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THE USE OF NON-SIMULATION APPROACHES IN ESTIMATING VEHICLE REQUIREMENTS IN AN AUTOMATED GUIDED VEHICLE BASED TRANSPORT SYSTEM

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ABSTRACT

With the increasing need to automate material-handling functions in manufacturing and warehousing facilities, many plant managers are finding themselves in positions where they must decide whether or not automatic guided vehicle systems (AGVS) are economically justifiable. Whether the suggestion of AGVS is pursued any further or killed at the very early stage of the decision process is greatly dependent on the initial projected total cost of the system. One of these sources of cost is the number of vehicles required to service the handling task. Simulation is the most reliable method to date in estimating vehicle requirements for complex systems. However, since simulation is very expensive and time-consuming, several non-simulation based calculation approaches have been used to estimate vehicle requirements at the early stages of decision making. In this paper, the performance of four non-simulation or analytical approaches to vehicle estimation are compared to those obtained through detailed simulation under various vehicle dispatching strategies. It is found that the non-simulation techniques far underestimated the requirement under most of the dispatching strategies and gave close estimates in only one of the strategies. The performances of the techniques are characterized and the conditions for using them to provide more accurate estimates for better initial economic justification of AGVS are outlined.

INTRODUCTION

One of the requirements for the proper selection of a material-handling system is the ability of the systems planner to identify the alternative equipment candidates for the task, collect the necessary data on each candidate, and perform feasibility and economic analysis to identify the best candidate. For automatic guided vehicle systems, this requires, amongst other things, the determination or estimation of the number of vehicles required for the

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handling operation. Amongst the several factors that affect the required number of vehicles are the following:

(1) the system layout;
(2) the location of load transfer points;
(3) the trip exchanges between workcenters per unit time;
(4) the vehicle-dispatching strategy;
(5) system reliability; and
(6) speed of travel.

For a given make of vehicle, data on vehicle reliability and the range of operating speed is readily obtainable from the manufacturer. The number of unit load exchanges between workcenters is independent of the types of vehicle selected, assuming that load sizes are fixed. This narrows the number of factors to three principal items, namely:

(1) the guide-path layout.
(2) location of load transfer points.
(3) vehicle dispatching strategies.

Items 1 and 2 are layout-related problems. At present, there is still no systematic way to select an optimal guide-path layout for an automatic guided vehicle system (AGVS). Specification of guide-path layout is done mostly by a commonsense procedure rather than through any exact solution methodology. The analyst generally follows some guide lines to arrive at a solution. Thereafter, the problem of vehicle requirements is addressed. Because of the magnitude and the complexity of the layout problem, the vehicle requirements problem is generally not addressed at the same time as the layout requirements problem. Thus, for a known material flow volume and system layout configuration, minimizing the number of vehicles required to service the handling needs of a facility depends on the vehicle dispatching methods that are operational. The vehicle dispatching problem is concerned with how load pickup and delivery orders are assigned to vehicles for satisfaction. The actions of dispatching strategies determine the number of empty vehicle runs that take place during a shift. Vehicle dispatching and control procedures are also responsible for the degree of interference actually experienced by the vehicles during any time interval. The vehicle dispatching component of the transport system is the main driving force for distributing the vehicles throughout the network.

In job shop operations where order generation is very random, and the sections of the shop from where the orders are generated do not follow any recognized pattern, the only reliable method for estimating vehicle requirements is through a detailed simulation. Because simulation is a very time-consuming process, vehicle estimation through detailed simulation is generally not used in the early stages of system planning. Simulation is resorted to at an advanced stage when it is almost certain that AGVS will be the adopted equipment. During the early stages, vehicle estimates are made through rough hand calculations. The solution obtained through the hand calculation is then used to perform aggregate economic analysis to determine whether the use of AGVS is justified for that application.

In this study, the performance of four methods of vehicle estimation through hand calculation or analytical procedures will be compared to those provided by a detailed simulation procedure under different vehicle dispatching methods. The results from such comparisons can be of immense value to system planners since they can be used to detect directions for adjusting the results of the hand calculations in order to obtain a more reliable estimate of the required number of vehicles at the early stages of system planning, or during the equipment selection stage. The sharpened estimate not only results in a substantial saving in planning and error costs but also improves the quality of the selection decision made.

ANALYTICAL OR CALCULATION-BASED ESTIMATION TECHNIQUES

If the calculation of vehicle requirements is based only on the distance traveled by loaded vehicles without accounting for empty runs and interferences, the vehicle requirements calculation problem would be trivial. However, to account for empty run times, interferences, and breakdowns, several methods of estimation have been proposed. The various techniques are discussed shortly. To simplify the calculations that follow, the following variables are defined:

- n = number of workcenters in the facility;
- β_i = node label corresponding to the pickup station at workcenter i, $i = 1, 2, \ldots n$; for the modeling of the AGVS guide path as a network consisting of arcs and nodes, see Ref. [3];
- α_i = node label corresponding to the delivery station at workcenter i, $i = 1, 2, \ldots n$. β_i and α_i need not be distinct;
- f_{ij} = expected number of loaded trips required between workcenter i and workcenter j during the period or shift;
- T = length of the period or shift during which the f_{ij} exchanges occur (hours);
- $d(\beta_i, \alpha_j)$ = distance between node β_i and node α_j;
- V = average vehicle travel speed (ft/min); uniform speed is assumed;
- t_l = mean time to load a vehicle, min;
- t_u = mean time to unload a vehicle, min;
- e = efficiency of vehicle after accounting for breakdowns.

Requirements calculations—Case 1

In this method of estimation, it is assumed that the distance covered by vehicles making empty runs is equal to the distance traveled by loaded vehicles [1]. Therefore, the number of required vehicles, N, is calculated as

$$N = \left[2 \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{f_{ij} d(\beta_i, \alpha_j)}{V} + \sum_{i}^{n} \sum_{j}^{n} f_{ij}(t_l + t_u) \right] / (60T - t)e \tag{1}$$

where: t = expected lost time by each vehicle during a time period of T due to battery change (min), and e = vehicle efficiency, $0 < e \leqslant 1.0$.

The first term in the numerator accounts for total travel time (i.e. empty and loaded) required while the second factor accounts for the total load pickup and delivery time.

Requirements calculation—Case 2

This method of requirements calculation requires that estimates of blocking time factor and idle time factor be made [2]. The estimates on blocking and idle time factors are used to refine the estimate on vehicle requirement. Using this technique, first the average distance per loaded trip, $\bar{D}$, is calculated, where

$$\bar{D} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} d(\beta_i, \alpha_j)}{\sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij}}. \tag{2}$$

Mean travel time per trip, t_A, with no adjustment for blocking and idleness is given by

$$t_A = \bar{D}/V. \tag{3}$$

where $\bar{D}$ is in feet and V is in ft/min.

Mean travel, and load and unload time per trip, $\bar{t}$, after accounting for blocking, idleness

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and vehicle efficiency, is given by

$$\bar{t} = \frac{(1+b+c)t_A}{e} + t_l + t_u \tag{4}$$

where: b = blocking time factor, $0 \leqslant b < 1.0$; c = idle time factor $0 \leqslant c \leqslant 1$; and e = vehicle efficiency as previously defined, $0 < e \leqslant 1.0$. Blocking and idle time factors are facility dependent and have to be estimated for each facility. In the literature [2], the ranges of value suggested are $0.10 \leqslant b \leqslant 0.15$ and $0.10 \leqslant c \leqslant 0.15$. The number of vehicles is then given by

$$N = \left(\frac{\sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij}}{T} \right) \Big/ \frac{60}{\bar{t}} \tag{5}$$

The numerator of the above expression is the average required number of trips per hour. The denominator is the number of trips made per hour per vehicle.

Requirements calculation — Case 3

This method of calculation requires the computation of the net traffic flow into a workcenter [1]. For workcenter i, the net inflow f_i is given by

$$f_i = \sum_{j=1}^{n} f_{ji} - \sum_{j=1}^{n} f_{ij} \tag{6}$$

If $f_i > 0$, it implies there are more deliveries into workcenter i than pickups. Therefore, there will be f_i empty runs from the delivery station of workcenter i to some pickup stations. On the other hand, if $f_i = 0$, the method assumes no empty runs will be made from workcenter i. Every vehicle that delivers a load from center i will leave with a load to another center. If $f_i < 0$, then center i will be a net importer of empty vehicles. If $f_i > 0$, center i is a net exporter of empty runs. If $f_i = 0$, center i is self-sufficient. If center i is a net exporter, it will export to the nearest center with $f_i < 0$. If the nearest center with $f_i < 0$ is not unique, some rule is applied to ensure that all import needs of centers with $f_i < 0$ are satisfied. In order to satisfy all import needs throughout the shop, the technique requires that

$$\sum_{i=1}^{n} f_i = 0 \tag{7}$$

To minimize the computation required in determining the total distance covered by empty runs when some allocation rules are employed, an approximation method is more often used. The total distance covered by empty runs between workcenters is determined according to the relationship:

$$D_1 = \left[\frac{\sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} d(\beta_i, \alpha_j)}{\sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij}} \right] \left(\sum_{\forall i f_i > 0} f_i \right). \tag{8}$$

Alternatively, D_1 is estimated according to the relationship:

$$D_1 = \left[\frac{\sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} d(\beta_i, \alpha_j)}{\sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij}} \right] \left(\sum_{\forall i f_i < 0} (-f_i) \right). \tag{9}$$

The first term in the expression for D_1 is a measure of the average distance traveled by loaded vehicles. The second term is simply the number of empty runs between workcenters.

Another source of empty runs in this technique is due to intra-workcenter empty vehicle assignment. If the delivery and pickup stations within a workcenter i are physically separated, then a vehicle delivering at α_i will travel empty to β_i. Thus, distance due to empty vehicle transfer within workcenters is

$$D_2 = \sum_{i=1}^{n} \left[\min\left\{ \sum_{j=1}^{n} f_{ij}, \sum_{j=1}^{n} f_{ji} \right\} d(\alpha_i, \beta_i) \right] \tag{10}$$

Distance incurred due to loaded runs between workcenters is

$$D_3 = \sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} d(\beta_i, \alpha_j) \tag{11}$$

The number of vehicles required is then given by

$$N = \left[\frac{D_1 + D_2 + D_3}{V} + \sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij}(t_u + t_l) \right] \Big/ (60T - t) \tag{12}$$

Requirements calculation—Case 4

The reasoning behind this technique is that in a job shop environment, the sequence at which load pickup requests are generated from the workcenters is very random. The number of requests from a center is equal to the number of load pickups required from that center. If the sequence of order generation is random, it is argued that, in the long run, the sequence in which requests are satisfied will also tend to be random. Since vehicles are always freed from assignments at delivery stations, it is at these stations that vehicle reassignment decisions are made. The next station a vehicle is reassigned to is, therefore, a function of the vehicle dispatching rules in force. With a fair dispatching rule, if i and j represent workcenters, then the number of times vehicles are reassigned to workcenter j, given that they completed a delivery task at i, is a function of: (1) the number of deliveries to i; (2) the number of pickups from j, and (3) the total number of pickups required during the period T. Dispatching a vehicle from the delivery station of center i to the pickup station of center j involves an empty run. Thus, the number of empty runs from center i to center j is given by g_{ij}, where

$$g_{ij} = (\text{Expected no. of deliveries to } i) \times (\text{Expected no. of pickups from } j) / (\text{Expected total no. of pickups throughout the system})$$

$$= \frac{\left(\sum_{k=1}^{n} f_{ki} \right) \left(\sum_{k=1}^{n} f_{jk} \right)}{\sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij}} \tag{13}$$

Therefore, the total distance of empty runs from center i to j is equal to

$$D'_{ij} = g_{ij} d(\alpha_i, \beta_j) \tag{14}$$

The total distance of loaded runs from center i and j is given by

$$\overline{D}_{ij} = f_{ij} d(\beta_i, \alpha_j) \tag{15}$$

The distance traveled between stations i and j is the sum of empty and loaded run distances, D_{ij}, where

$$D_{ij} = D'_{ij} + \overline{D}_{ij} \tag{16}$$

The number of vehicles required to service the system is therefore calculated according to

$$N = \left[\frac{\sum_{i=1}^{n} \sum_{j=1}^{n} D_{ij}}{V} + \left(\sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} \right)(t_u + t_l) \right] \Big/ (60T - t) \tag{17}$$

EXAMPLE OF CALCULATING REQUIREMENTS USING THE TECHNIQUES

Consider the facility shown in Fig. 1. There are eight workcenters producing five different products. Other relevant data regarding the operation are given in Table 1. The problem is to provide an estimate of the number of vehicles necessary to satisfy the handling needs of the shop under the given scenario.

Steps required for calculation

(1) Calculate the load traffic intensity between workcenters (Table 2).

(109)

TABLE 1

Product type	Route	Expected no. of loads per 8 hr. shift
1	1, 3, 2, 5, 8	40
2	1, 6, 5, 4, 7, 8	40
3	1, 4, 6, 8	40
4	1, 7, 2, 3, 8	40
5	1, 2, 6, 3, 5, 7, 4, 8	40

Average vehicle traveling speed = 150 ft/min;
Average load and unload times = 15 s;
Efficiency of vehicles ≈ 100%;
No battery recharge is required per 8 hour period.

TABLE 2

Required load trips between workcenters (f_{ij})

From \ To	1	2	3	4	5	6	7	8
1	0	40	40	40	0	40	40	0
2	0	0	40	0	40	40	0	0
3	0	40	0	0	40	0	0	40
4	0	0	0	0	0	40	40	40
5	0	0	0	40	0	0	40	40
6	0	0	40	0	40	0	0	40
7	0	40	0	40	0	0	0	40
8	0	0	0	0	0	0	0	0

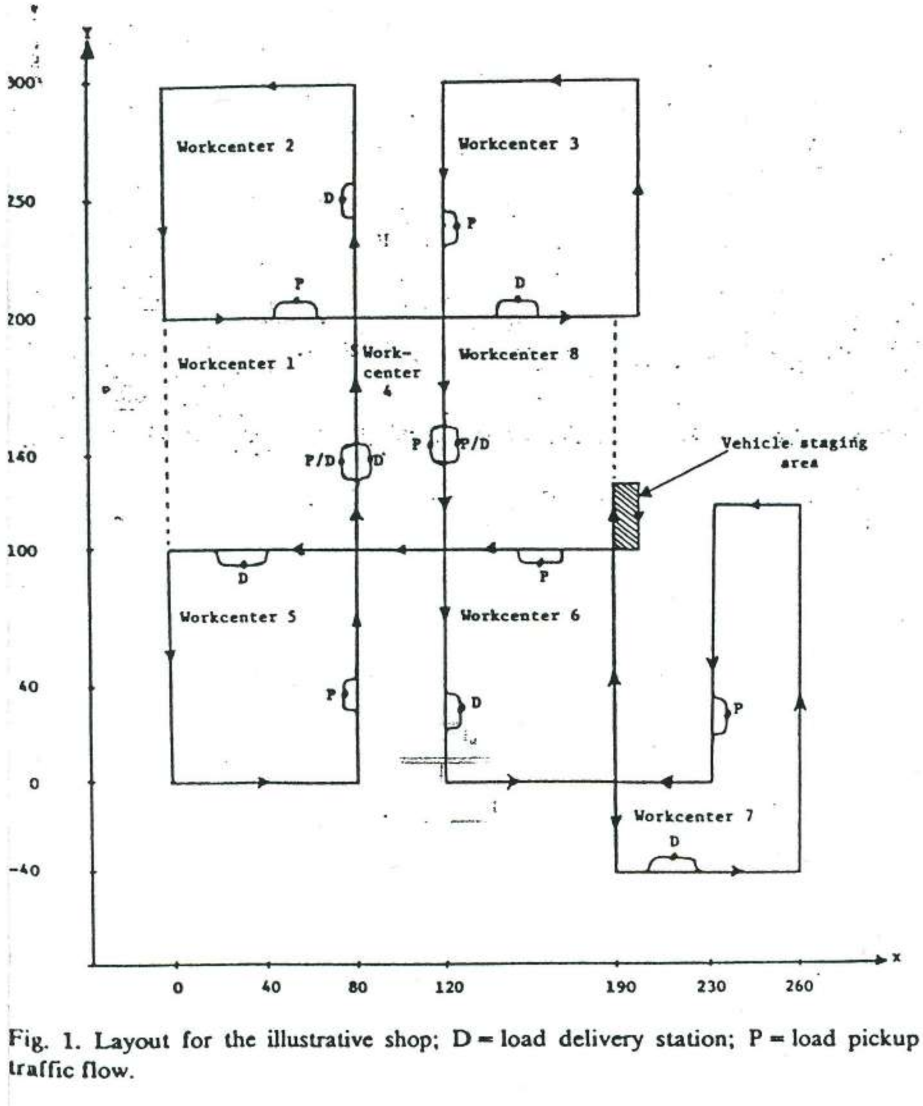

Fig. 1. Layout for the illustrative shop; D = load delivery station; P = load pickup station; ——►— = direction of traffic flow.

(2) Calculate distances between load transfer stations (shortest route) as given in Table 3. The distance calculation is based on the paper by Egbelu and Tanchoco [3].

Using the data on trip requirements and the distance matrix, the calculation of vehicle requirement by each of the methods proceeds as illustrated below. Note that when loaded vehicles leave a workcenter i to another j for load delivery, departure occurs from β_i and delivery occurs at α_j.

Requirements calculation—Case 1

Total pickup and delivery time = 920 (0.25 + 0.25) min = 460 min.

Total transport distance = 2 [40(136.84) + 40(161.55) + 40(330.39) + ⋯ + 40(358.39) + 40(527.23)]ft = 550,666.63 ft

Total travel time = total distance/average velocity = (550666.63 ft)/(150 ft/min) = 3671.11 min.

Using eqn. (1), the number of vehicles required

$$N = (3671.11 + 460)\ \text{min/day} \times \frac{\text{vehicles}}{(480 - 0)\ \text{min/day}}$$

$$= 8.61 \text{ vehicles}$$

$$N = 9 \text{ vehicles.}$$

Requirements calculation—Case 2

Let $b = 0.15$, blocking time factor, and $c = 0.15$, idle time factor.

The total number of loaded trips K is given by

$$K = \sum_{i=1}^{8} \sum_{j=1}^{8} f_{ij} = 920 \text{ trips.}$$

The mean distance traveled by loaded vehicle is given by eqn. (2) as

$$\overline{D} = \sum_{i=1}^{8} \sum_{j=1}^{8} f_{ij} d(\beta_i, \alpha_j)/K$$

$$= \frac{275333.5 \text{ ft.}}{920 \text{ trips}} = 299.28 \text{ ft/trip.}$$

Using eqn. (3), mean trip time,

$$t_A = \overline{D}/V$$

$$= (299.28 \text{ ft/trip})/(150 \text{ ft/min})$$

$$= 1.995 \text{ min/trip}$$

The mean time per trip after accounting for blocking, idleness, pickup time, delivery time, and system efficiency (eqn. 4) is found using

$$\bar{t} = (1 + b + c)t_A + t_u + t_l$$

$$= [(1.30)(1.995)] + 0.25 + 0.25 \text{ min}$$

$$= 3.094 \text{ min.}$$

From eqn. (5), the total number of vehicles N equals

$$N = \left(\tfrac{920}{8}\right)/\left(\tfrac{60}{3.094}\right) \text{ vehicles} = 5.93 \text{ vehicles}$$

$$N = 6 \text{ vehicles.}$$

Requirements calculation—Case 3

This method requires that eqn. (6) be used for each workcenter i.

$$f_i = \sum_{j=1}^{n} f_{ji} - \sum_{j=1}^{n} f_{ij}$$

Using this equation, $f_1 = -200$, $f_2 = 0$, $f_3 = 0$, $f_4 = 0$, $f_5 = 0$, $f_6 = 0$, $f_7 = 0$, and $f_8 = 200$. Since $f_1 < 0$, there is a net shortage of vehicles at workcenter 1; similarly, workcenter 8 has a surplus of vehicles. By this technique, the surplus vehicles released at the delivery station of center 8 will be exported to service workcenter 1. The total distance due to empty runs from eqn. (8) or (9) is equivalent to

$$D_1 = 299.28 \text{ ft/trip} \times 200 \text{ trips} = 59{,}856 \text{ ft.}$$

However, in this particular example, since the allocation of the empty vehicles to centers with a shortage is unique, an exact procedure

TABLE 3

From–To matrix of distances between load transfer stations (feet)

		Workcenter							
		1		2		3		4	
		α_1	β_1	α_2	β_2	α_3	β_3	α_4	β_4
Workcenter									
1	α_1	0.0	0.0	136.84	418.97	161.55	453.68	330.39	181.55
	β_1	0.0	0.0	136.84	418.97	161.55	453.68	330.39	181.55
2	α_2	582.52	582.52	0.0	294.84	413.68	705.81	582.52	433.68
	β_2	300.39	300.39	106.84	0.0	131.55	423.68	300.39	151.55
3	α_3	557.81	557.87	681.94	964.07	0.0	304.84	557.81	408.97
	β_3	265.68	265.68	389.81	671.94	96.84	0.0	265.68	116.84
4	α_4	330.39	330.39	136.84	418.97	161.55	453.68	0.0	181.55
	β_4	161.55	161.55	285.68	567.81	310.39	602.52	161.55	0.0
5	α_5	378.97	379.97	503.10	785.23	527.81	819.94	378.97	547.81
	β_5	126.84	126.84	250.97	533.10	275.68	567.81	126.84	295.68
6	α_6	388.39	388.39	512.52	794.65	537.23	829.36	388.39	557.23
	β_6	151.55	151.55	275.68	557.81	300.39	592.52	151.55	320.39
7	α_7	690.52	690.52	814.65	1096.78	839.36	1131.49	690.52	859.36
	β_7	358.39	358.39	482.52	764.65	507.23	799.36	358.39	527.23
8	α_8	161.55	161.55	285.68	567.81	310.39	602.52	161.55	330.39
	β_8	161.55	161.55	285.68	567.81	310.39	602.52	161.55	330.39

for calculating the total length due to empty runs should be used. Hence, D_1 is equivalent to

$$D_1 = 200d(\alpha_8, \beta_1)$$
$$= 200\ (161.55)\ \text{ft} = 32{,}310\ \text{ft}$$

The distance traveled within workcenter transfers due to empty vehicles is given by eqn. (10) as

$$D_2 = [120(294.84) + 120(304.84) + 120(181.55) + 120(264.84) + 120(249.55) + 120(344.84)]\ \text{ft}$$
$$= 196{,}854.94\ \text{ft}.$$

From eqn. (11), the distance traveled by loaded vehicles is

$D_3 = 275{,}333.31$ ft (previously calculated).

The number of vehicles required, N, is given by eqn. (12):

$$N = \left[\frac{D_1 + D_2 + D_2}{V} + \sum_i \sum_j f_{ij}(t_u + t_l)\right] \Big/ 60T$$

$$= \left[\frac{504498.13}{150} + 920(0.25 + 0.25)\right] \Big/ 480$$

$= 7.97$ vehicles

$N = 8$ vehicles

Requirements calculation—Case 4

This technique requires the calculation of a matrix of empty runs between workcenters. To calculate this, the number of deliveries and pickups from each workcenter is required. Using the F-matrix (Table 2) calculated earlier, we obtain Table 4.

5		6		7		8	
α_5	β_5	α_6	β_6	α_7	β_7	α_8	β_8
340.39	592.52	315.68	552.52	477.81	809.94	181.55	181.55
340.39	592.52	315.68	552.52	477.81	809.94	181.55	181.55
592.52	844.65	567.81	804.65	729.94	1062.07	433.68	433.68
310.39	562.52	285.68	522.52	447.81	779.94	151.55	151.55
567.81	819.94	543.10	779.94	705.23	1037.36	408.97	408.97
275.68	527.81	250.97	487.81	413.10	745.23	116.84	116.84
340.39	592.52	315.68	552.52	477.81	809.94	181.55	181.55
171.55	423.68	146.84	383.68	308.97	641.10	330.39	330.39
0.00	264.84	681.94	918.78	844.07	1176.20	547.81	547.81
136.84	0.0	429.81	666.65	591.94	924.07	295.68	295.68
398.39	650.52	0.0	249.55	174.84	506.97	557.23	557.23
161.55	413.68	136.84	0.0	298.97	631.10	320.39	320.39
700.52	952.65	675.81	551.68	0.0	344.84	859.36	859.36
658.39	620.52	343.68	219.55	144.84	0.0	527.23	527.23
171.55	423.68	146.84	383.68	308.97	641.10	0.0	0.0
171.55	423.68	146.84	383.68	309.97	641.10	0.0	0.0

Next, calculate the matrix G of empty runs allocated to workcenters, where g_{ij} is calculated according to eqn. (13). For example,

$$g_{21} = \frac{(120)(200)}{920} = 26.09$$

TABLE 4

Number of load transfers

Workcenter	No. of deliveries	No. of pickups
1	0	200
2	120	120
3	120	120
4	120	120
5	120	120
6	120	120
7	120	120
8	200	0

$$g_{23} = \frac{(120)(120)}{920} = 15.65$$

$$g_{81} = \frac{(200)(200)}{920} = 43.48$$

$$g_{34} = \frac{(120)(120)}{920} = 15.65$$

$$g_{38} = \frac{(120)(0)}{920} = 0$$

$$g_{82} = \frac{(200)(120)}{920} = 26.09$$

The completed G matrix is given in Table 5. If G_i is the number of deliveries (i.e. stops) made by vehicles at the delivery station of center i, then in g_{ij} times of those G_i stops, the vehicles will be dispatched empty to pick up loads from center j.

The distance covered by loaded vehicles is 275,333.5 ft (previously calculated). The dis-

TABLE 5

Matrix of empty vehicle assignments between workcenters (g_{ij})

From \ To	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	26.09	15.65	15.65	15.65	15.65	15.65	15.65	0.0
3	26.09	15.65	15.65	15.65	15.65	15.65	15.65	0.0
4	26.09	15.65	15.65	15.65	15.65	15.65	15.65	0.0
5	26.09	15.65	15.65	15.65	15.65	15.65	15.65	0.0
6	26.09	15.65	15.65	15.65	15.65	15.65	15.65	0.0
7	26.09	15.65	15.65	15.65	15.65	15.65	15.65	0.0
8	43.48	26.09	26.09	26.09	26.09	26.09	26.09	0.0

tance covered by empty runs is obtained according to eqn. (14)

$$D' = \sum_{i=1}^{8} \sum_{j=1}^{8} g_{ij} d(\alpha_i, \beta_j)$$

$$= [26.09(582.52) + 15.65(294.84) + 15.65(705.81) + \cdots + 26.09(383.68) + 26.09(641.10)]$$

$$= 543{,}958.0 \text{ ft (empty run distance)}.$$

Using eqns. (14), (15) and (17), the number of vehicles required is then given by N, where

$$N = \frac{1}{(60 \times 8 - 0)} \left[\frac{(275{,}333.5 + 543{,}958.0)\text{ ft}}{150\text{ ft/min}} + 920 \text{ trips} \times (0.25 + 0.25)\text{min/trip} \right]$$

$$= 12.34 \text{ vehicles}$$

$$= 13 \text{ vehicles}.$$

The calculated vehicle requirement obtained from each of the techniques is as summarized below:

Method 1: 9 vehicles;
Method 2: 6 vehicles;
Method 3: 8 vehicles;
Method 4: 13 vehicles.

With four different estimates of vehicle requirement as shown, the logical question to ask becomes, "Which estimated value should be used for initial system planning before any detailed simulation study is undertaken?" Characterization of the solutions obtained is the objective of this paper. Such characterization will guide analysts in adopting a method or combination of methods for obtaining a more accurate estimate of vehicle requirements during the preliminary stages of project initiation.

DISPATCHING OF VEHICLES FOR ORDER SATISFACTION

The vehicle-dispatching system in an AGVS environment is that aspect of system control that determines which pickup task should next be assigned to a vehicle when it is released from a previous assignment. The release of a vehicle from a previous assignment generally occurs when the load the vehicle was transporting is delivered to its destination. Thus, all vehicle releases from previous assignments occur at load delivery stations of some workcenter. At the time of the release, the vehicle can be reassigned immediately if there is an outstanding pickup order at the time. Otherwise, the vehicle is set idle and probably reassigned when a task becomes available.

Two main approaches are used for assigning pickup tasks to vehicles in an AGV system; one is static and the other is dynamic. In the static approach, all load pickup assignments are made to vehicles at the beginning of the period or shift [4,5]. As the load pickup tasks arise during the shift, they are satisfied by the vehicles according to the assignment made at the beginning of the shift. This approach of assignment is more amenable to operations that are paced and automated such that the supposed times of order requests are known at the beginning of the shift. Because of the stochastic nature of activities in a manufacturing system, the assumption of perfect predictability of order request times seldom holds. Rarely will any manufacturing and warehousing system satisfy this assumption of predictability. Perhaps the closest type of manufacturing to satisfy this assumption will be an assembly task [4,5].

The dynamic approach of assignment of tasks to vehicles is generally called dispatching. In the dispatching approach, assignment decisions are not made ahead of time but are postponed until a pickup request is made and one or more vehicles become available. Thus, assignment decisions are made one at a time and in a sequential manner as the shift progresses. Because assignment decisions are delayed as much as possible, it is not necessary to know ahead of time when an order is to be placed. Furthermore, the approach permits the dispatching subsystem to consider the prevailing state of the shop in making assignment decisions.

The static approach of assignment is generally obtained by solving a mathematical programming formulation of the handling task to obtain the optimum scheduling decision. When optimum vehicle scheduling decisions are made, the result is that the minimum number of vehicles will be required to service the handling task. The dynamic assignment approach uses heuristic algorithms or rules to make assignment decisions. This heuristic procedure coupled with the fact that decisions are made sequentially rather than simultaneously is expected to yield an inferior result overall compared to the static case, in terms of the total number of vehicles required. The required number of vehicles obtainable from the dynamic approach, will be at least as large as that found by the static method.

In this paper, the dynamic task assignment (dispatching) approach is adopted. This adoption is based on the simplicity of implementation and the practicality of the approach. The method recognizes the dynamic and stochastic changes that occur in a manufacturing system.

Vehicle dispatching problems, as discussed by Egbelu and Tanchoco [3] can be classified into "workcenter initiated task assignment (dispatching) problems" and "vehicle initiated task assignment (dispatching) problems". In workcenter initiated task assignment problems the requirement is to select an available vehicle to dispatch to a workcenter. On the other hand, in vehicle initiated task assignment problems, the decision is to select a workcenter to which a vehicle must be dispatched when it becomes available.

Several rules exist within each class of problem to assign priorities to vehicles or workcenters. To operate an AGV system requires that at least one rule member from each of the two rule families be operational at all times. In other words, combination of at least one rule from each rule family is required [3]. In this study, only some of the rules will be included. A more detailed exposition of these and other rule variations is given in the literature [3]. The rules considered in this paper are the following:

Workcenter initiated task assignment rules

(1) random vehicle (RV) rule;
(2) nearest vehicle (NV) rule;
(3) longest idle vehicle (LIV) rule.

Vehicle initiated task assignment rules

(1) random workcenter (RW) rule;
(2) shortest travel time/distance (STT/D) rule;
(3) maximum outgoing queue size (MOQS) rule;
(4) minimum remaining outgoing queue space (MROQS) rule;
(5) modified first come–first served (MFCFS) rule.

In the next Section, the effects of these rules in setting vehicle requirements for a facility will be evaluated through simulation. Because of the ability of simulation to incorporate several characteristics of the system modeled, it is still the most accurate method for determining vehicle requirements for a system. The results of the simulation experiments are then compared to those obtained by the calculation-based methods in order to characterize their adequacy as estimating tools under various dispatching situations.

ANALYSIS OF THE ADEQUACY OF THE VEHICLE REQUIREMENT ESTIMATORS

Simulation was used to evaluate the effectiveness of the calculation methods in estimating vehicle requirements for a given application in relation to the dispatching rules in force. The layout of the facility used as a basis for the evaluation and comparison is that given in Fig. 1. The assumptions and additional data that describe the operation of the shop are outlined below and given in Table 6.

(1) The shop operates one 8-hour shift per day.
(2) Any battery recharging of the vehicles is done during the off-shift period.
(3) Vehicle breakdowns during the 8-hour shift are negligible.
(4) The number of jobs to be processed during a shift are known at the beginning of the shift. Jobs exist as unit loads and are all available at the start of the shift.
(5) The distribution of part types by ratio in each shift is known.
(6) All parts originate from the raw material storage area and terminate at the finished parts area.
(7) A vehicle can transport one unit load at a time.

TABLE 6

Additional data for illustrative shop

Job type	Processing time per unit load (min)
1	1.0, 5.0, 10.0, 7.0, 0.0
2	1.0, 8.0, 5.0, 10.0, 7.0, 0.0
3	1.0, 9.0, 9.0, 0.0
4	1.0, 10.0, 5.0, 10.0, 0.0
5	1.0, 8.0, 7.0, 9.0, 10~~.0, 8.0,~~ 5.0, 0.0

Work-center no.	No. of machines	Queue capacities (unit loads)	
		Input	Output
1	1	Infinite	5
2	5	5	5
3	5	5	5
4	5	5	5
5	5	5	5
6	5	5	5
7	5	5	5
8	0 (storage)	Infinite	Infinite

To assess the effectiveness of each of the analytical methods, the activities of the shop were simulated over an 8-hour period to determine the minimum number of vehicles required to support the handling tasks under different scenarios of vehicle dispatching. The estimation of vehicle requirements through simulation has been considered to be most reliable [6]. With one replication per rule combination, the simulated vehicle requirements for the shop are given in Table 7. Generally, several replications will be required to validate the result statistically. Because of the supporting results that follow in subsequent Sections of this paper and the fact that the focus here is not on carrying out in-depth statistical evaluation, additional replications are not pursued in this study. The simulation language, AGVSim [7], was used for the purpose. The parameter E, which measures the distance between the center of

TABLE 7

Simulated vehicle requirements by dispatching rules combinations

	Vehicle initiated dispatching rules				
	RW	STT/D	MOQS	MROQS	MFCFS
RV	13 [a]	9 [b]	18	13 [a]	13 [a]
NV	13 [a]	9 [b]	18	13 [a]	13 [a]
LIV	13 [a]	9 [b]	18	13 [a]	13 [a]

[a] In these rule combinations, with 12 vehicles, 196–199 unit loads out of 200 were completed. Thus required vehicles may be 12 with more replications.

[b] In these rule combinations, with 8 vehicles, 198 unit loads out of 200 were completed. Again, required vehicles could be 8.

an intersection and its checkpoint in AGVSim, was assigned the value of 3 ft.

From the results in Table 7, the simulated requirements ranged from a minimum of 9 vehicles for all rule combinations that included the STT/D rule to a maximum of 18 vehicles for all rule combinations that included MOQR. The other remaining rule combinations indicated 13 vehicles. Blocking and locking effects accounted for the higher requirements of 18 vehicles suggested by rule combinations that involve MOQR. The shop and workcenter locking and blocking phenomena are explained in the literature [3]. The fact that for any given "vehicle initiated dispatching rule", the same estimates are obtained regardless of the applicable "workcenter initiated dispatching" rule in force, suggests that workcenter initiated dispatching rules are ineffective in influencing vehicle requirements. This suggestion of ineffectiveness is not unexpected since, for a busy shop, vehicles would rarely remain idle to require invoking a workcenter initiated rule if the minimum number of vehicles is used. Therefore, any references to vehicle dispatching rules in the remainder of this paper will be assumed to imply one of the "vehicle initiated rules" unless otherwise specified.

Comparing the simulated estimates and the analytical estimates, with the exception of the STT/D rule, it can be seen that the estimates provided by three of the analytical methods (i.e., cases 1, 2, and 3) fell well below the simulated requirement of 13 vehicles given by three (i.e. RW, MROQS, and MFCFS) of the five vehicle initiated rules. In fact, the 6 vehicles estimated by Case 2 of the analytical method is just about half the simulated requirement of 13 vehicles. Thus, if the illustrative facility was an actual system and any one of the dispatching rules RW, MOQS, MROQS, and MFCFS is considered for adoption, then the estimated vehicle requirements (with the exception of that given by Case 4) would have been unquestionably too low and any economic justification of an AGV system based on the estimates would most likely be on the optimistic side and perhaps grossly erroneous. The estimates of three of the analytical methods as they currently stand would have required major adjustments upwards to be rendered useful. On the other hand, where the STT/D rule is used as a basis for vehicle dispatching, the differences between the simulated estimate and the analytical estimates are far less significant as the tabulated results show. The estimating error ranged from zero to 4 vehicles. The estimate given by the first (i.e., Case 1) analytical method corresponds exactly to the simulated requirement of 9 vehicles. The second best estimate of 8 vehicles came from Case 3. Case 2 underestimated by 3 vehicles whereas case 4 overestimated and posted the largest estimating error of 4 vehicles. Of the four calculation-based estimates discussed here, Case 2 is the most widely quoted in practice [2], despite its tendency to give inferior estimates. The results shown here suggest that its estimates are generally optimistic and need to be adjusted upwards to be rendered useful as a basis for an initial system justification and planning tool. With the exception of STT/D and MOQS rules, the estimate given by Case 4 of the analytical method agrees with those obtained under the majority of the dispatching rules.

These results give the impression that using the STT/D rule leads to minimum vehicle requirements. The impression is not always true. As described in [3], the STT/D rule is very sensitive to the location of load transfer stations. This sensitivity leads to shop locking as described in [3]. Unless some form of anti-locking device is implemented, the shop will remain deadlocked as time passes and no further parts will be produced. An illustration of the application of an automatic anti-locking system is described in [3]. AGVSim also incorporates an anti-locking logic. Unless load transfer stations are properly located, the effectiveness of the STT/D rule cannot be generalized. In the layout used in this example, the pickup stations have been well located to minimize the blocking effect due to the STT/D criterion.

Workcenter locking and the implementation of an anti-locking system is wasteful of the transport resource. The use of MOQR in the illustrative shop resulted frequently in workcenter locking, which accounted for its poor performance in requiring far more vehicles than any of the other four rules. The locking effect is very difficult to account for in any estimating equation.

VARIATIONS IN MATERIAL FLOW VOLUME

To further evaluate the adequacy of the analytical procedures as tools for estimating vehicle requirements, the shop's material flow volume was subjected to increases of 25% and 50% and the vehicle requirements re-estimated. Increases of 25% and 50% represent total outputs of 250 and 300 unit loads respectively. The 20% distribution by ratio for all job types and all other shop parameters remained unchanged. The same scenarios were also simulated to determine the simulated requirements. Since vehicle requirement was previously determined to be insensitive to "workcenter initiated rules", only the Nearest Vehicle (NV) sub-rule was considered from the category. All the five sub-rules RW, STT/D, MOQS, MROQS, and MFCFS of the "vehicle initiated rules" sub-family were considered. For the 25% increase, the calculated and simulated vehicle requirements were as given in Tables 8 and 9 respectively. As table 8 indicates, the analytical estimates are 11 vehicles in Case 1, 8 in Case 2, 10 in Case 3, and 16 in Case 4. Again, with the exception of that given by Case 4, all the other estimates are well below the simulated requirements obtained under the rules RW, MOQS, MROQS, and MFCFS. Most of the analytical methods proved to be grossly inadequate under these rule conditions. This is not the case when the method-4 estimator is used. Its vehicle estimate is in perfect agreement with the simulated requirements obtained under the rules RW, MROQS, and MFCFS. All techniques lose their estimating effectiveness under the MOQS rule.

TABLE 8

Vehicle requirements calculated by analytical technique (250 unit loads)

Method of estimation	Required no. of vehicles	
	Estimated	Actual
Case 1	10.76	11
Case 2	7.41	8
Case 3	9.96	10
Case 4	15.42	16

TABLE 9

Simulated requirements (250 unit loads)

	Vehicle initiated dispatching rules				
	RW	STT/D	MOQS	MROQS	MFCFS
Vehicles required	16 [a]	11 [b]	21	16 [a]	16 [a]

[a] In these cases, 247 out of 250 unit loads were completed by 15 vehicles.
[b] 10 vehicles completed 248 out of 250 unit loads.

TABLE 10

Vehicle requirements calculated by analytical technique (300 unit loads)

Method of estimation	Required no. of vehicles	
	Estimated	Actual
Case 1	12.91	13
Case 2	8.89	9
Case 3	11.95	12
Case 4	18.51	19

TABLE 11

Simulated requirements (300 unit loads)

	Vehicle initiated dispatching rules				
	RW	STT/D	MOQS	MROQS	MFCFS
Vehicle requirements	20 [a]	14 [b]	23 [c]	21	20 [a]

[a] With 19 vehicles 297 out of 300 unit loads were completed.
[b] With 13 vehicles 298 out of 300 unit loads were completed.
[c] With 20 vehicles 298 out of 300 unit loads were completed.

On the other hand, with the exception of Case 4, the analytical methods performed relatively well when compared to the simulated requirement obtained under the STT/D rule. Again, as in the previous comparison, the estimate obtained from Case 1 corresponded exactly with that obtained by simulation. The estimate from Case 2 is again the most inferior of the three methods.

Tables 10 and 11 contain the requirements for the case of 50% increase in output volume. Unlike the case of 25% increase, none of the methods gave an exact estimate that agrees with the simulated requirements under any of the rules. With the exception of method 4, the analytical estimates are again less in error with the STT/D rule than with other rules. The method-2 estimate was far more optimistic, inadequate, and again inferior, yet this technique (i.e., method 2) seems to enjoy the greatest application in actual desgin situations.

On the other hand, method 4 gave an estimate that is closer to the simulated vehicle requirements under the rules RW, MOQS, MROQS, and MFCF. All other methods gave overly optimistic estimates that would be grossly inappropriate if the dispatching rules RW, MOQS, MROQS, and MFCFS are the planned operational rule.

TECHNIQUE CHARACTERIZATION FOR USEFUL APPLICATION

The non-simulation based techniques discussed here have been used and may continue to be used in making major equipment decisions in actual settings, even though no characterization of their limitations has been made. A lack of understanding of the limitations of these techniques can result in unwarranted abuse as analysts can use them to justify their own equipment biases. Before these techniques are used in actual decision processes, it is necessary that the decision makers should understand the strengths and weaknesses of the methods as outlined below:

(1) The calculated requirements are simply estimates and, in general, do require some adjustments depending on the type of dispatching rules employed. The non-simulation based methods can account for layout and material volume effect but do not, at present, capture the dispatching effect.

(2) Where shortest-distance based rules are used and the conditions that favor shop locking are removed, the calculation techniques provide fairly good estimates. The actual requirement would fall in the neighborhood of that given by method 1 but less than that given by method 4.

(3) Estimates provided by method 2 are overly optimistic under most heuristic dispatching rules. The actual requirement will be higher.

(4) Under most dispatching rules, especially those that do not use distance as a criterion, most of the present non-simulation based techniques generally underestimate the actual vehicle requirement. Method 4 gives superior estimates in these circumstances than any of the other methods. Method 2 is miserably inadequate under these scenarios.

(5) When the prevailing dispatching rules lead to occasional shop locking, the estimating abilities of the calculation methods are

totally in error, inappropriate and hopeless. These estimates tell almost nothing about the actual requirement even when an automatic anti-locking rule is incorporated as part of the shop operating system. Ensuring the removal of all conditions that favor workcenter and shop locking during the design of the guide path layout is the first step towards obtaining reliable estimation without using simulation.

CONCLUSIONS

A basis for selecting the proper analytical technique for directly estimating vehicle requirements, without simulation analysis for initial system planning in an AGV system, is presented. The appropriateness of four analytical procedures for estimating vehicle requirements in relation to vehicle dispatching rules is discussed. In general, the technique provide good estimates under all the dispatching rules. Some techniques, of course, perform better under some dispatching rules than others. For the STT/D rule, a good estimate is obtained only under the provision that conditions which encourage shop locking have been eliminated through proper system layout planning. As discussed in [3], the STT/D dispatching rule is very prone to locking and blocking phenomena. Under the majority of the dispatching rules tested, the ability to estimate vehicle requirements by most of the analytical methods are overly optimistic and, at best, good.

Amongst factors such as system layout and material flow volume, vehicle requirements are greatly affected by the vehicle dispatching rules adopted. Analytical, non-simulation based techniques for estimating vehicle requirements for AGV systems must recognize the relationship between requirements and dispatching policies. As a result, the adequacy of an estimating technique is a function of the dispatching rules in force. By recognizing this relationship, raw analytical estimates can be properly adjusted to obtain a more accurate measure of requirements without resorting to detailed simulation analysis. The use of simulation analysis is too expensive to undertake during the search phase of the material handling equipment to be selected. Unless procedures for obtaining more accurate vehicle requirements are established, equipment selection decisions for which AGVS is a candidate are likely to be wrongly resolved and, if rightly resolved, to be done so using the wrong data.

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