Redesigning storage assignment and order-picking policies of a miniload AS/RS system

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Redesigning Storage Assignment and Order-picking Policies of a Miniload AS/RS System: A Case Study

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Abstract

Miniload AS/RS have become increasingly more popular as their application becomes more diverse. Efficient Customer Response (ECR) and smaller order sizes are major pulling forces for the use of miniload AS/RS systems. In the last fifteen years miniload systems capabilities and reliability have improved greatly. Many miniload AS/RS installations have reduced drastically manual labor. However, they have not increased substantially the effectiveness of rapid response. Reasons for this include the wrong use of space available and the use of poor operational policies.

This paper presents the results of an analytical study performed for redesigning storage assignment and operational policies of the spare part miniload system of the Dutch Royal Airforce in the Netherlands. The miniload system contains all small spare parts needed for maintenance of transport-planes, jet fighters, and helicopters in use in the air force.

In this paper first we describe the system under-study along with the objectives of the study. We then review briefly the design and operational issues in a miniload AS/RS system. Afterwards the approach taken in redesigning is discussed. Here we present the analytical model used for assignment of spare parts to trays and assignment of trays to storage locations, the operational policies developed for order picking and sortation operations, and the results. A modified travel time model is used for choosing suitable picking polices and a mixed-integer linear programming model is developed for loading properly the miniload system in different working shifts. Finally we draw our conclusions.

Introduction of Case study

In an effort to consolidate spare parts inventories and improve the customer response time, in mid 1995 the Dutch Royal Airforce built an automated miniload system for its distribution center in a base where the major repair shop is located. The warehouse now contains most of the small spare parts needed for maintenance of transport-planes, jet fighters, and helicopters in use in the air force. Prior to this time, the spare part inventories were scattered around at different military air bases. A step-wise plan was prepared to move gradually a major part of these spare parts inventories to this base. Next to this miniload system, a full-pallet handling automated warehouse system was also built for large size parts. In this study we limit ourselves to the miniload system.

The miniload system in use consists of 4 aisles each side of which containing 1128 locations (24 vertical locations and 47 horizontal locations). In the start-up period in 1995, the warehouse contained about 40,000 parts which gradually will increase to 100,000 parts by reducing the size other spare parts warehouses . Each location in the miniload system contains a tray on which there may be different number of bins, depending on the size of the parts stored in those bins. In the system there are 10 different sorts of trays and the number of bins on each tray may vary from 1 to 60. Prior to this study, the assignment of parts to trays and assignment of tray to storage locations were based respectively on the physical characteristics of parts and the closest free location assignment rule.

The warehouse supports the demand of 20 different bases in the Netherlands including the base self. The delivery lead-time expected is 24 hours from the moment of issuing orders, which are sent by EDI to the distribution center. The functions of the distribution center can be summarized as follows:

- Receiving: spare parts are coming from manufacturers, military bases (in the Netherlands and abroad), and the repaired shop in the base under study. The receiving quantities vary with time for different supply sources.
- Controlling: the incoming parts are controlled for the quantity and quality. New identification bar codes are generated whenever necessary.
- Internal transport: the controlled parts are moved from expedition center to the miniload system. This handling is currently performed manually but in the near future it is to be automated using an AGV system.
- Storage: good arriving at the miniload system are assigned to specific bin locations on a specific trays.
- Order-picking & Retrieving: orders received during the day are compiled during the night based on their item-lines' bin and tray locations. An order-picking list is generated which is used for retrieving items during the day. In case of arriving emergency orders, these are treated with higher priority during the day.
- Packing: parts destined to a demand center are sorted and packed for shipping at the other side of the picking stations
- Grouping: parts retrieved from pallet-load warehouse and parts packed from the miniload system are grouped and sorted based on their destination address. This activity is performed mostly in the expedition center.

As can be noted the storage assignment and order picking policies in use were rather simple and not based on analytical models. Therefore, a study was set up to re-evaluate and redesign the current storage assignment and operational policies in order to meet with the growing number of items stored in the miniload and the pressure to the distribution center for reliable lead-time.

Design and Operational Issues in a Miniload AS/RS System

Almost 20 years have passed since the Automated Storage and Retrieval System (AS/RS) had first introduced to the logistics market, and now different automated warehouse types are employed in various industries for the effective logistics and processing (Schwind (1996)). Inventory reduction, a parallel development, has not made the warehousing function obsolete but made higher demands on warehousing systems for reducing costs and shortening delivery lead-times (Frazelle (1989)). This section briefs the literature concerning the miniload AS/RS system.

In a miniload AS/RS a mechanical storage/retrieval (s/r) device transports *storage bins*, containing several small loads, to and from an order picking (Input/Output (I/O)) station. In the system investigated in this paper we have an I/O station with two pick positions located at one end of the aisle. At each aisle one order picker by turns picks from the left and the right position. The s/r device may operate in single or dual mode. We will restrict ourselves to the dual operating mode: After one bin is processed by the picker it can be taken back by the mechanical device to its home position in the rack (*storage location*) returning with the next bin in the picking sequence, while the picker is processing the other. This process is commonly described as *dual command order picking*, as opposed to *single command order picking* where only one storage or retrieval is performed per cycle.

For the *design* of a miniload AS/RS important issues are physical layout, aisle design, number of aisles, equipment and storage technology (interested reader should see Muralidharan *et al.* (1995) for a list of papers published on design issues). However, these design issues have to be considered in connection to the issues of *item allocation* (random or dedicated storage, correlated assignment, decision of the storage racks in A/B/C-zones) and *operating policy* (order picking in strict or batch mode, sequencing of line items). Gray *et al.* (1990) describe a case-study where on the basis of a multi-staged hierarchical decision approach utilizing a sequence of coordinated mathematical models substantial savings are obtained.

Once the hardware configuration for a miniload AS/RS is determined and the system has been installed, changing demand structures, item characteristics or throughput requirements may ask for reconsidering the employed strategies which were valid when designing the system. In extreme cases additional storage or control equipment is needed. Furthermore, redesign of pick-stations (by creating the possibility of queueing unprocessed bins) and offline or remote orderpicking may increase the picking rate of the system. However, in this paper we will concentrate on the improvements to be reached with item assignment and operating solutions, yielding a reduced picker idle time, a reduced mean travel time of the s/r device, and/or a clever sequence of the line order items.

Item allocation forms the first category of possibilities to improve system performance. Depending on the individual and correlated demand characteristics line items may be stored in *random* or dedicated (*fixed*) locations, in specified zones (*classes*) or combined in the same bin if they are requested together frequently in one order or batch of orders (*correlated assignment*). If all bins are stored in fixed locations we obviously assign the bin with the highest demand rate to the location with the lowest travel time, yielding the so-called *full turnover-based storage*. This system needs a larger storage facility than *random storage*, where each bin may be stored in any open (possibly near the next visited) location. When turnover frequencies are non-stationary shuffling of storage locations may be employed when the s/r-device is idle (Muralidharan *et al.* (1995)). With *class-based storage* locations are grouped in classes, according to an ABC-analysis of demand rates of bins. Class A (with the lowest travel times locations) for example stores all bins of the top 10-20% of bins from which 80-90% of yearly demand is requested (fast moving items). Within classes random or fixed storage may be employed. Fixed assignment of line items to bins and bins to locations is especially worth considering for the class(es) with the highest demand rates. The same holds for *correlated assignment*. Due to different sizes of the items it may be necessary to create several *bin types*. This will complicate storage strategies further.

Operating strategies like *strict and batch order picking* form another category of possibilities to reduce mean travel time and/or picker idle time for part-to-picker systems. With *strict order picking* all line items of one order are picked after each other in some convenient *sequence*. Accumulating all quantities of one order without errors is therefore simple. However, the mean travel time of the s/r device per line item will be high as compared to more sophisticated strategies. With *batch order picking* several orders are batched together; line items and quantities of different orders are joined for the picking process. In this way mean travel time per line item will be reduced by approximately the numbers of orders per batch. Now a sortation process is needed to compose the separate customer orders from the accumulation of the same items of different orders. Furthermore, order filling errors may occur more frequently as compared to strict order picking. Both with strict and batch order picking *sequencing of line items* can be employed to reduce travel time and/or picker idle time. In some cases sequences can be composed which are characterized by matching the time needed for picking from one bin to the travel time needed for retrieval of the next bin. A *static or dynamic approach* may be employed when sequencing line items for batch picking (Goetschalckx and Ashayeri (1989)). The first one divides all requested line items in one or more *shifts* and determines an efficient sequence of dual command cycles for each shift, while the second approach may dynamically adapt the sequence each time newly requested line items appear. Clever sequencing potentially delays a particular customer order and requires a sophisticated information control system, thus increasing system costs.

Redesigning Approach

The approach taken in redesigning the miniload system is given in Figure 1. In the approach adapted in this paper we use several published results concerning storage assignment and operational policies. After an extensive data collection, an analysis of the current system performance was conducted in order to have a reference point for comparison of alternative redesigning scenarios. At this step (step 1) we also looked into possible improvements of current system performance without major changes. Then ate step 2 storage assignment polices were investigated. Different assignment scenarios were studied. Using the result of these studies, the impact of alternative order picking policies on the system performance were evaluated (step 3).Steps 2 and 3 are of iterative nature. Finally at step 4, an analysis of sorting operations is performed. Here below we will discuss the analyses conducted at each step.

Step 1: Analysis of Current System Performance

The first step was to measure the performance of the current storage assignment and operational policies of the AS/RS. According to Bozer and White (1984) the expected single command travel time (STT), travel time between two locations (TTB) and dual command travel time (DTT) for an random storage system under a strict order picking system can be calculated as follows:

The calculation of the expected dual command travel time

$E(STT) = [1+(1/3)b^2]\,T$

$E(TTB) = [(1/3)+(1/6)b^2-(1/30)b^3]\,T$

$E(DTT) = E(STT) + E(TTB) = [(4/3)+(1/2)b^2-(1/30)b^3]\,T$

where:

$T = \max(t_h, t_v)$

$b = \min[(t_h/T), (t_v/T)]$

t_h = time needed for the s/r to reach the end of the aisle from the I/O station = (L/S_h)

t_v = time needed for the s/r to reach the top of the rack from the I/O station = (H/S_v)

L = length of the rack in meters (= 43.71 m)

H = height of the rack in meters (= 3.36 m)

S_h = horizontal speed (= 180 m/min)

S_h = vertical speed (= 40 m/min)

Applying these formulas to our case results in:
E (STT) = 15.15 s, E(TTB) = 5.13s and E(DTT) = 20.28 s

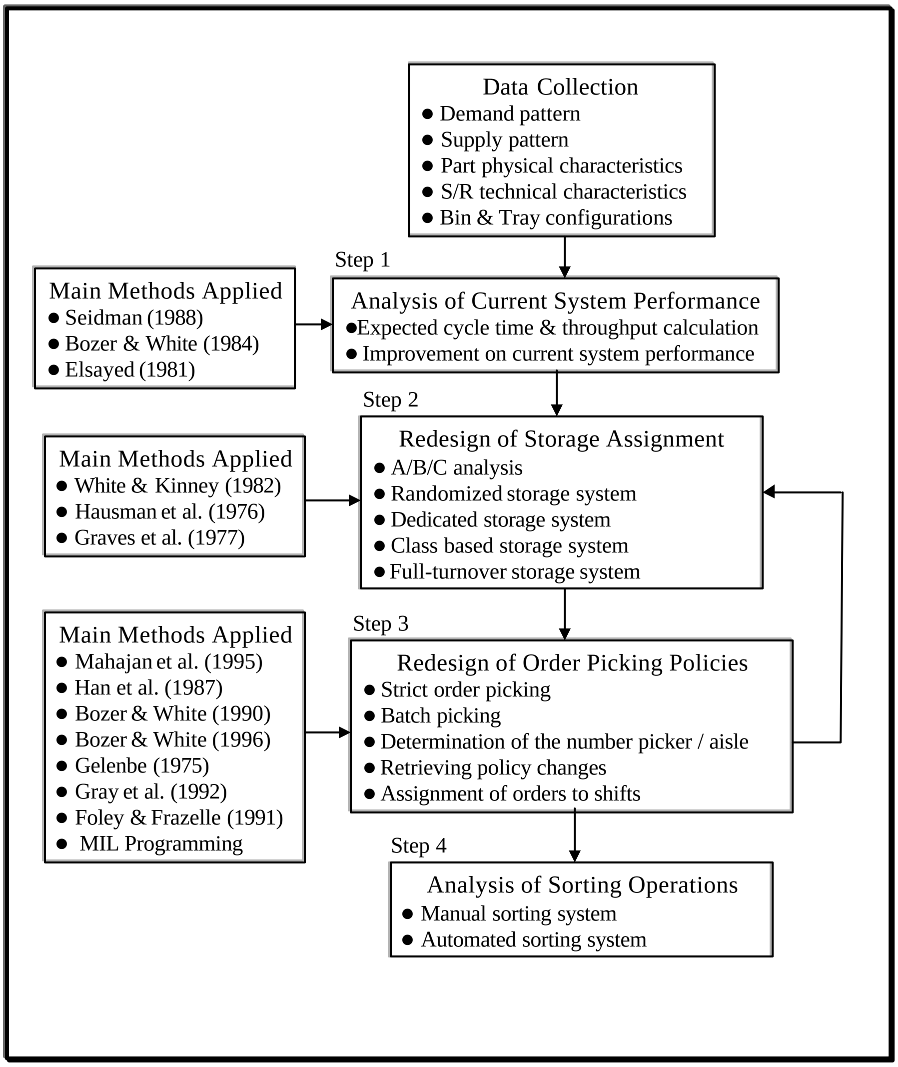

Figure 1: The Redesigning approach adapted for the case study

The expected dual command cycle time (CT) can be calculated by adding 4 times the fixed (pickup / dropoff) time (w) needed for the storage or the retrieval of a bin, which in our case is 9 seconds. Thus, the expected dual command cycle time is 56.28 seconds (E (CT) = E(DDT) + 4w). According to this calculation the handling speed of the system is approximately 64 cycles per hour. Because the order picking policy is strict order oriented only 1 operation takes place per cycle. The throughput of the current storage and order picking system is therefore equal to almost 64 operations per hour.

Having checked the performance of current operation, we tried first to improve the current system without major changes: adjust the order picking policy without changing the random storage system. The current operation strategy is strict order picking, which means all line items of one order are picked after each other in some convenient sequence. As the storage system is still random the probability for a location to be used for a retrieval or storage is the same for every location, i.e. the expected single command cycle times will remain unchanged (15.15s). Furthermore the fixed storage and retrieval time of the s/r (w) can not be reduced.

Here we applied Han *et al* (1987) Nearest Neighbour (NN) algorithm to minimise the expected travel time between the storage and the retrieval location of a dual command cycle. Take R as the set of n locations in which the requested items of certain batch of orders are stored, this means n dual command cycles have to be performed in order to pick these items. Take S as the set of m free storage locations in the racks of one aisle.

The NN algorithm

Repeat step 1 to 4 until R = ö:

1. Select the pair, r å R and s å S, with the minimum travel time between the locations. The travel time between 2 locations is equal to the maximum of the horizontal and vertical travel time between them;
2. Execute the cycle, in which storage and retrieval take place in respectively s and r;
3. Eliminate element r from the set R;
4. Eliminate element s from the set S and add element r to set S.

Bozer and White (1984) show how to calculate the expected travel time between locations when applying the NN algorithm. The outcomes for some values of n and m are shown in the table below. The current number of free locations m in one aisle (in both aisle faces) is somewhere between 25 and 60.

Table 1: The expected travel time between locations and the expected cycle time using the NN algorithm

M	**n**	**E (TTB)**	**Reduction in E (TTB)**	**E (CT)**	**Reduction in E (CT)**
current situation (n=1; 25<m<60)		5.13		56.28	
25	1	0.81	84%	51.98	7.6%
25	10	0.40	92%	51.55	8.4%
50	1	0.56	89%	51.71	8.1%
50	10	0.28	95%	51.43	8.6%

E (TTB) reduces, when n increases. But the parameter m plays the major role in reducing the expected travel times between locations. The result for n equals 10 are slightly better than those with n equals 1, but nevertheless it is better to choose n equals 1 for the following 2 reasons:

- the order picking policy "strict order picking" can remain intact when n=1, no extra sorting system needed;
- the NN algorithm with n=1 is faster and easier to apply and calculate then when n > 1.

Based on the findings the combination n=1 and m=50 is chosen for the NN algorithm which results in an estimated throughput of 69 operations per hour (3600 / 51.71).

It is important to note that the NN algorithm will never result in large reduction of the cycle time, because only 9% of the expected cycle time is travel time between locations. However, changing the storage and order picking system can influence another 27% of the expected cycle time (9% plus 27% for the travel times from the I/O point to the locations). The remaining 64% consists of fixed storage and retrieval time. In order to improve the throughput of the system the average cycle time from the I/O point to the locations has to decrease and the average number of operations per cycle has to increase. This means we need to redesign the storage and order picking policies to accomplish better results (steps 2 and 3 of the approach).

Step 2: Redesign of Storage Assignment

To redesign the storage assignment it is necessary to group items based upon their physical characteristics (the storage space needed). A group here refers to a set of items which need the same type of bin and the same number of locations for storage (given the items' height some items need 2 adjacent storage locations in height). Then a correlation analysis per group has to be performed to assign the items to bins in order to increase the average number of operations per cycle. After item allocation, one can start allocating the bins to locations (*dedicated storage system*) or to classes of locations (*class based storage system*) based on the average number of operations per bin. Bin allocation based on the operation frequency of bins reduces the average cycle time needed.

Unfortunately this theoretical analysis as described above could not be executed, since the dimensions of the spare parts are not registered. Thus an alternative approach was taken. Here, we perform an ABC analysis (White and Kinney (1982)) to identify the items accountable for the major part of workload. We take the "number of operations during 1995" (TO95) as an estimate for the expected number of operations per year for the future. The results of the ABC analysis can be found in the table below.

Table 2: The results of the ABC analysis

Class	**Condition**	**# items**	**# items (%)**	**# operations**	**# operations (%)**
A	TO95 5	3,150	21%	44,933	77%

B	2 TO95 4	3,701	25%	10,108	17%
C	0 TO95 1	8,120	54%	3,006	5%
	Totals	14,971		58,047	

Only 21% of the items are accountable for 77% of the workload of the miniload. An item can be assigned easily to classes using the TO95 value or the expected number of operations per year when this value is not available. No need to mention that the ABC analysis has to be repeated every year with the latest data available.

Dedicated or Class Based Storage Policy

Having defined the items' classes, it is now feasible to assign the items of each class to bins creating A, B and C bins and then assign the A, B, C bins to dedicated location of an aisle.

Note that the bins' occupation rate is approximately 60% per aisle. Thus the change from a random storage system to a dedicated or class-based storage system will not introduce a storage capacity problem.

In the class-based storage policy the items of a class are assigned to specified zones of the aisle. In order to assign groups of items to bins and bins to zones, we need to know the number of bins and locations needed per class.

Number of storage bins needed per group

Number of bins needed per group (h,s) = $\lceil n_{h,s} / \text{capacity}_s \rceil$

Where:

group (h,s) = the group of items requiring storage bin type s and h locations (in height)

$n_{h,s}$ = total number of item of group (h,s)

capacity_s = capacity of a bin of bin type s

$\lceil x \rceil$ = the smallest integer bigger than x

Number of storage bins needed per class

$$\text{BordCapacity}_k = \sum_{h=1}^{\text{MaxHeight}} \sum_{s=0}^{9} \left\lceil \frac{n_{h,s}^k}{\text{Capacity}_s} \right\rceil$$

Where:

BordCapacity_k = Number of bins needed for class k (k = A, B, C)

MaxHeight = Maximum number of locations needed for storage of an item of class k (= 1 or 2)

$n_{h,s}^k$ = Number of items of group (h,s) of class k

Number of locations needed per class

$$\text{LocationCapacity}_k = \sum_{l=1}^{\text{BordCap}_k} h_l^k$$

with:

LocationCapacity$_k$= Number of locations needed for class k (k = A, B, C) BordCapacity$_k$ = Number of bins needed for class k (k = A, B, C) h_l^k = Number of vertical adjoining locations needed for storing bin l of class k

The above calculations could not be implemented directly at the miniload warehouse of Royal Airforce because the exact storage space requirement per item is not known. In order to proceed with the study, a sample of items was used to measure the distribution of items over groups of bins (a group refers to the use of same bin type and same number of vertical adjacent locations (1 or 2) for storage).

Composition of the snap check

The A-class is divided into 3 sub-classes A1, A2 and A3 of more or less the same size.

Table 3: The split up of the A class: A1, A2 and A3

Class	Condition	# items	# items (%)	# operations	# operations (%)
A1	TOT94 11	1,142	36%	31,357	70%
A2	7 TOT94 10	983	31%	8,027	18%
A3	5 TOT94 6	1,025	33%	5,549	12%
	Totals	3,150		44,933	

The sub-class A1 contains 7% of the total number of items (21% * 36%) and is accountable for 54% of the total number of operations during 1995 (77% * 70%). The items of A1 are taken as a sample for the following reasons:

- The items of the A1 class are very representative for the total system regarding storage space needed;
- The storage space needed by the items of A1 (in total 1,142 items) could be measured within the time frame available (approximately 5 working-days);

Results of the snap check

The 2 main results of the snap check are:

- The 1,142 A1 items need 105 storage bins in total, this means in general an average of 10.9 items per bin;
- From these 105 bins, 99 need one location and only 6 need two locations for storage; i.e. in general 6% of the bins need two locations.

The number of bins and locations required per class can now be calculated based upon these results. Then a set of locations in the aisle can be reserved for each class based on the travel times to these locations. Before allocating item-to-bin and bin-to-location for each of the classes, the ravel times to the locations were determined. Locations in an aisle were numbered from 1 (location with the lowest travel time) to 2,256 (location with the largest travel time). The travel time to a location is determined by taking the maximum of the horizontal (t_h) and vertical travel times (t_v) to a location, while ignoring the acceleration and deceleration times.

The class-based storage system

The number of storage bins and locations needed per (sub-)class are calculated based on the results of the snap check. The total number of locations needed to store all the items of the department under study is 1,459. The total number of locations of an aisle of an AS/RS equals 2,256 which leaves 797 locations unused and free. The free locations are divided over the classes based on the number of locations required per class. The results of these calculations are represented in table 4.

Table 4: Storage capacity needed per class (class-based storage policy)

Class	**No. of Items**	**No. of bins needed (# items / 10.9)**	**No. of locations needed (# bins x 1.06)**	**No. of free locations ((#loc/1459)x797)**	**Total number of locations needed**
A1	1142	105	111	61	172
A2	983	91	97	53	150
A3	1025	94	100	55	155
B	3701	340	361	197	558
C	8120	745	790	431	1221
Total	14971	1375	1459	797	2256

The class with the highest operation frequency in 1995 (A1) will be assigned to those locations with the lowest travel times to the I/O station. Then the class with the second highest operation frequency in 1995 (A2) will be assigned to the not yet assigned locations with the lowest travel time to the I/O station; and so on. This will result in the reduction of expected cycle time and increase in throughput of the AS/RS. The item assignment to locations is given in the table 5.

Table 5: The distribution of items over available locations (class-based storage policy)

Class	**Items**	**Locations**
A1	1..1142	1..172

A2	1143..2125	173..322
A3	2126..3150	323..477
B	3151..6851	478..1035
C	6852..14971	1036..2256

One of the main characteristics of the class-based storage policy is that within each class the random storage policy applies. This means the items of a class can be assigned to bins based on their storage space needed and the bins can be assigned randomly to the locations of the class.

Full turnover-based storage system

We now consider a full turnover-based storage system for the A1-class instead of the random system, an adjusted class-based storage system. There are several reasons for investigating an adjusted class-based storage system:

1. the A1-class contains items for which 10 operations or more are needed per year. If the bins with the highest turnover are assigned to fixed locations near to the I/O point, then the expected cycle time will decrease. As a result of this the throughput will improve.
2. the chance that two items are needed on the same day is the biggest for this class.

To change the assignment of items in the A1-class, the A1 items are to be assigned to the A1 bins (item-to-bin allocation) and A1 bins should be assigned to A1 locations (bin-to-location allocation).

Item-to-bin allocation

The goal of item-to-bin allocation is to increase the average number of operations per cycle. In order to bring those items together on one bin which are often needed together (e.g. bolt and nut) Frazelle and Sharp (198?) recommend to do a correlation analysis. However the correlation analysis is not feasible, since the data is missing to perform this analysis. The item-to-bin allocation policy we used, is described below.

The item-to-bin allocation policy

$A_{h,s}^{k}$:= The set of items stored together on bin k of group (h,s);
$n_{h,s}^{A1}$:= Total number of items of group (h,s) of the A1-class;
$Capacity_s$:= The capacity of bin type s;

Initialization : k=1, i=1, Counter=1, $A_{h,s}^{k} = \emptyset$ (for each value of h, s en k);

1. Consider all the items of group (h,s). Sort them in descending format based on their turnover (yearly number of operations). Number the items based on this sorted list from high to low (item 1 is the item with the highest turnover and item $n_{h,s}^{A1}$ is the one

with the lowest turnover);

2. If Counter ≤ $Capacity_s$ and i ≤ $n_{h,s}^{A1}$, then add item i to set $A_{h,s}^k$. Repeat step 2 with i=i+1 and Counter=Counter+1.
   If Counter > $Capacity_s$ and i ≤ $n_{h,s}^{A1}$, go to step 3.
   If i > $n_{h,s}^{A1}$, go to step 4.

3. Take k=k+1 and Counter=1. Repeat step 2.

4. End of assignment. $A_{h,s}^k$ is the set of items which should be stored together on bin k of group (h,s).

The policy used tries to approach to the correlation analysis policy by grouping items with the highest turnover in order to increase the chance of performing more than 1 operation per cycle.

Bin-to-loaction allocation

For bin allocation the following three data-elements are of interest:
1. The expected number of operations per bin (BIN95)
2. The number of locations required per bin
3. The travel times from the locations to the I/O point

All the data required for bin allocation is in place. Based on what criteria should the bins be assigned to locations. If all bins only needed one location for storage the criteria is pretty obvious, namely BIN95. Because some of the bins need 2 vertical adjacent locations, the criteria will be BIN95/Height. Height is the number of locations needed. The bin allocation can be formulated as a linear program, however, the assignment problem can be simplified as the following procedure.

The bin-to-location allocation policy

l = bin index;
j = location number;
L = total number of A1 bins;
M = total number of A1 locations;
V := the set of locations already used for storage for bins already considered in the procedure

Initialisation:
l = 0;
V = ∅.

1. Order the locations based on increasing travel times to I/O point (j=1..11). Location 1 has the lowest travel time to the I/O point, location 111 the largest one.

Order the storage bins based on decreasing values for BIN95/Height (bin index: 1..105). Bin 1 has the largest criteria value, bin 105 the lowest.

2. Take l=l+1. Assign bin l of the list to the first location j (and if the bin needs 2 locations assign to the first 2 vertical adjacent locations) of the ordered list which does not belong to set V. Add the location(s) assigned to bin l to set V.

3. Repeat step 2 if l<L, otherwise go to step 4.

4. End of assignment procedure.

The result of this bin allocation policy is that the locations with the lowest travel times to the I/O point are expected to be visited the most by the s/r.

Capacity reservations per class

Given the full turnover-based storage system, the storage capacity requirements for the adjusted class-based storage system can be determined (see table 6).

Table 6: Storage capacity needed per class (adjusted class-based storage policy)

Class	No. of Items	No. of bins needed	No. of locations needed	No. of free locations	Total No. of locations needed
A1	1142	105	111	3	114
A2	983	91	97	57	154
A3	1025	94	100	59	159
B	3701	340	361	212	573
C	8120	745	790	466	1256
Total	14971	1375	1459	797	2256

The adjusted class-based storage policy tries to improve the overall throughput by applying the full turnover-based storage policy for the A1 class.

Step 3: Redesign of Order Picking Policies

As mentioned before conducting this study the picking policy was strict order per order picking policy with a convenient sequence of picking. In the first step of the approach we showed that NN heuristic could improve the system performance.

At step3 we try first to measure the system performance under two newly suggested storage assignment policies without considering pick operation at the end of aisle. Then we compute the performance when the pick operation is included. To determine the expected cycle time analytical models were developed and validated through simulation. Our experience show that the Bozer and White (1990 and 1996) models either under-estimate or over estimate the expected cycle time.

Considering that E {throughput} = (1 / E { $t_{as/rs}$ }) * 3600,
where:
$t_{as/rs} = t_{storage} + t_{time\text{-}in\text{-}between} + t_{retrieve} + 4 * 9$

now we need to determine each leg travel time. The expected travel time from I/O to every location is equal to the expected travel time from that location to I/O. Thus we can write:

$$E\{t_{storage}\} = E\{t_{retrieve}\} = \sum_{i=1}^{n} t_i \bullet p_i$$

where:
t_i = travel time to location i (taking into account the acceleration & decelration times)
p_i = handling percentage for location i (from total number of handelings in an aisle face per time unit)
n = total number of locations in an aisle (= 1128)

a) Strict order picking

$$E\{t_{time\text{-}in\text{-}between}\} = \sum_{i=1}^{n} \sum_{j=1}^{n} p_i \bullet p_j \bullet t_{ij}$$

where:
t_{ij} = travel time from location i to location j

and $\sum_{i=1}^{n} \sum_{j=1}^{n} p_i \bullet p_j = 1$

b) Classed-based picking

Under this policy we start picking first in class A1 then class A2, etc. The expectde travel time in between two locations for this case is determined as follows:

$E\{t_{time\text{-}in\text{-}between}\}$ =

$$p_{A1} \bullet \frac{\sum_{i=1}^{a1} \sum_{j=1}^{a1} p_i \bullet p_j \bullet t_{ij}}{\sum_{i=1}^{a1} \sum_{j=1}^{a1} p_i \bullet p_j} + p_{A2} \bullet \frac{\sum_{i=a1+1}^{a2} \sum_{j=a1+1}^{a2} 2\ p_i \bullet p_j \bullet t_{ij}}{\sum_{i=a1+1}^{a2} \sum_{j=a1+1}^{a2} p_i \bullet p_j}$$

$$+\ p_B \bullet \frac{\sum_{i=a2+1}^{n} \sum_{j=a2+1}^{n} p_i \bullet p_j \bullet t_{ij}}{\sum_{i=a2+1}^{n} \sum_{j=a2+1}^{n} p_i \bullet p_j}$$

$$p_{A1} = \sum_{i=1}^{a1} p_i\ , \quad p_{A2} = \sum_{i=a1+1}^{a2} p_i\ , \quad p_B = \sum_{i=a2+1}^{n} p_i\ , \qquad p_{A1} + p_{A2} + p_B = 1$$

where:

- a1: the number of the last location in class A1
- a2: the number of the last location in class A2

Given this picking policy one can also find a better storage division for different classes by “trial and error”. To start “a1” and “a2” will get the values as suggested in the previous step, however these could be modified such that the expected travel time in between is minimized.

The results of these measurements are given in tables 7 and 8.

Tabel 7: Throughput in case of class-based storage system

	Picking Policy	
	Strict order picking	Picking per class
E $\{t_{storage} + t_{retrieve}\}$	9.93	9.93
E $\{t_{tussen\_reis}\}$	4.48	3.50
E $\{t_{as/rs}\}$	50.40	49.42
E {throughput}	71.43	72.84

Tabel 7: Throughput in case of full turnover based storage system

	Picking Policy	
	Strict order picking	Picking per class
E $\{t_{storage} + t_{retrieve}\}$	7.88	7.88
E $\{t_{tussen\_reis}\}$	4.28	3.04
E $\{t_{as/rs}\}$	48.17	46.92

E {throughput}	74.74	76.72

c) Batch picking

In case of batch picking the chance of picking several items from a location increases. Fot this situation the expected storage / retrieval time and the expected travel time in between two locations can be calculated based on the following procedure.

The probablity of visiting location i = 1 – the probablity of not visiting location i

$$1 - (1-p_i)^{x/2}$$

where: x = batch size (total number of order lines) in an aisle
x/2 = batch size in an aisle face

The following expections can be obtained:

$$E\{t_{storage}\} = E\{t_{retrieve}\} = \frac{\sum_{i=1}^{n} (1 - (1-p_i)^{x/2}) \bullet t_i}{\sum_{i=1}^{n} (1 - (1-p_i)^{x/2})}$$

$$E\{t_{time\text{-}in\text{-}between}\} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} (1 - (1-p_i)^{x/2})(1 - (1-p_j)^{x/2}) \bullet t_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} (1 - (1-p_i)^{x/2})(1 - (1-p_j)^{x/2})}$$

Like earlier calculations, the above expections can be used to determine the expected ducal cyle time. The resluts of this study are given in tables 9 and 10.

Table 9: Number of dual cycles per hour batching picking - class-based storage system

	Batch size		
	125	250	375
E $\{t_{as/rs}\}$	51.01	51.64	52.24
E {throughput}	70.59	69.75	68.58

Table 10: Number of dual cycles per hour batching picking – full turnover-based storage system

	Batch size		
	125	250	375
E $\{t_{as/rs}\}$	50.70	51.87	52.71

E {throughput}	71.05	69.45	68.36

The above results suggest that the expected throughput is lower than the former picking policies discussed here above. However, this is not he case since the number of items picked is larger. To get a feeling about the accuracy of the analytical model presented and at the same time to learn about the number of handling a simulation study was conducted and the results are given in tables 11 and 12. Note that in these tables E{throughtput_1} refers to the earlier definition of expected throuput, while E{throughput_2} refers to a new defintion given below, which take into account the batching issue.

E {throughput_2} = (1 / E { $t_{as/rs}$ }) * 3600 * E { number of handling per tray}

Table 11: Simulation study - batching picking - class-based storage system

	Batch size		
	125	250	375
E {number of location visited}	103.76	175.98	228.79
E {number of handelings per tray}	1.20	1.42	1.64
E {$t_{as/rs}$}	51.02	51.63	52.25
E {throughput_1}	70.56	69.73	68.90
E {throughput_2}	85.00	99.05	112.93

Table 12: Simulation study - batching picking - full turnover -based storage system

	Batch size		
	125	250	375
E {number of location visited}	84.20	139.26	183.70
E {number of handelings per tray}	1.48	1.80	2.05
E {$t_{as/rs}$}	50.69	51.86	52.70
E {throughput_1}	71.02	69.42	68.32
E {throughput_2}	105.43	124.61	140.23

Note that in the simulation studies the E {$t_{as/rs}$} provide almost the same as the analytical models. The results also show that the full turnover-based storage system under a batch picking outperforms the class-based storage system as the size of batch increases. The important issue here is whether a picker is able to catch up with the speed of s/r machine or whether the s/r machine should wait for a picker.

d) The effect of pick time on the expected throughput

When the pick time from a tray is included in the study the dual cycle time is obtained as follows:

$t_{dual\text{-}cycle}$ = max [pick time, s/r cycle time]. If we consider pick time to be t_{pick}, then $t_{dual\text{-}cycle}$ = max [t_{pick}, $t_{as/rs}$].

We define E{throughput}=1 / E { t_{cycle} }*3600*E{number of handelings per tray}

Bozer and White (1990) show that the process of determining the dual cycle time when the pick operation is included can be formuated as renewal process, wher the bith takes place when the picker and s/r machine commence their service. Folley and Frazelle (1991) argue that the process cannot be consider as renewal process as the cycles are dependent on each other. Neverthless their results is comparable with the renewal theory. In a separate study we extend the method of Bozer and White (1990) to a generalized Erlang distribution. However in this case we use simultion. In the simultion study we take into that for the case of full-turnover based storage system the loaction of last retrieve should be remebered. The results are given in tables 13 and 14.

References

1. Ashayeri, J., and M. Goetschalckx (1989), Classification and Design of Order Picking, *Logistics World*, June, pp. 99-106.
2. Azadivar, F. (1987), Minimum cost modular design of automated warehousing systems, *Material Flow,* **4**, 177-188.
3. Bafna, K. M . (1997), An Analytical Approach to Design High-Rise Stacker Crane Warehouse Systems, Ph. D. Dissertation, Purdue University, Lafayene, Indiana.
4. Baker, E. K. (1983), An Exact Algorithm for the Time Constrained TSP. *Operations Research,* **31** (5), 938-945.
5. Balas, E., and Christofides, N. (1981), A restricted Lagrangean approach to the travelling salesman problem. *Mathematical Programming*, **21**, 19-46.
6. Bartholdi, J. J., and Platzman, L. (1985), Design of Efficient Bin-Numbering Schemes for an Automated Warehouse Carousel Storage System, Technical Report TR-85-09, Material Handling Research Center, Georgia Institute of Technology.
7. Bassan, Y., Roll, Y., and Rosenblatt, M. J. (1980), Internal layout design of a warehouse. *AIIE Transactions,* pp. 317-322.
8. Bozer, Y. A., (1978), A Minimum Cost Design for an Automated Warehouse, Masters Thesis, Georgia Institute of Technology, Atlanta, Georgia.
9. Bozer, Y. A., and White, J. A. (1990), Design and performance models for end of aisle order picking systems. *Management Science,* **36** (7), 852-866.
10. Bozer, Y. A., and White, J. A. (1984), Travel-Time Models for Automated Storage/Retrieval Systems, *IIE Transactions,* **16 (**4), 329-338.
11. Bozer, Y. A., and White, J. A. (1984), Travel time models for AS/RS, *IIE Transactions,* **16** (4), 329-338.
12. Bozer, Y. A. (1986), Optimizing Throughput Performance in Designing Order Picking Systems, Ph. D. Dissertation, Georgia Institute of Technology, Atlanta, Georgia.
13. Bozer, Y. A., Schorn, E. C., and Sharp, G. P. (1990), Several heuristics for the Chebshev TSP, *IIE Transactions,* **22** (3), 223-254.
14. Bozer, Yavuz A., and John A. White (1996), A generalized design and performance analysis,
15. Egbelu, P. J. (1991), Framework for dynamic positioning of storage/retrieval machine in an automated storage/retrieval system, *International Journal of Production*

Research, 29 (1), 17-37.

16. Elsayed, E. A. (1981), Algorithms for optimal material handling in automatic warehouse systems, *International Journal of Production Research*, **19** (5), 525-535.
17. Eynan, Amit, and Meir J. Rosenblatt (1994), Establishing Zones in Single-Command Class-Based Rectangular AS/RS, *I.I.E. transactions : industrial engineering, research and development*, **26**, (1), 38-
18. Foley, R.D., and E.H. Frazelle (1991), Analytical Results for Miniload Throughput and the Distribution of Dual Command Travel Time, *I.I.E. Transactions : Industrial Engineering Research and Development*, **23**, 273-
19. Frazelle, E. H. (1987), Small Parts Order Picking: Equipment and Strategy, Technical Report, Material Handling Research Center, Georgia Institute of Technology.
20. Frazelle, Ed (1989), Small parts order picking: equipment and strategy, Proceedings of the 10th International Conference on Automation in Warehousing, Dallas, Texas.
21. Goetschalckx, M. P. (1983), Storage and Retrieval Policies for Efficient Order Picking Operations, Ph.D. Dissertation, Georgia Institute of Technology, Atlanta, Georgia.
22. Goetschalckx, M., and Ratliff, H. D. (1990), Shared storage policies based on duration of stay of unit loads, *Management Science*, **36** (9), 1120-1132.
23. Golden, B., Bodin, L., Doyle, T., and Steward, W. (1980), Approximate TSP algorithms, *Operations Research*, **28** (3), Part II.
24. Graves, S. C., Hausman, W. H., and Schwarz, L. B., 1977, Storage retrieval interleaving in automatic warehousing systems, *Management Science*, **23** (9), 935-945.
25. Gray, Ann E., Karmarkar, Uday S., Seidmann, Abraham (1990), Design and operation of an order-consolidation warehouse: models and application, Center for Manufacturing and Operations Management, William E. Simon Graduate School of Business Administration, University of Rochester, New York, CMOM Working Paper Series.
26. Han, M., McGinnis, L. F., Shieh, J. S., and White, J. A. (1987), On Sequencing Retrievals in an Automated Storage/Retrieval System, *IIE Transactions*, **19 (1)**, 56-66.
27. Hausman, W . H ., Schwarz, L. B., and Graves, S. C . (1976), Optimal Storage Assignment in Automatic Warehousing Systems, *Management Science*, **22 (**6), 629-638.
28. Hill, John M (1988), Controlling Material Handling Systems in Manufacturing and

Warehousing, Proceedings of the 1988 Material Handling

29. Hwang, H., Baek, W., and Lee, M. K. (1988), Clustering algorithms for order picking in an automated storage and retrieval system, *International Journal of Production Research*, 26.

30. Joon-Mook, L., Kil-Soo, K., Bong-Jin, Y. and H. Hwang (1996), Determination of an optimal configuration of operating policies for direct-input-output manufacturing systems using the Taguchi method , *Computers & Industrial Engineering*, **31** (3-4), 555-560.

31. Kaylan, A., and D.J. Medeiros (1988), Analysis of storage policies for miniload AS/RS, *Engineering Costs & Production Economics*, **13**, 311-318.

32. Kim, K.H. (1993), A joint determination of storage locations and space requirements for correlated items in a miniload automated storage-retrieval system, *International Journal of Production Research,* **31**, 2649.

33. Laporte, Gi, and Martello, S., (990), The selective TSP, *Discrete Applied Mathematics,* 26.

34. Lee, H.F., and S.K. Schaefer (1997), Sequencing methods for automated storage and retrieval systems with dedicated storage, *Computers & Industrial Engineering*, **32**, 351-362.

35. Lin, S., and Kernichan, B . W. (1965), An Effective Heuristic Algorithm for the TSP, *Bell System Technical Journal,* **21** (2), 498-516.

36. Linn, R. J, and Wysk, R. A. (1990a), An expert system framework for automated storage and retrieval system control, *Computer and IE*, **18** (1), 37-48.

37. Linn, R. J., and Wysk, R. A. (1987), An analysis of control strategies for an AS/RS, *Canadian Journal of Operations Research and Information Processing,* **25** (1), 66-83.

38. Linn, R. J., and Wysk, R. A. (1990b), An expert system based controller for an automated storage/retrieval system, *International Journal of Production Research,* **28** (4), 735-756.

39. Muralidharan, B., Linn, R.J., and R. Pandit (1995), Shuffling heuristics for the storage location assignment in an AS-RS, *International Journal of Production Research,* **33** **(**6), 1661-1672.

40. Oudheusden, D.L. van and W. Zhu (1992), Storage layout of AS / RS racks based on recurrent orders, *European journal of operational research,* **58** (1), 48-

41. Padberg, M., and Rinaldi, G. (1990), Facet identification for the systematic TS polytope *Mathematical Programming,* **47**, 219-257.

42. Parker, R. G., and Rardin, R. L. (1983), The travelling salesman problem—an update of research, *Naval Research Logistics Quarterly,* **30**, 69-96.

43. Perry, R. F., Hoover, S. V., and Freeman, D. R. (1984), An optimum seeking approach to the design of automated storage/retrieval system, *Winter Simulation Conference,* 349-354.

44. Pliskin, J. S., and Dorld, 1982, Ranking alternative area assignments—a multiattribute approach, *IIE Transactions,* 19-26.

45. Rizo-Patron, A., Bozer, Y. A., and McGinnis, L. F. (1983), Analytic and Simulation Models for Advanced Automated Storage/Retrieval Systems, Technical Report TR-82-04, Material Handling Research Center, Georgia Institute of Technology.

46. Roberts, S;D., and Reed, R. (1978), Optimal warehouse bay configurations, *AIIE Transactions,*

47. Roll, Y., and Rosenblatt, M. J. (1987), Shifting in warehouses. *Material Flow,* **4**, 147-157.

48. Rosenblatt, M. J., and Roll, Y. (1984), Warehouse design with storage policy consideration, *International Journal of Production Research,* **22** (5), 809-821.

49. Schwarz, L B., Graves, S. C., and Hausman, W. H., Scheduling Policies for Automatic Warehousing Systems: Simulation Results, *IIE Transactions,* **10 (**3), 260-270.

50. Schwarz, L. B., Graves, S. C., and Hausmann, W. H. (1978), Scheduling Policies for AS/RS, *AIIE Transactions,* **10** (3), pp. 260-270.

51. Schwind, Gene F (1996), Miniloads: No limit to applications, Material Handling Engineering [MTH] , **51 (**8) 46-48.

52. Warehouse Modernization and Layout Planning Guide, Department of the Navy, Naval Supply Systems Command, NAVSUP Publication 529 (March 1985).

53. White, J. A., and Kinney, H. D. (1982), Storage and Warehousing. In *Handbook of Industrial Engineering,* chapter 10.4, G. Salvendy (ed.) (New York: Wiley).

54. Zollinger, H. A. (1975), Planning, Evaluating, and Estimating Storage Systems, presented at the Advanced Material Handling Technology Seminar, Purdue University, Lafayette, Indiana (April 29-30).

In the approach adapted in this paper we use several published results concerning storage assignment and operational policies. These are: Hausmann *et al.* (1976) found optimal storage assignments with dual cycles and compared it with random storage assignments. Graves *et al. (* 1977) and Schwarz *et al.* (1978) developed a deterministic model to study the combined effect of interleaving, storage assignment, and job sequencing, and the result was later validated by a computer simulation. Elsayed (1981) studied algorithms for optimal order picking in automatic warehousing system. Bozer and White (1984) studied alternative I/O locations and various dwell point strategies for the AS/RS for racks that are not square in time. Linn and Wysk (1987) studied the performance of different control algorithms for unit load AS/RS when the demand is subject to a seasonal trend. Han *et al. (* 1987) studied the throughput improvement by retrieval sequencing in unit load automatic AS/RS when several retrievals are available and dual command cycles are preferred. Hwang *et al.* (1988) studied ways to pick up the products from an AS/RS to satisfy customer orders. They listed all the orders to be processed, broke them into tours, and solved as a travelling salesman problem (TSP) for those tours. Goetschalckx and Ratliff (1990) developed a storage policy for a unit load warehouse based on duration of stay. Linn and Wysk (1990a, 1990b) and Muralidharam et al. (1995) addressed restoring policies. Egbelu (1991) studied the framework for dynamic dwell points of storage/retrieval machines by using linear programming to minimize the service response time in an AS/RS. Bozer and White (1996) presented an analytical design algorithm to determine the near-minimum number of pickers required in an end-of-aisle order-picking operation in an automated miniload system.

1. The storage space needed for A1 items will be used to apply a fixed storage policy for the A1 sub-class. This reason will become clear later on during the study:

Appendix II: The bin-to-location assignment model

The model

$$Min \sum_{l=1}^{L} \sum_{j=1}^{M} c_{lj} x_{lj}$$

$s.t.$

$$(1) \sum_{l=1}^{L} x_{lj} = 1 \quad , j = 1, \dots, M$$

$$(2) \sum_{j=1}^{M} x_{lj} = h_l \quad , l = 1, \dots, L$$

$$(3)\ x_{lj} = 0,\ 1 \quad , \text{for each } l \text{ and } j$$

The description

x_{lj} = 1, if bin l is assigned to location j

= 0, else

c_{lj} = $(d_l\ r_j) / h_l$

d_l = number of operations needed per year for bin l

r_j = travel time to location j from I/O point

h_l = number of locations needed for bin l

L = total number of bins

M = total number of locations needed for storage

The results

The bin with the highest ratio c_{lj} is assigned to the location(s) with the shortest travel time to the I/O point. The bin with the second highest …. And so on.