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DESIGN AND ANALYSIS OF COMPUTER-AIDED CART SYSTEMS FOR PICKING DISCRETE ITEMS

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ABSTRACT

This paper examines operational instructions and design policies for implementing computer-aided cart systems from the standpoint of efficiency. From results of analysis it is found that the operator should follow his/her basic routing for efficient retrieving items. In designing the cart systems it is better to make an intermediate shortcut from the efficient standpoint. In addition, optimization analysis is performed to determine the number of carts under three basic criteria, i.e., the minimum-time criterion, the minimum-cost criterion, and the maximum-profit criterion. A numerical example is presented, based on an actual case.

1 INTRODUCTION

The computer-aided cart systems are installed for retrieving various types of discrete items, such as cosmetics and daily necessities, which are put on the racks. The computer-aided cart systems are utilized for retrieving relatively low amount of items; that is all kinds of items on the rack facility are not always retrieved. This type of the cart system comprises loading and unloading stations, IC card reader/writer, computers, carts, and racks with an indicator light. Each operator drives an assigned cart during his/her operations.

When introducing the computer-aided cart system, there are a lot of alternatives. Management has to decide particular specifications of the cart system, such as the number of aisles, the installation of a shortcut, considering the frequency of picking items.

In this paper, operational instructions and designing policies are examined from the efficient standpoint, and analytical results are indicated. In addition, optimization analysis is performed in an attempt to determine the optimum number of carts to meet the management goals from both economic and physical standpoints.

2 COMPUTER-AIDED CART SYSTEMS

2.1 Outline of the System

The computer-aided cart system, researched in this paper, is one employing an IC card and optical-space relay communication. Figure 1 illustrates a computer-aided cart system. This system is adopted to pick various kinds of discrete items from rack facilities. When the demand for an item is relatively great, the digital picking systems with conveyors are utilized (Takakuwa 1990). On the contrary, when the rate of picking items is relatively low, the computer-aided cart systems are used.

Each item received, usually arrives in units of palettes, which are shipped by container. Then, they are itemized one by one by a depaletizer. Product codes corresponding to each item are input in advance into the computer. Thereafter, items are to be stored in an automated storage/retrieval system (AS/RS), being put in relatively small containers. Seven stocker cranes are being operated in the system considered here. The system can accommodate up to 15,500 containers. One container enters an automated warehouse, and reaches its designated cell in fifteen seconds. This system is controlled by a main-frame computer. An order from a customer is transferred to a computer as data in orders received. The computer is utilized for the inventory control and the sales management. In addition, the computer provides a series of data to be used in the computer-aided cart system. The data sorted by the computer are transferred to a reading machine which is connected with a personal computer.

Figure 2 shows the layout of one of typical cart system with four-aisle with a shortcut. While each operator is performing a series of his/her operations, he/she is carrying one given IC card. First, an operator inserts the IC card into a reading machine. A

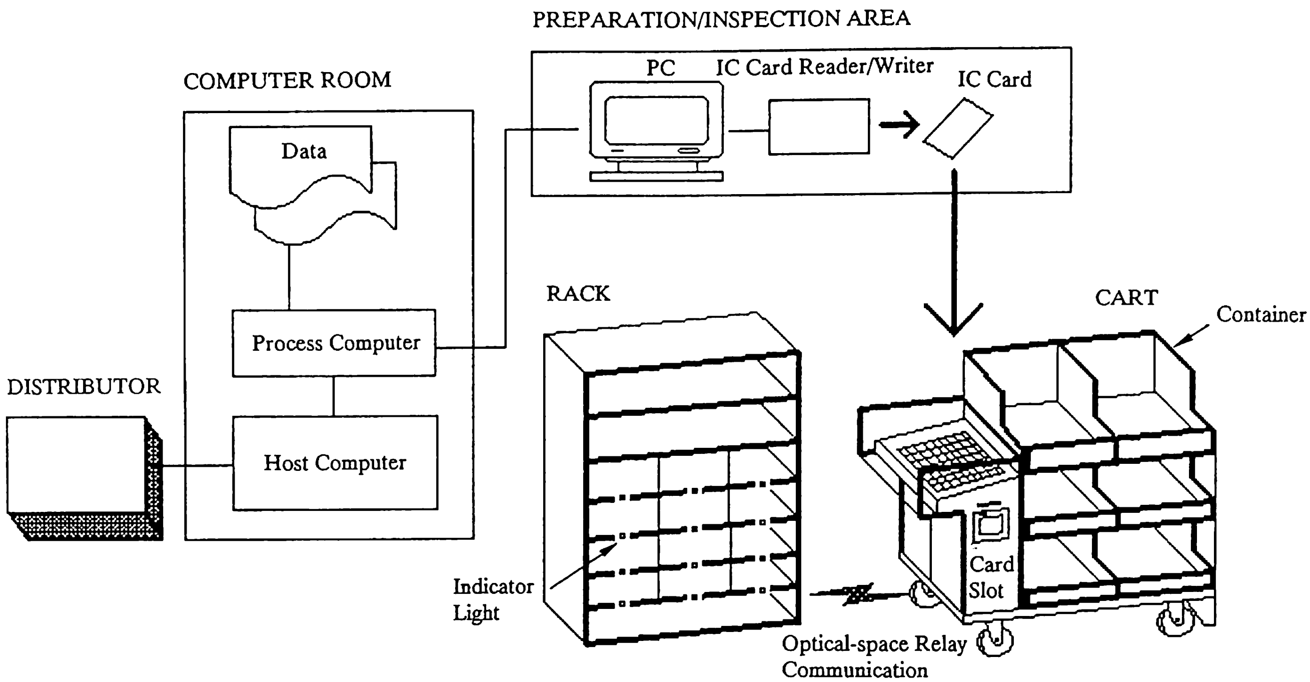


Figure 1: Computer-Aided Cart System

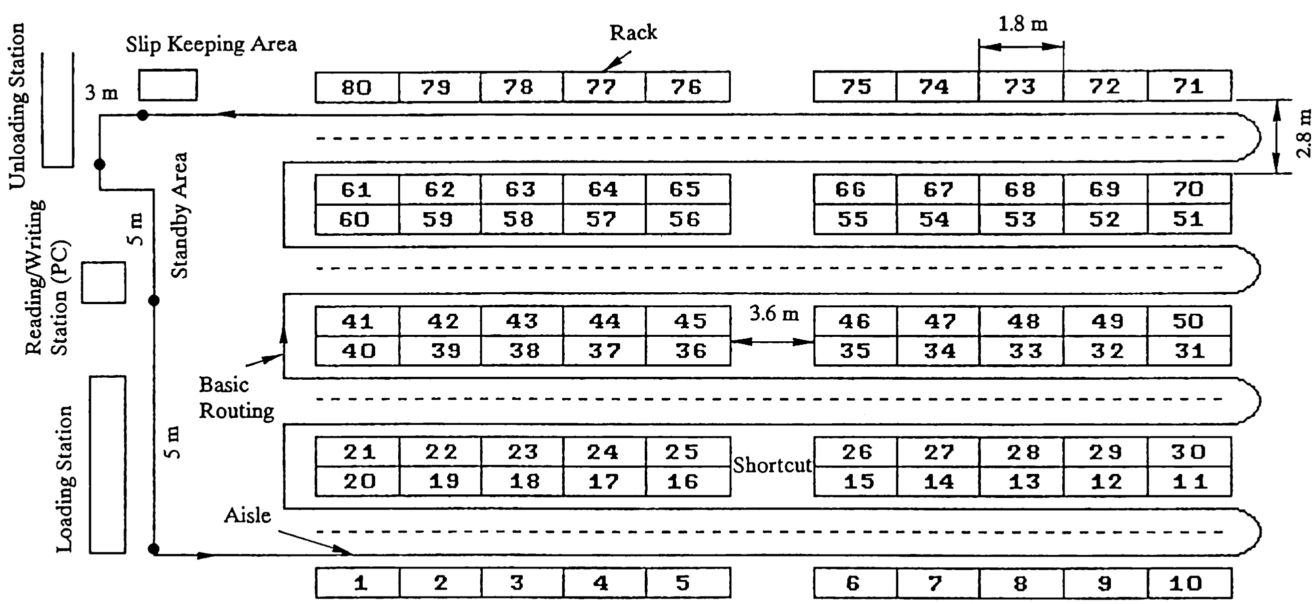


Figure 2: A Layout And Basic Routing (4-Aisle With Shortcut)

single card can hold enough data equal to the informational quantity which is written on 100 slips of paper. An operator inserts the card containing data into a card-slot of his/her cart. Then, the numbers of the racks pertaining to each given item are indicated on the panel of the cart. When the operator arrives in front of the currently designated rack, the corresponding numbers of cells of racks are displayed on the panel of the cart. A quantity of the items to be retrieved is indicated, after he/she pushes a button, by optical-space relay communication. At the same time, on the corresponding rack, an indicator light points out the respective item and the quantity of that particular item. After picking out the exact item(s) from the rack, the operator puts it in the container on the cart. Then, he/she advances down the aisle to the rack which contains the item to be retrieved next. After the operator finishes retrieving all designated items, he/she pushes the button of "completion," and then proceeds to unload the containers from the cart at the designated area. After finishing the task, he/she drives his/her cart to the reading machine area in order to renew the current content of the IC card with new data. This has been one cycle of a series of operations.

IC cards are useful for progressive management of processes and operations such as reading and writing of data for retrieval. In an inspection stage of a shipment, a label containing a bar code is attached on each examined container. In examining this real life model, they are trying to decrease stock quantity by 30% and to decrease expenses of physical distribution by 20%, in adopting the computer-aided cart systems.

2.2 Characteristics of the System

2.2.1 Quick and Accurate Retrieval

First of all, an operator can easily take out and perform his/her operations. Transference of data from a computer to a cart is performed through an IC card. Traditionally, direction of the contents of operations to each operator has been performed through order slips. Therefore, an operator may read a wrong slip and may even perform a wrong operation. On the other hand, by adopting the computer-aided cart system, direction is indicated in digital and graphic modes to an operator. For this reason, an operator rarely makes mistakes, and even a newcomer can perform his/her operations fast.

2.2.2 Classification by the Type of Item and Customer

Secondly, an operator can pick out items, classified by the type of item and customer. An operator picks out the correct item from the rack, where a sensor turns on a corresponding indicator light. Then, he/she puts it in a container on the cart. Since classification has been made and the quantity is indicated for each container, he/she can now classify by the type of item and customer at the same time. Hence, he/she does not need to classify retrieved items later. Moreover, by partitioning a container on a cart into two sections, an operator can pick out items for up to 12 customers.

2.2.3 Flexibility

Thirdly, The computer-aided cart systems can be installed with much flexibly, depending on the quantity of items to be treated. The number of racks and the number of carts can be easily modified. If the system is fixed rigidly, the associate software must be changed drastically at the time of changing the system. Also, in modifying the orbits of automated guided vehicles (AGV), huge time and expense would be necessary. In the computer-aided cart system, an operator drives a cart, so that this system is not a complete automatic system.

2.3 Movement of the Cart

An operator can retrieve an item on the right rack of the aisle on which he/she is driving his/her cart. Basic main flow of the movement of the cart is mentioned as follows.

First of all, a personal computer inputs data, concerning the rack from which an operator will retrieve items, on an IC card. Next, he/she drives his/her cart to the area of supply containers. In that area, a container is loaded on the cart. Then, the operator goes directly toward the rack containing the item(s) to be retrieved first. An aisle corresponding to the small order of the rack number is chosen in this case. The order of his/her operations is based on a basic route within a course. An operator picks out the designated items in the cells of the right rack facilities according to the flow of carts and order of items. In addition, a transfer to the adjacent rack facilities is performed along the easiest course (cart A in Figure 3). In transferring, an operator must advance by one-way traffic in a course, that is, going back is prohibited. However, two-way passing of two operators is allowed, when operators are moving along shortcuts between two rack aisles. In other words, the two operators may pass each other on a shortcut. When an operator moves to the opposite side of the aisle, he/she is allowed to move counterclockwise from his/her current position. This type of movement occurs under the following two situations (carts B and C). The first is the case that there is no operation left any more in the rack facilities of the current aisle. In the next case, he/she must change the current direction, based on the given policy for the choice of shortcuts. He/she can also pass another cart stopping to pick items in each aisle. However, he/she can not pass other moving carts.

Suppose that an operator proceeds to a cell of the rack from which he/she will pick up an item. If another cart is currently working there, the operator makes

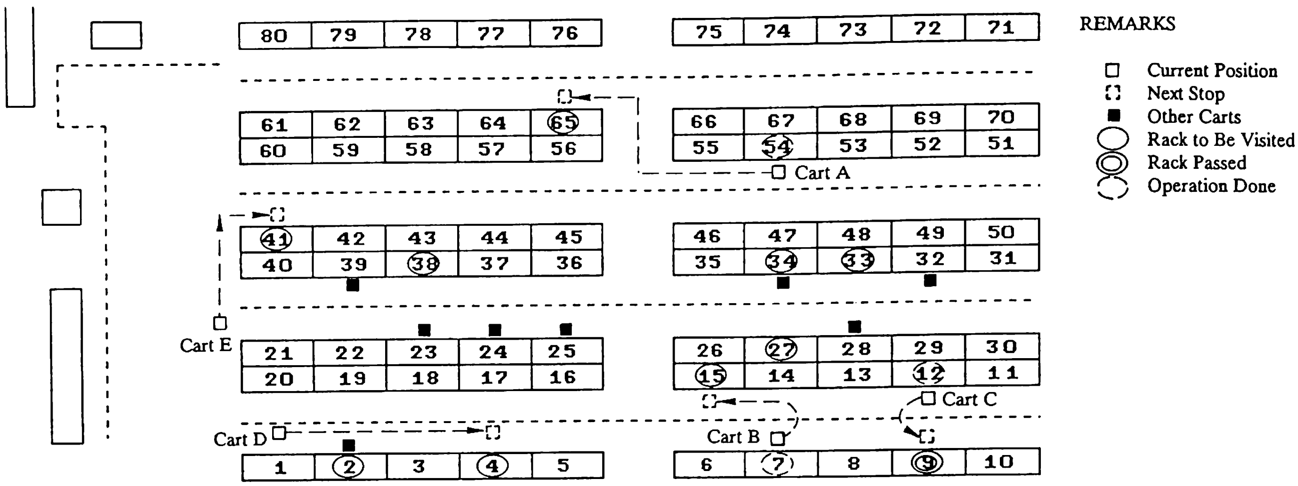


Figure 3: Movement Of Carts

a choice between two alternatives. The first alternative is that he/she executes other operations, which are scheduled to do later, at one pair of rack aisles ahead, and then he/she returns to the position of the rack left undone (cart D in Figure 3). The second alternative is that the operator waits at the position until the other operator finishes his/her current operation. In this case, it is not allowed for two operators to execute at the same time. Also, two carts can not be routed jointly in an aisle.

In entering the next aisle, if more than some given number of carts are in the aisle, the operator may seek to enter the following aisle ahead (cart E in Figure 3). If a similar situation occurs in the following aisle, he/she does the same again. This action can be performed at most twice successively. In case the operator fails to enter three successive aisles, he/she must enter the first canceled aisle, no matter how many carts there are in that aisle.

After the operator completes his/her cycle of retrieving items, he/she takes the completed slip to the designated area to place it into a box located there. Next, the operator puts the completed container on the conveyor. Finally, he/she enters the IC card into the personal computer to read the data. By obtaining data from the card, the personal computer determines whether all operations are complete. When the series of the operations mentioned above are finished, work contained in the data is complete. If a series of operations are performed without mistakes, then the operator drives his/her cart to the standby area. He/she awaits the next instruction at that position. In this way, if all operators finish their operations completely, and they all return to the standby area, simulation is ended.

3 SIMULATION ANALYSIS

3.1 Experimental Conditions

Experimental conditions on operation time are summarized in Table 1. Major distances in the cart systems researched here is indicated in Figure 2. The Simulation is performed by SIMAN (Pegden, Shannon, and Sadowski 1990).

3.2 Measures of Performance

The simulation was run until one hundred rounds of carts were made completely, and statistics were measured and recorded. While a number of performance measurement variables were recorded, the principal variables were selected from the efficiency standpoint, as followed:

(1) Total flow time.
(2) Time between arrivals.
(3) Time to complete one cycle.

Hence, the above three measures of performance were examined for the four-aisle cart system with a shortcut, by varying the number of carts allocated. Also, the rate of picking items was set to 10% (i.e., the operator retrieves items from eight racks out of eighty

Table 1: Time Parameter Of Simulation

Items	Time Delay/Speed
Reading/Writing Station	120 (sec.)
Loading Station	20 (sec.)
Slip Keeping Area	20 (sec.)
Unloading Station	30 (sec.)
Time to Pick an Item	[5,30] (sec.) (uniform)
Cart Speed	0.50 (m./sec.)

racks). The average values of the measures on three runs are shown in Figure 4. Average total flow time decreases as the number of carts increases, with a minimum of 20 carts and thereafter. However, average time between arrivals decreases slightly as the number of carts increases even at more than 20 carts. On the other hand, the average time to complete one cycle increases as the number of carts increases, because carts may be delayed due to interference by one another in aisles. Hence, total flow time is concluded to be the most suitable for the measure of performance to represent efficiency of the cart systems.

Figure 5 shows the total flow time in relation to the number of carts assigned, varying the rate of picking items, i.e., 5 %, 10 %, 15 %, and 20 %. It is observed that the total flow time can be minimized by assigning enough carts.

3.3 Operational Instructions for Driving Carts

In this section, the following two operational policies are established to seek more effective routing. By performing simulation experiments together with statistical tests, Corresponding hypotheses are examined from the standpoint of efficiency.

[Operational Instruction No.1] An operator is planning to pick out an item on a certain rack. If another operator is currently working there, the operator passes by and executes other operations first.

[Operational Instruction No.2] In entering the aisle, if there is a certain number (five or more in this case) of carts working there, an operator goes to the following aisle which is not crowded and enters that aisle.

Simulation run were differentiated by the following four factors:

Factor A: Rate of Picking.
- A_1: 5 %.
- A_2: 10 %.
- A_3: 15 %.
- A_4: 20 %.

Factor B: Number of Carts.
- B_1: 5 units.
- B_2: 10 units.
- B_3: 15 units.
- B_4: 20 units.

Factor C: Operational Instruction No.1.
- C_1: Carrying the instruction.

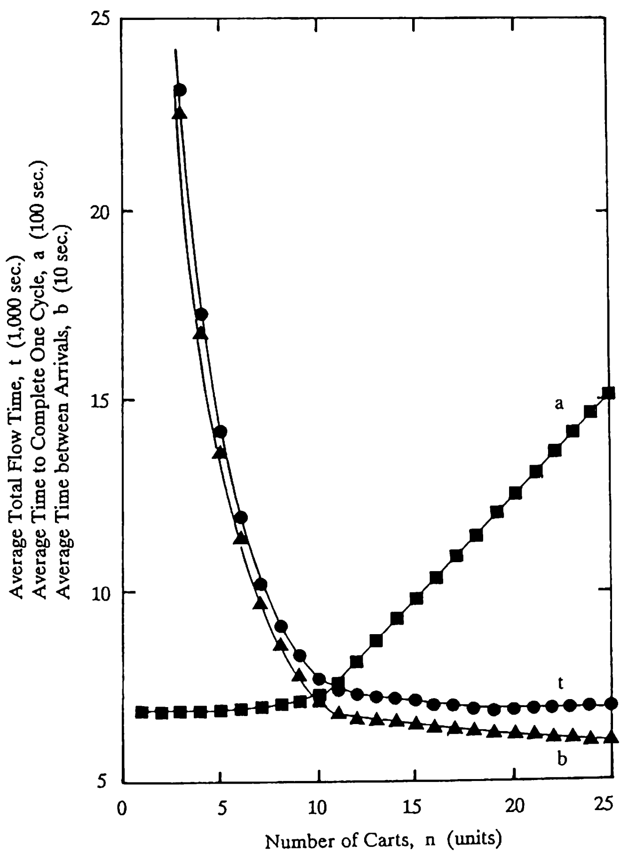


Figure 4: Measures Of Performance

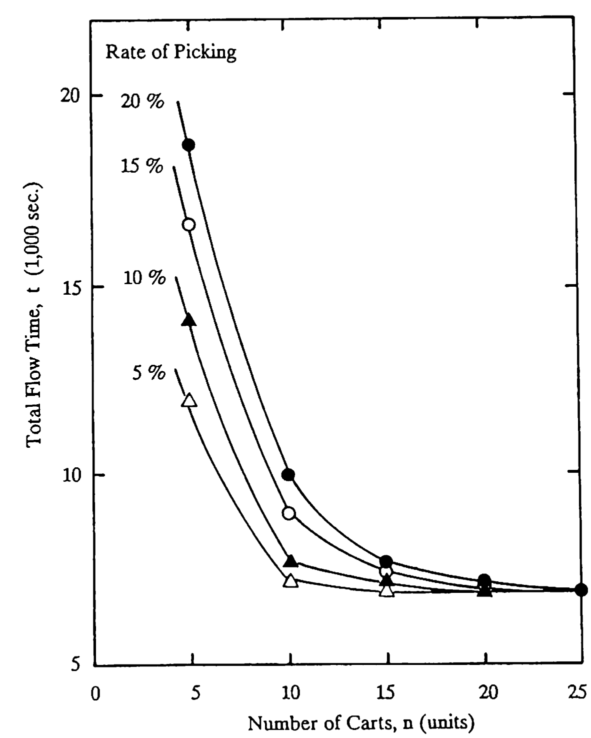


Figure 5: Total Flow Time In Relation To Number Of Carts

C_2: Not carrying the instruction.
Factor D: Operational Instruction No.2.
D_1: Carrying the instruction.
D_2: Not carrying the instruction.
Summary statistics of the output variable were analyzed via a factorial analysis of variance program for a experimental design involving single observation data. The design is 4x4x2x2, where factor A is the rate of picking with four levels, factor B is the number of carts with four levels, factor C is the operational instruction No.1 with two levels, and factor D is the operational instruction No.2 with two levels.

Summary results of the analysis of variance for the output variable (total flow time) are given in Figure 6. The operational policy No.1, factor C, has a significant effect on this variable. Contrary to our expected results, the use of the operational instruction No.1 increases the total flow time. The operational instruction No.2, factor D, has a significant effect on the variable, and the use of this operational policy increases the total flow time as well. First-order interactions with factors C and D are plotted in Figure 6.

3.4 Policies for Designing Computer-Aided Cart Systems

In this section, the following two policies are established to seek more efficient cart systems.
[Design Policy No.1] The number of installed aisles has influence upon efficiency, under the condition that the total number of racks and the total distance along all aisles are the same. It is more efficient to install as many aisles as possible.
[Design Policy No.2] By establishing an intermediate shortcut, an operator can move to the adjacent aisles more conveniently. Hence, it is more efficient to let carts operate in the system with an intermediate shortcut.

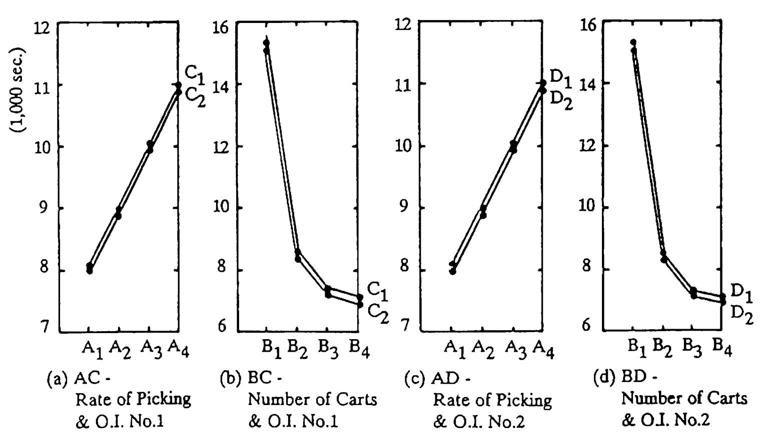
Figure 7 shows five-aisle cart systems without a shortcut. Total distances along the basic routings are designed to be equal for all alternative layouts. Based on the results of the previous section, operational instructions Nos. 1 and 2 are not carried in the following experiments. In other words, an operator does not pass by and execute other operation first, even though another operator is currently working a designated rack. Also, he/she proceeds to the next aisle, no matter how many carts there are in that aisle.

Factors A and B are the same as in the previous experiments, except adding B_5(25 units) of factor B.
Factor E: Number of Aisles.
E_1: 4 aisles.
E_2: 5 aisles.
E_3: 10 aisles.
Factor F: Shortcut.
F_1: System without shortcut.
F_2: System with shortcut.
In this case, the design is 4x5x3x2, where factor A is the number of aisles with four levels, factor B the number of carts with five levels, factor E is the number of aisles with three levels, and factor F is the installaztion of a shortcut with two levels.

Summary results of the analysis of variance for the variable (total flow time) are given in Figure 8. First-order interactions with factors E and F are plotted in Figure 8. The number of aisles in cart systems, factor E, has a significant effect on this variable. The more aisles installed in the system, the more efficient the system. Furthermore, the installation of a shortcut decreases the total flow time, as expected.

3.5 Discussion of Results

From a result of the statistical test, it is not concluded



Source	F Ratio	Sig
A	35,888.74	1 %
B	332,446.93	1 %
C	53.79	1 %
D	12.45	1 %
A x B	11,393.68	1 %
A x C	12.65	1 %
A x D	1.68	N/A
B x C	10.08	1 %
B x D	3.13	N/A
C x D	0.24	N/A
A x B x C	2.58	N/A
A x B x D	1.14	N/A
A x C x D	2.01	N/A
B x C x D	5.11	5 %

Figure 6: Operational Instructions

that it would be more efficient for an operator to put off the work at the rack already occupied by another operator. On the contrary, in the case which the rate of retrieving items is relatively small, efficiency of work is less. It might take more time for an operator to return to the skipped position in the aisle. Moreover, when fewer carts were allocated in the system, the above-mentioned tendency closed up. In the case that more carts are allocated, there is no difference in efficiency between the two alternatives, i.e., putting off and not putting off operations.

Even though an operator changes the order of entering aisles, efficiency of work does not become improved. Therefore, even in the case that there are already lots of carts, he/she should not change order of entering aisles, and he/she should follow his/her basic routing.

To examining one of design policy, three types of the cart systems are investigated; these three systems contain 4, 5, and 10 aisles respectively. It is observed that the number of aisles has influence upon efficiency

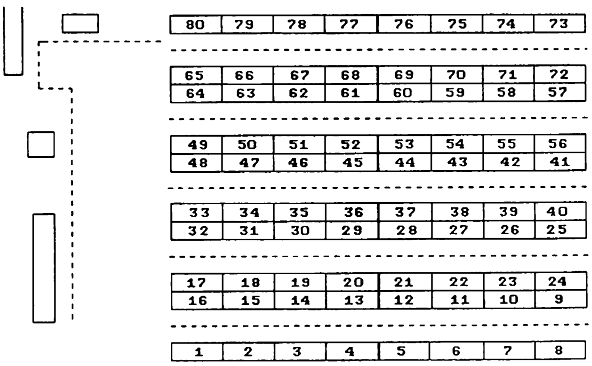


Figure 7: Layout of Racks
(5-Aisle Without Shortcut)

of work as the result of tests. Especially, when fewer carts are allocated, carts may move efficiently through the system. As a possible reason, carts may get more opportunities to interfere with other carts in the system with fewer number of aisles. In a case which more carts are allocated, the difference of this tendency becomes diminished. This means that interference between carts often occurs in the system containing a sufficient number of carts.

In a case which fewer carts are allocated and the rate of retrieval is low, it may be better to make an intermediate shortcut from the efficiency standpoint. An operator passes through the shortcut, so that he/she can route to the adjacent aisles quickly. However, in case that much more carts are allocated, efficiency of whole work is identical, regardless of existence of an intermediate shortcut.

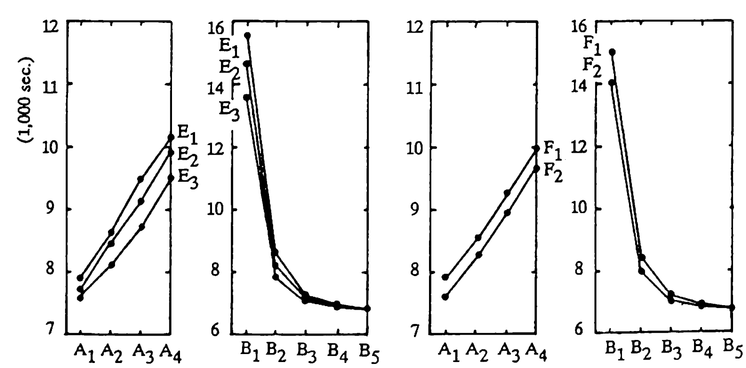
4 OPTIMIZATION

4.1 Determining Specification of the Cart System

An economic analysis of alternatives would be necessary to select the economical system. When performing cost comparison among alternatives it is necessary to collect the following information:

(1) initial cost.
(2) annual maintenance cost.
(3) any irregular cost.
(4) service life.
(5) salvage value.

These estimates should be collected for all of the cart systems to be considered. When this information has been collected, cost comparison then can be made among the alternative systems on a before tax basis.



(a) AE - Rate of Picking & Number of Aisles
(b) BE - Number of Carts & Number of Aisles
(c) AF - Rate of Picking & Shortcut
(d) BF - Number of Carts & Shortcut

Source	F Ratio	Sig
A	1,781.76	1 %
B	18,400.86	1 %
E	223.35	1 %
F	155.11	1 %
A x B	696.42	1 %
A x E	7.53	1 %
A x F	2.47	N/A
B x E	85.44	1 %
B x F	59.82	1 %
E x F	14.76	1 %
A x B x E	2.10	5 %
A x B x F	0.99	N/A
A x E x F	1.16	N/A
B x E x F	8.99	1 %

Figure 8: Design Policies

Then, recommendations can be made to management regarding the most economical system to install. Cost information on the specific systems considered here is summarized in Table 2. Initial cost comprises rack facilities and a set of indicator light controllers, which is considered to be installed commonly. Annual interest rate of 10% was selected for this case. The term "unacost", as used here implies uniformity from year to year with the end of the year as part of the definition (Jelen and Black 1983). The exact cart system to be selected will depend on whether the management is emphasizing low cost or high efficiency among the eligible alternatives.

4.2 Determining the Optimum Number of Carts

4.2.1 Problem Statement

Once an appropriate cart system is decided to install, then it is necessary to determine the optimum or reasonable number of carts/operators on a day-by-day basis. In performing cart assignments, the amount of items to be retrieved should be known or estimated in advance.

In this section, optimization analysis is performed for an operational problem of cart systems, based on three evaluation criteria.

4.2.2 Measures of Performance

(1) Total flow time: The total flow time, t (sec., h., etc.), represents a time length from the beginning of the first operation of the first cart to the end of the last operation of the last cart.

(2) Cost: Cost, c ($, etc.), comprises mainly operating costs and general expenses in the cart system. The direct cost k_d ($/h.unit, etc.) is proportional to the number of carts. Denoting the indirect cost by k_i($/h., etc.), the cost required to retrieve a certain number of items is given by:

$$c = (k_d\, n + k_i)\, t$$

where n is the number of carts stationed.

(3) Profit rate: The profit is obtained by retrieving and sorting items in some specified amount of containers. This situation is often seen in operation divisions or subcontract plants. The profit rate, p,($/h., etc.) here is referred to be the profit per a unit time interval, and it is obtained by dividing the gross profit, by the total flow time.

$$p = [r - (k_d\, n + k_i)\, t] / t$$

where r is the revenue for treating a certain amount of operations.

4.2.3 Evaluation Criteria

The following three fundamental evaluation criteria are utilized in the traditional single-objective manufacturing optimization (Hitomi 1979). These three evaluation criteria are applied to optimization of computer-aided cart systems.

(1) Minimum-time criterion: The minimum-time criterion maximizes the amount of products finished in a unit time interval; hence, it minimizes the total flow time in cart systems. It is the criterion to be adopted

Table 2: Cost Comparisons Among Alternative Investments

Alternatives	Initial cost ($1,000)	Uniform End-of-Year Expense ($1,000)	Salvage Value ($1,000)	Service Life (Years)	Unacost ($1,000)	Ratio of Costs
(1) 4-Aisle without Shortcut	44	4.4	4.4	10	11.285	-
(2) 4-Aisle with Shortcut	48	4.8	4.8	10	12.311	1.091
(3) 5-Aisle without Shortcut	45	4.5	4.5	10	11.541	1.023
(4) 5-Aisle with Shortcut	50	5.0	5.0	10	12.824	1.136
(5) 10-Aisle without Shortcut	50	5.0	5.0	10	12.824	1.136
(6) 10-Aisle with Shortcut	60	6.0	6.0	10	15.389	1.364

when an increase in physical productivity or productivity efficiency is desired, neglecting the cost needed and/or profit obtained.

(2) Minimum-cost criterion: The minimum-cost criterion refers to finishing all designated items to be retrieved at the least cost, and coincides with the maximum-profit criterion if the unit revenue is constant. This criterion is to be adopted when there is ample time for operation.

(3) Maximum-profit-rate criterion: The maximum-profit-rate criterion maximizes the profit in a given time interval. This criterion is to be recommended when there is insufficient capacity for a specific time interval. "Profit rate" usually means "return on investment" in the field of economics and engineering economy. In the evaluation criteria for economic operation here, "profit rate" means "profit per unit time interval." Where work demands are large compared to the system capacity, a larger total profit is obtained by handling a larger amount of items as result of reducing unit production time associated with sacrificing associated cost, rather than based upon the minimum-cost criterion.

4.2.4 Numerical Example

In this section, a numerical example is used to illustrate the process of optimization for the four-aisle cart system with a shortcut. In this case, the rate of picking is assumed to be 10%, that is, items on eight racks out of eighty racks are to be retrieved by each operator. Let r = 1,000 ($), k_d = 10 ($/h. unit), and k_i = 50 ($/h.). The other conditions are the same as those mentioned in sections 2 and 3.

The total flow time, the cost, and the profit rate are functions of number of picking carts with minimum or maximum points at the corresponding optimum numbers of carts. Figure 9 shows such curves versus number of carts. Each value is obtained as the average of values after performing three simulation runs. From Figure 9, the optimum numbers of carts are obtained:

The minimum-cost number of carts (n_c): 10 (units)
The maximum-profit-rate number of carts (n_p): 11 (units)
The minimum-time number of carts (n_t): 20 (units)

The total flow time and the cost are fairly flat at their minimum points. Hence, increase in the total flow time or the cost is small even if the number of carts deviates from the optimum values. The two optimum number of carts under the minimum time and the minimum cost criterion determines a non-

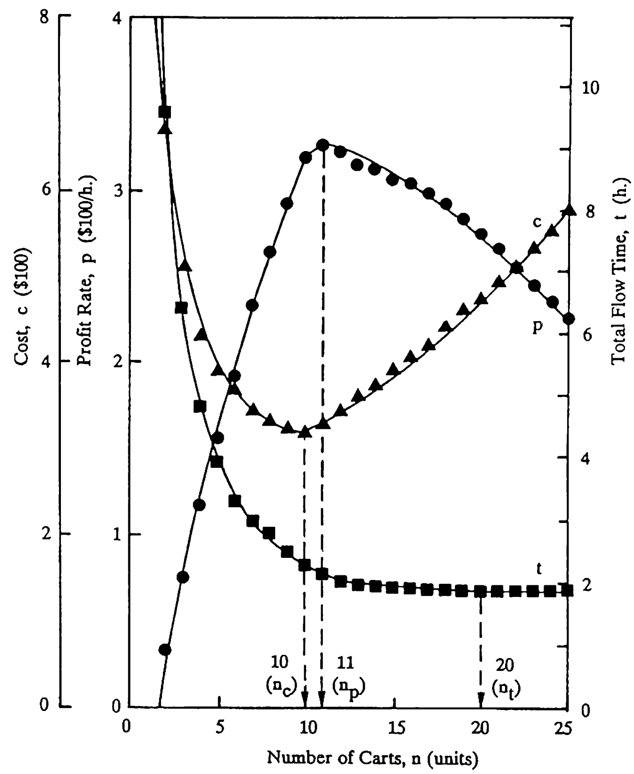


Figure 9: Optimum Numbers Of Carts Under Three Criteria

inferior range. Hence, deviation of the number of carts should be directed towards the inside of the non-inferior range so that the increase in the cost or the total flow time can be kept lower. Numbers of carts in this range are to be employed in preference to numbers of carts outside the range. Therefore, numbers of carts in the non-inferior range are to be preferred solutions in multiple objective optimization considering three operational goals. The numbers of carts in the range construct nondominated (Pareto optimum, or efficient) solution sets. An optimal selection from among them should be done from the managerial standpoint.

When optimizing the number of carts under multiple objectives, the conflicting objectives of the total flow time, the cost, and/or the profit rate are ranked and/or weighted. Together they compose an integrated operation goal.

An efficient approach, which was originally proposed for determining the optimum number of AGVs, may be applied to determine the optimum number of carts for the computer-aided cart systems (Takakuwa 1989).

5 SUMMARY

This paper presents analytical results of computer-aided cart systems. Characteristics of computer-aided cart systems are clarified from the standpoint of efficiency. In addition, Optimization analysis is performed to find the optimum number of carts to allocate under three basic criteria. The procedure is also presented using a numerical example based on an actual case.

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