the system as a result of the best system configuration



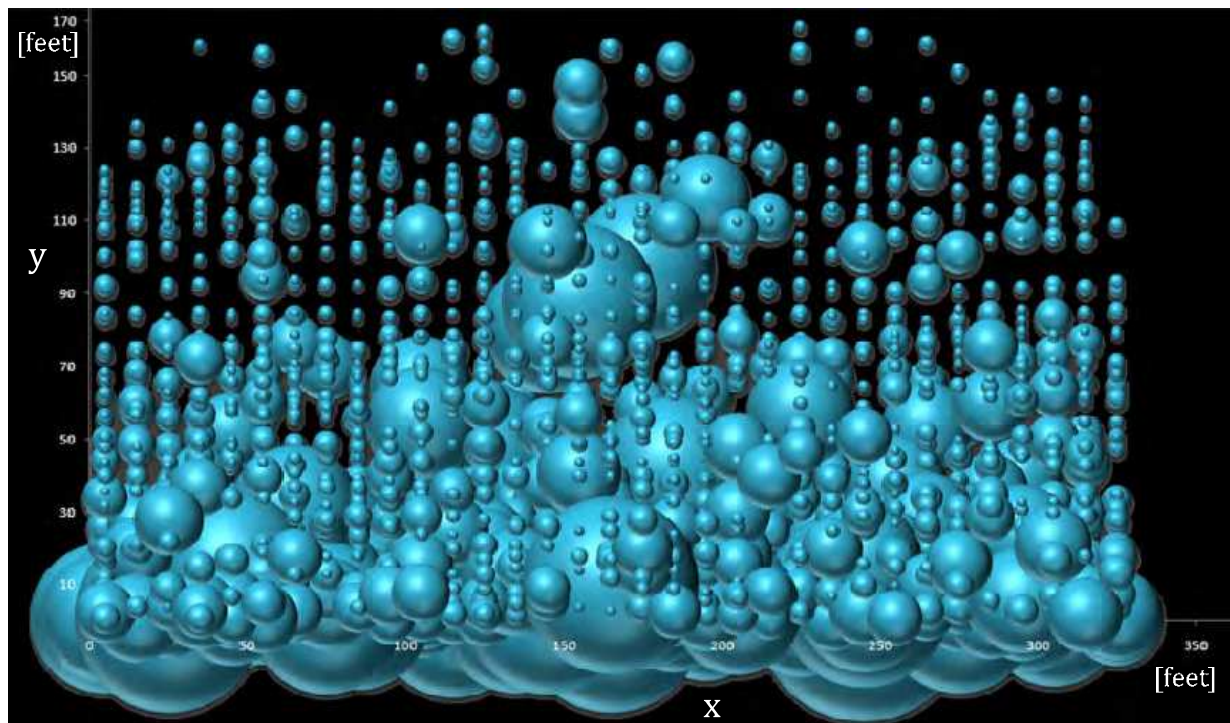


Fig. 15. Storage assignment in return strategy with I/O located at  $(x,y)=(170,0)$

- System validation and analysis of vehicle congestions by the execution of a dynamic and visual evaluation of system performance. A similar analysis can be conducted by the adoption of visual interactive simulation commercial tool, e.g. AutoMod <sup>TM</sup> simulation software. The development of ad hoc tools for a similar analysis conducted on warehousing systems is achieved.

## 6. Acknowledgment

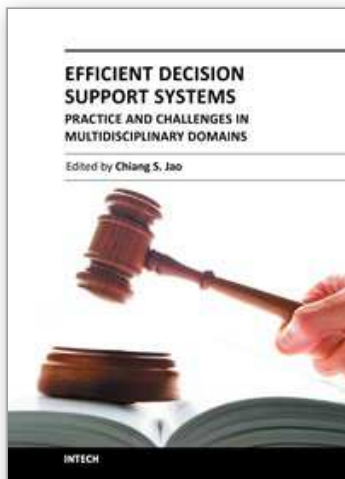
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## **Efficient Decision Support Systems - Practice and Challenges in Multidisciplinary Domains**

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