Vehicle Requirement Analysis of an AGV System using Discrete-Event Simulation and Data Envelopment Analysis

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***Abstract*—Deployment of Automated Guided Vehicle (AGV) as a material transportation system (MTS) within a manufacturing plant is becoming more common. It is due to the reasons that AGV systems provide higher flexibility and reliability attributes compared to the other transportation system. In order to establish an AGV system, it is critical for an organization to determine their vehicle requirements. This paper proposes simulation-based vehicle requirement estimation for multi-load AGV operation in manufacturing industry.**

Keywords- Automated Guided Vehicle; multi-load capacity; material transportation system; Data Envelopment Analysis

I. INTRODUCTION

The impact of increasingly demanding customers and stiffer competition resulting from the globalization of markets and supply-chain have driven manufacturing industry worldwide to enhance their competitiveness. This pushes the industrial enterprises to increase system efficiency as well as to have flexibility in coping with dynamic demand changes and fluctuations.

MTS is one of the critical aspect need to be improved to ensure that production flow could run as scheduled. In selecting MTS types, AGV is preferred over other transportation approaches due to the flexibility and mobility attributes it could offer.

Recently, AGVs have been deployed in many other industrial sectors which include container terminals, hospital and warehouses [1],[2],[3]. Numerous researches worldwide have contributed towards the betterment in establishing an efficient AGV system. Extensive review on researches conducted on AGV has been made by [4].

In designing an AGV system, there are several requirements need to be carefully considered. Among the important factors include:

i) design factors – fleet size, guide path design, loading capacity and
ii) operational factors – vehicle dispatching and routing, utilization rate, positioning of an idle vehicle and conflict resolution approach.

Although significant technical advancements have been made since the early days of AGV operation, there are still rooms for improvement particularly in optimizing the operation of large scale AGVs fleet.

This paper aims to i) propose a simulation-based vehicle requirement analysis for multi-load MTS and ii) investigate system performance when MTS design and operational parameters are varied.

II. PROBLEM BACKGROUND AND RELATED TECHNIQUES

A. Vehicle Requirement Estimation for Automated Material Transportation System

In implementing an AGV system, there are several aspects need to be planned. One of the key perspectives is to determine the number of vehicle needed for material transportation purpose. This is particularly important due to several reasons. Under-estimated fleet size simply means insufficient medium of transportation that might affect the schedule of the entire shop floor. Meanwhile, over-estimated fleet size requires bigger capital investment will result to under-utilized vehicles while increasing operational-related cost. This highlights the importance to determine minimum number of vehicles required.

There are two main approaches in analyzing the fleet size requirement – analytical and simulation methods. Analytical methods employ mathematical models and heuristic algorithms. Nevertheless, realistic material transportation planning is a very complicated task. This is due to the reason that the number of vehicles needed is affected by various design parameters as well as dynamic operation variables which include randomness in job arrivals, traffic congestion, alternate vehicle routing and failure. The impact of each factor and their interactions are difficult to be analyzed and verified using analytical method especially when large scale transportation system is considered. This justifies the importance of applying simulation method to analyze vehicle requirements.

In this paper, we utilized a simulation approach in investigating the interactions of design parameters and the

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resulted system performance. Based on the outcomes, we can forecast the required number of AGVs.

B. Data Envelopment Analysis

In designing any transportation system, design engineer need to resolve multiple conflicting objectives within specific constraints and consequently determine an outcome with appropriate balance of all objectives.

One of an effective technique that can be used to resolve multi criteria decision making (MCDM) is Data Envelopment Analysis (DEA). DEA is a nonparametric method conducted to determine technical frontier of a specified data set based on specific objectives. Originated for economic purposes, it has been utilized to solve engineering and operational research problems.

DEA measures the relative efficiency, h_0 of decision making units (DMUs) which account for the ratio of cumulative weighted outputs over the sum of weighted inputs. In this paper, DMU refers to an alternative setting solution in solving the specified case problem. Linear Programming (LP) methodology is used to realize DEA in measuring the efficiency of multiple decision-making units (DMUs) when the production process presents a structure of multiple inputs, m and outputs, s. Based on the acquired efficiency for all DMUs, technical frontier of the entire solutions could be identified thus enabling proper decision making process. Conventional LP model for DEA [6] are provided in Eq. (1) where H_j is the relative efficiency of k-th DMU, α_k is the weight of the output k, β_k is the weight of the input k, y_{kj} is the output value produced by DMU-j and x_{kj} is the value of input-i of DMU-j. Fig. 1 illustrates an example of Pareto Frontier graph with both B and C are Pareto Frontiers and would provide the best solutions based on the required performance.

$$\max H_j = \sum_{r=1}^{m} \alpha_k y_{kj}$$

Subject to

$$\sum_{i=1}^{n} \beta_i x_{ij} = 1$$

$$\sum_{k=1}^{m} \alpha_k y_{kj} - \sum_{i=1}^{n} \beta_i x_{ij} \le 1, \; j = 1,2,\ldots s$$

$$\beta_i \ge 0, \; i = 1,2,\ldots,m$$

$$\alpha_k \ge 0, \; k = 1,2,\ldots,n \tag{1}$$

C. Queueing Theory

In any manufacturing system, buffer space is typically allocated as temporary queue storage to store WIP products to be processed. Whenever queue is utilized, operational time and cost factors are involved. Therefore, queue is an important component that needs to be modeled correctly. The importance increases particularly when queue is the immediate medium that AGVs operate with.

Thus, it is necessary to provide an appropriate mathematical representation. In this study, queuing model defined by Little's Law [5] is applied to the transportation systems for numerical modeling. The theorem is defined in (2) and (3) where Q is the set of queues, L stands for average number of items in the queueing system, λ is for job arrival rate and W represents the queue's flow time.

$$L_q = \lambda W_q \tag{2}$$

$$L = \frac{1}{Q} \sum_{q=1}^{Q} L_q \tag{3}$$

III. Simulation Model

A simulation model based on realistic automotive-related industrial application has been adopted. The model possesses certain technical specifications and assumptions as the following:

1) System specification

- The shop floor layout used in the manufacturing system is based on process layout. There are 19 process centers in the system where each process has a set of machines as shown in Fig. 2.
- 'IN' refers to the incoming raw material station while 'OUT' refers to the outgoing finished good station.
- There are 5 job sets with each possessing specific number of operation sequences. The detail of the job sets are described in Table I.
- In order to acquire stable data on the production flow, the warm up period are fixed for 2 hours. Thus, data for analysis purpose are only collected after the warm up period.
- Jobs arrival rates are varied with mean, E follow a Poisson distribution.

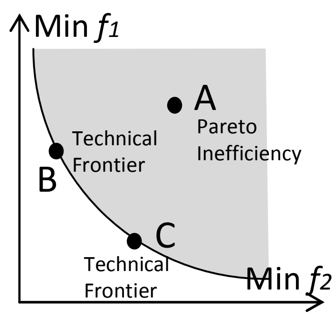

Figure 1. Example of Pareto Frontier graph

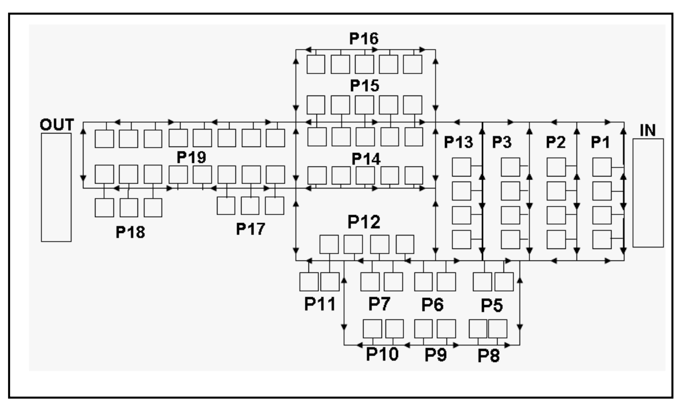

Figure 2. FMS Layout.

2) *Machine specification*

- The number of machines, m in the system is fixed.
- Machine's processing times are normally distributed with standard deviation, $\sigma = 0.5$ minutes
- In allocating specific operation to a machine within a process group, rounded uniform distribution function were used.
- Task loading and unloading times are fixed at 0.5 minute each.
- Finite numbers of input and output machine buffers are used.
- Dispatching rule is employed for the input and output buffers in prioritizing tasks in queue waiting for i) processing on a machine and ii) transportation.

3) *AGV specification*

- Multiple loading capacity AGVs are deployed for material handling purpose.
- The number of AGVs, v in the system is known.
- Vehicles' velocity, vel_x are constant at 40 m/min.
- The travel paths connecting the processing machines are bidirectional.
- There is no other material handling medium used.
- All machines and AGVs are assumed to operate at 100% efficiency.

IV. EXPERIMENTAL DESIGN

A. Simulation Experiment

The experiments conducted were designed to investigate several perspectives of the AGV operation. The experiment plans are classified based on the following aspects:

1) *AGV Design Parameters (DP)*
AGV design parameter refers to the factors that are contemplated during the development of an AGV system. There are several parameters that can be selected from. In this paper, two critical factors studied are number of vehicle (*NOV*) and AGV loading capacity (*CAP*).

2) *Performance Indicators (PI)*

- System Throughput (*STH*)
STH is the amount of finished goods produced by a system over a period of time. It is used to measure the system-wide performance.
- Mean Flow Time (*MFT*)
Flow time refers to the time duration in which a job stays in the system. *MFT* complies with (4) to (7) where i is job and j is operation, tt_{ij} stands for traveling time, tp_{ij} for machine processing time, tt_{ij} for loading/unloading time and tq_{ij} for queueing time. In computing the *MFT*, elements needed include total operation time, O_{ij}; job completion time, C_i; job flow time, F_i; job released time, R_i.

$$O_{ij} = tp_{ij} + tt_{ij} + tu_{ij} + tq_{ij} \tag{4}$$

$$C_i = \sum_{i=1}^{n} O_{ij} \tag{5}$$

$$F_i = C_i - R_i \tag{6}$$

$$MFT = \frac{1}{n}\sum_{i=1}^{n} F_i \tag{7}$$

- Total Distance Traveled (*TDT*)
AGVs' traveled distances are used as an indicator. *TDT* computation is defined in (8) where ta_x is the vehicle's total available time, pt_x is the percentage of traveling and vel_x is the AGV's traveling velocity.

$$TDT = \sum_{x=1}^{v} (ta_x * pt_x * vel_x) \tag{8}$$

Simulation of the material transportation has been developed using SIMUL8 simulation software. SIMUL8 is one of the most widely utilized commercial event-driven and decision support simulation software [7].

The detail of the experiment design parameters is summarized in Table II. Analysis was carried out to determine the performance of agent-based AGV control system. Simulation has been carried out testing all of the combination of experimental factors over 8-hour production time based on a full factorial design. Hence, 24 numbers of simulations were conducted.

B. Application of DEA Method

Looking from the decision-making perspective, selecting the appropriate combination of *NOV-CAP* should be conducted based on specific methodology taking into account all of the important criteria. It is due to the fact that each combination will give different result on the objective functions. In a real application, decision makers would like to know the trade-off characteristics of all the functions before any investment is to be made. This study utilizes the Pareto optimality concept in choosing the best combination where all of the *NOV-CAP* combinations are identified and categorized as either technical frontier or not.

TABLE I. DETAIL OF JOB SPECIFICATION

Job ID	Volume Mix (%)	Process sequence (processing time in minutes)
1	25	P 1 (4) - P 2 (8) - P 3 (3) - P 14 (4) - P 17 (1) - P19 (12) - P 20 (1)
2	25	P 1 (4) - P 2 (8) - P 3 (3) - P 6 (3) - P 7 (1) - P 14 (4) - P 17 (1)- P 19 (12)- P 20 (1)
3	20	P 5 (2) - P 6 (3) - P 7 (1) - P 15 (5) - P 17 (1) - P 19 (15) - P 20 (1)
4	15	P 1 (4) - P 2 (8) - P 3 (3) - P 4 (4) - P 13 (3) - P 14 (4) - P 17 (1) - P 19 (15) - P 20 (1)
5	15	P 8 (3) - P 9 (5) - P 10 (1) - P 11 (8) - P 12 (4) - P 16 (6) - P 17 (1) - P 19 (22)- P 20 (1)

This is carried out using DEA method. DEA systematically explore the technical frontier of Pareto efficient rules by measuring the optimum relative efficiency of *NOV-CAP* combinations with regards to multiple criteria. In this research, 24 possible *NOV-CAP* combinations are accounted as DMUs and its respective achievement of the objectives are used as the output values of the DEA model. The achievements are typically multi-dimensional as several objectives could be measured simultaneously.

Predefined simulation parameters acts as the inputs of the DEA model. In formulating the DEA model for this research, two inputs – respective fleet size and vehicle's loading capacity and two outputs – total duration needed for the system to complete a job and total distance travelled were selected. The condition aims to have an efficient manufacturing environment that considers both the production and transportation aspects.

V. RESULT AND ANALYSIS

A. *Performance Analysis*

Several analyses have been carried out with the intention to determine data obtained from the simulations. Performance analysis indicates the outcomes of the system performance based on the stated PIs. Meanwhile, variance analysis was conducted to ensure that the experiments carried out are statistically meaningful.

Deployment of different vehicle loading capacity resulted in different *STH* outcomes. The result shown in Fig. 3 shows that single-loading AGV is not capable to achieve the throughput obtained by fleet of multi-load AGV. Naturally, the deployments of vehicles with larger loading capacity directly contribute to increase system throughput when compared to the same fleet size with lower capacity. Generally, the minimum fleet size of 20-AGV with 5-loading capacity are capable to complete 90% of the transportations requirement of the system.

TABLE II. DESIGN PARAMETER

	Factors	Value range
1	Number of vehicle	5, 10, 15, 20, 25, 30
2	Loading capacity	1, 5, 10, 15

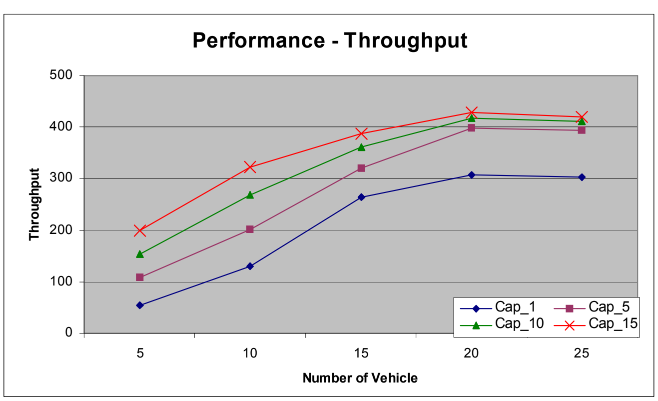

Figure 3. System Throughput

Furthermore, the data on average *TDT* for each vehicle has been analyzed and depicted in Fig. 4. Generally, AGVs with single loading capacity have problem in minimizing traveling distance. Vehicle with 10 and 15 capacities have the same pattern in term of *TDT*. There are also small differences between both capacity groups which reflect that the capacity might not be fully utilized for AGV with 15 loading capacity.

Apart from the throughput, we also studied the mean flow time of the system. Generally, vehicle with any loading capacity will have a decrement of *MFT* when the number of vehicles increases as illustrated in Fig. 5. However, there are distinguishing differences of *MFT* when the number of vehicles increased. Single-load AGV hardly obtained the same *MFT* produced by multi-load AGV even when the number of vehicle is large. This might be due to the traffic congestion reason.

B. *Variance Analysis*

In order to further analyze the performance of multi-load AGVs operation, variance analysis (ANOVA) has been conducted using Minitab software. Experiments were executed at α = 0.05 significance level. Table III depicts the effect of *DPs* on the *PIs*. Based on the result collected, it can be indicated that *NOV* has an important influence on all *PIs* while *CAP* evidently affected the *TDT* as the P-values are below the significance level.

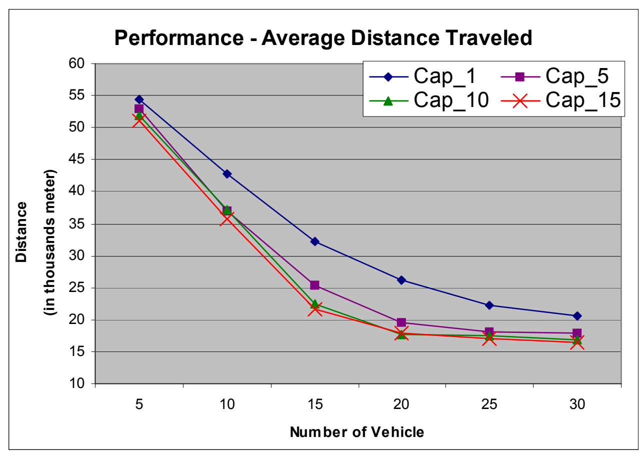

Figure 4. Comparison of Average TDT.

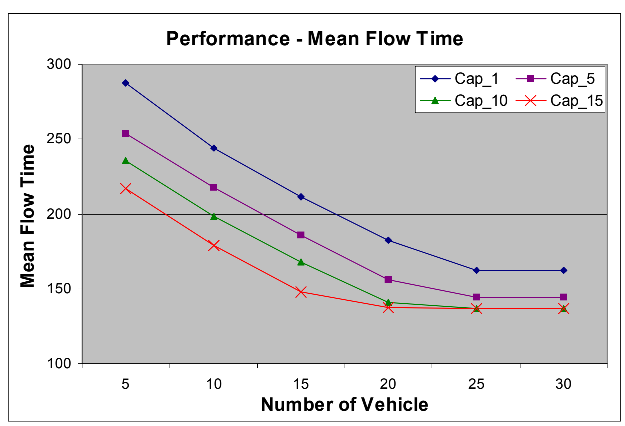

Figure 5. Comparison of MFT.

TABLE III. RESULT OF ONE-WAY ANOVA

DP	*PI*	*DF*	*SS*	*MS*	*F*	*P*
	STH	5	218259	43652	11.63	0.000
NOV	*MFT*	5	28572	5714	11.83	0.000
	TDT	5	1.73E+11	3.45E+10	10.75	0.000
	STH	3	62723	20908	1.87	0.106
CAP	*MFT*	3	7681	2560	1.73	0.133
	TDT	3	4.6423E+10	1.55E+10	1.68	0.023

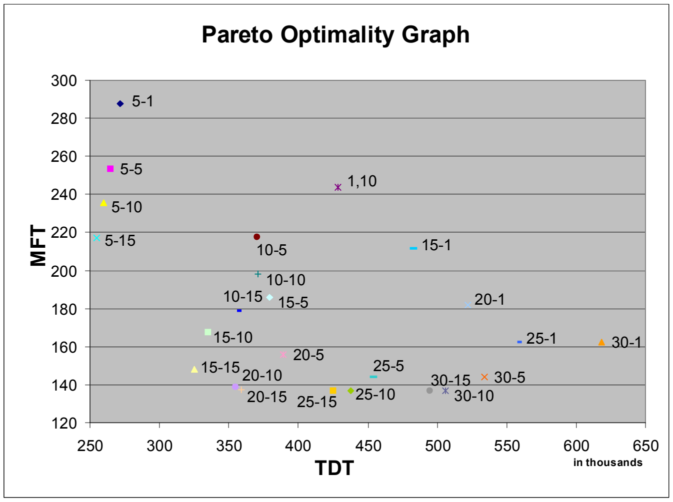

Figure 6. Pareto Frontier Graph

C. *Technical Frontier Determination*

Finally, a Pareto optimality graph has been obtained based on DEA methodology to acquire the understanding on how the result could be used as a decision making tool. Fig. 6 shows the Pareto optimal solutions based on *MFT* and *TDT* requirements with each node represents a specific DMU.

VI. CONCLUSION

The research has successfully achieved its aims in providing necessary information on analyzing vehicle requirement using discrete-event simulation and DEA methods where it could be used as a decision support tool. Based on the specified objectives and performance measures, a set of solutions are obtained and decision maker is able to decide on the necessary fleet size.

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