Simulation Analysis of Models for Estimation of Empty Travel Time of Vehicles in Non-automated Material Handling Systems

In designing or redesigning a facility like manufacturing plant or warehouse, an integral part is a proper selection of material handling system. Despite large alternatives, including automated material handling systems with conveyors or automated guided vehicles, most facilities today use for material handling man-driving vehicles (non-automated discrete material handling system). Proper design of such systems requires determination of required number of vehicles. Determination of empty vehicle travel time is based on either time consuming simulation or non-simulation approach using estimation.

The main goal of this paper is to review and analyse some proposed methods for empty travel time estimation of non-automated discrete material handling systems. Results obtained by estimation methods are compared with the simulation results.

Keywords: Discrete non-automated material handling system, empty travel time estimation methods, simulation analysis.

1. INTRODUCTION

In designing a new facility like manufacturing plant or warehouse, an integral part is a proper selection of material handling system. Despite large alternatives, including automated material handling systems with conveyors or automated guided vehicles, most facilities use man-driving vehicles (non-automated discrete material handling system), usually forklifts. Proper design of such systems requires determination of required number of vehicles.

Even redesign of existing facilities, like improvement of layout design which is often with the goal of reduction of total transportation, requires analysis of proposed new solution including determination of required number of vehicles. In most existing facilities today, especially smaller ones, we can find only one or few man-driving, non-automated vehicles used for loading, transport and unloading loads between departments and/or machines (workplaces). For determination of required number of vehicles or for calculation of vehicle’s utilisation in a proposed redesign, a proper method of calculation of total transport time is required. Based on the number of trips between locations (from-to matrix), distances between locations based on layout (distance matrix) and transport/handling parameters (speed of travel, loading times, unloading times), it is quite easy to calculate total time required for loading, unloading and transport of loads. However, determination of empty vehicle travel time is based on either time consuming simulation or non-simulation approach using estimation.

Searching for methods to estimate empty vehicle travel time leads to plenty papers dedicated to automated guided vehicle systems (AGVS), but surprisingly no papers especially dedicated to non-automated transporters. In AGVS there exists a control system with various dispatching rules that are mostly not applicable for transport systems in smaller job shops, workshops or smaller warehouses. Proposed algorithms also usually assume larger fleets where proper scheduling and routing of automated vehicles is required due to the congestions and deadlocks. In smaller facilities only few vehicles are employed, sometimes even only one, with mostly low utilisation.

The main motivation of the research presented in this paper, originally presented on MHCL 2017 conference, was to review proposed methods for empty travel time estimation developed for AGVS and to analyse their usage for non-automated discrete material handling systems, especially those employing only one or two vehicles. For selected example of production process, varying throughput (production volume) and layout, results obtained by estimation methods are compared with simulation results in order to get insights on estimation errors (differences between analytical results and simulation results), possible influence of vehicle’s utilisation on estimation error as well as possible influence of layout design (increased full travel time) on total empty travel time and estimation error.

2. EMPTY TRAVEL TIME ESTIMATION METHODS

In this section several most cited methods for empty travel time estimation, analysed in this paper, are shortly presented.

The first analytical models, whose development began in the early 1980’s, were designed to provide alternative solution for AGV system design since the
process of designing a simulation model required much effort and time. Most of the models were logically meaningful and comprehensible, mathematically simple calculation, used to determine the required number of vehicles to carry out transport processes based on pre-known data (transport intensity and distance matrices, and transport and production parameters), in a shorter period of time. Still today analytical estimation methods are preferable than simulation in early stage of design, during selection of material handling systems.

Already in the design of the first models focused on the AGV system design it was noted the importance of determining the time of empty travel, and soon that part of the calculation/estimation became the key item to which the most attention was given. Notation used in models is given at the end of the paper:

In [1] author presented four models for estimation of number of required vehicles (NRV), however one of them don’t estimate empty travel but directly NRV (based on estimated blocking and idle time). Two models were models presented by Beisteiner in [2] – for this paper named BEISTEINER 1 and BEISTEINER 2 model. Fourth model was proposed by author, named EGBELU model.

BEISTEINER 1 model is very simple. It is assumed that the distance travelled by empty vehicles is equal to the distance travelled by full vehicles. Therefore, for a given number of trips between each pair \( f_{ij} \) in from-to matrix and distances between workplaces, total empty travel is calculated as

\[
D_e = \sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} \cdot d_{ij}. \tag{1}
\]

BEISTEINER 2 model is based on calculation of net traffic flows into workplaces, as

\[
f_i = \sum_{j=1}^{n} f_{ij} - \sum_{j=1}^{n} f_{ji}. \tag{2}
\]

If there are more deliveries than pickups at workplace, there will be empty runs form that workplace to some others. And vice versa, if there are more pickups than deliveries at workplace, there will be empty runs to that workplace. Total empty travel distance is approximated as average distance travelled by full vehicles multiplied by number of empty runs between workplaces, as

\[
D_e = \left[ \sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} \cdot d_{ij} \right] \cdot \left( \sum_{j=1}^{n} f_{ij} \right). \tag{3}
\]

EGBELU model is based on the fact that in a job shop environment the sequence at which load pickups requests are generated is very random and assumption of fair dispatching rule. It calculates expected number of empty runs between two workplaces \( i \) and \( j \) from the expected number of deliveries at workplace \( i \) and expected number of pick-ups at workplace \( j \) using equation:

\[
g_{ij} = \frac{\sum_{k=1}^{n} f_{ik}}{\sum_{k=1}^{n} f_{jk}} \cdot \frac{\sum_{k=1}^{n} f_{jk}}{\sum_{l=1}^{n} f_{lj}}. \tag{4}
\]

Total empty travel distance is calculated simply multiplying expected number of empty trips between workplaces by distance between them, as

\[
D_e = \sum_{i=1}^{n} \sum_{j=1}^{n} \left( g_{ij} \cdot d_{ij} \right). \tag{5}
\]

In [3] authors presented a model for calculation of number of required vehicles, based on minimization of empty travel. As in BEISTEINER 2 model, this MAXWELL-MUCKSTADT model calculates net traffic flows into workplaces, however determination of empty runs is done by solving transportation problem (minimizing total empty travel). While Egbelu’s model is considered as “expected case”, this one is considered as “best case” (see [3] for more details about model).

In [4], authors presented a model for empty travel time estimation based on assumption that the vehicles that finish the transportation requirements stay at their current workplace. This assumption assures that the number of empty vehicles leaving a workplace is equal to the number of loads dropped off at that workplace. Similarly, the number of empty vehicles that will be needed at a particular workplace is equal to the number of loads that have to be moved from that workplace. They also assumed that vehicles are assigned to workplaces (called from next workplace) according to a random rule. The probability that a vehicle request at machine \( i \) is satisfied by a vehicle at machine \( k \) is \( f_{ik} \cdot f_{ki} \). The average empty vehicle travel distance per trip can be then calculated as

\[
d_e = \sum_{i=1}^{n} \left[ f_{ii} \cdot \sum_{k=1}^{n} f_{ik} \cdot d_{ik} \right]. \tag{6}
\]
The model, named here KOO-JANG model, calculates total empty travel as average travel distance per empty trip multiplied by number of empty trips (which is equal to the number of full trips), as

\[ D_e = \sum_{i=1}^{n} f_i \sum_{j=1}^{n} \left( f_j d_{kj} \right) \sum_{j=1}^{n} f_j \quad (9) \]

Analysis of the models presented in mentioned papers, as well as plenty other papers dealing with AGV system design (for more info about AGV systems’ design and control issues see review papers [5] or [6]), revealed that the performance of internal transport systems using AGVs depends on several factors such as number of trips between locations and distances (guide-path layout), but also vehicle scheduling and routing system. Exact information about load arrivals is usually only known a little moment in advance, therefore scheduling vehicles in these systems in advance is nearly impossible. The best solution is to use on-line dispatching rules [7]. It was proven that dispatching rules have unneglectable influence on AGV system’s performances, so dispatching rules are a key factor in determining the amount of empty vehicle travel [8]. Vehicle dispatching decisions are concerned with assigning vehicles and delivery requests to each other in real time based on the state of the system [9]. Some examples are rules such as random vehicle selection, longest idle vehicle selection, least utilized vehicle selection, nearest vehicle selection (as workplace initiated task assignment rules), or random workcenter, shortest travel time, maximum outgoing queue size, minimum remaining outgoing queue space, etc. (as vehicle initiated task assignment rules). However, in non-automated discrete material handling systems without computer control most dispatching rules are not possible to employ (or at least they are impractical to empower). In some applications of AGV systems there are only a few vehicles and jobs involved, with the simple scheduling algorithms. Jobs are usually handled in a First-come-First-serve (FCFS) fashion, and the nearest idle vehicle is usually chosen to serve a new job. The mission of routing is to find a suitable route (e.g. shortest-distance path, shortest-time path or minimal energy path) for every AGV from its origin to destination based on the current traffic situation. The route must be congestion-, conflict- and deadlock-free [10]. Here again, in non-automated discrete material handling systems with one or few human driving vehicles routes are chosen by driver and it could be assumed that there are no conflicts, congestions, while routes are simple to find optimal.

So in this paper above mentioned analytical models are applied to a classical production system where the vehicle is free to move in all directions between workplaces (along paths), and tasks are assigned to a free vehicles (random selection) according to the FCFS strategy.

3. SIMULATION ANALYSIS

For simulation analysis one simple production process was selected, consisting of 4 products processed in a production system with 8 discrete locations in a layout – inbound storage US (raw material storage), 6 workplaces RM 1 – RM 6 (machines/workcenters) and outbound storage IS (finished goods storage). Simulation model was built in Enterprise Dynamics 10 simulation software. Figure 1 presents the 2D model layout representing layout of the production system, which was also used to calculate distance matrix needed for analytical models. Technological processes of products (sequences of visiting workplaces) are given in Table 1, used also to define from-to matrix (number of trips between locations).

<table>
<thead>
<tr>
<th>Product</th>
<th>Sequence of operations</th>
</tr>
</thead>
</table>

Additional data, like processing time per unit load, were selected for the purpose of simulation in a way not influencing vehicle’s travel. The average velocity of vehicles was set to 3 m/s (acceleration and deceleration neglected), while loading and unloading time per unit load was 5 seconds. Simulation runs were set to 50 hrs (assuming no shift breaks).
The simulation analysis was done with 4 different experiments [11]. In first experiment production volume (number of products processed in a given time - throughput) was varied, in one selected layout. The idea was to analyse possible influence of intensity of work (vehicle’s utilisation) on empty travel and estimation error (difference between analytical result and simulation result). In second experiment three additional layout setups were made (changing locations of machines) for a selected throughput. The idea here was to analyse possible influence of layout design (variation of full travel for same production volume) on empty travel and estimation error. Third and fourth experiments were same as first two, however with additional vehicle.

3.1 Experiment 1 – influence of production volume

In experiment 1 production volume was varied in 5 different scenarios (M1-M5), leading to the utilisation of the vehicle from 34% till 93%. Table 2 presents results obtained with simulation and 5 analytical estimation models. As could be seen, 3 models (that are assuming FCFS dispatching rule) estimates empty travel quite well, while MAXWELL-MUCKSTADT and BEISTEINER 2 models heavily underestimates empty travel. EGBELU and KOO-JUNG models were most accurate, however most simple BEISTEINER 1 model is not much worse. The greater influence of traffic intensity (vehicle’s utilisation) is noticed for low utilisation, were models tend to have slightly higher difference between analytical result and simulation result (overestimation), however no correlation was found. This is visualized in Figure 2.

![Figure 2. Comparison of empty travel time](image)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Nr of products</th>
<th>Sim. $t_e$, s</th>
<th>Beinsteiner 1 $t_e$, s</th>
<th>Dev., %</th>
<th>Beinsteiner 2 $t_e$, s</th>
<th>Dev., %</th>
<th>Egbelu/Koo-Jang $t_e$, s</th>
<th>Dev., %</th>
<th>Maxwell-Muckstadt $t_e$, s</th>
<th>Dev., %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>381</td>
<td>18666</td>
<td>20365</td>
<td>9,10%</td>
<td>3484</td>
<td>-81,34%</td>
<td>19602</td>
<td>5,01%</td>
<td>7366</td>
<td>-60,54%</td>
</tr>
<tr>
<td>M2</td>
<td>549</td>
<td>29016</td>
<td>30012</td>
<td>3,43%</td>
<td>5078</td>
<td>-82,50%</td>
<td>28556</td>
<td>-15,99%</td>
<td>10614</td>
<td>-63,42%</td>
</tr>
<tr>
<td>M3</td>
<td>716</td>
<td>38304</td>
<td>38965</td>
<td>1,73%</td>
<td>6267</td>
<td>-83,64%</td>
<td>37052</td>
<td>-3,27%</td>
<td>13843</td>
<td>-63,86%</td>
</tr>
<tr>
<td>M4</td>
<td>884</td>
<td>46992</td>
<td>48229</td>
<td>3,29%</td>
<td>8212</td>
<td>-82,41%</td>
<td>45698</td>
<td>-2,13%</td>
<td>17091</td>
<td>-63,40%</td>
</tr>
<tr>
<td>M5</td>
<td>994</td>
<td>53334</td>
<td>54987</td>
<td>3,10%</td>
<td>9168</td>
<td>-82,81%</td>
<td>52444</td>
<td>-1,67%</td>
<td>19217</td>
<td>-63,97%</td>
</tr>
</tbody>
</table>

Table 2. Empty travel time ($t_e$) and deviations of analytical models from experiment 1

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Simulation FTT, %</th>
<th>Sim. $t_e$, s</th>
<th>Beinsteiner 1 $t_e$, s</th>
<th>Dev., %</th>
<th>Beinsteiner 2 $t_e$, s</th>
<th>Dev., %</th>
<th>Egbelu/Koo-Jang $t_e$, s</th>
<th>Dev., %</th>
<th>Maxwell-Muckstadt $t_e$, s</th>
<th>Dev., %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 - L3</td>
<td>10,89</td>
<td>18882</td>
<td>19594</td>
<td>3,77</td>
<td>3352</td>
<td>-82,25%</td>
<td>19600</td>
<td>3,80</td>
<td>7366</td>
<td>-60,99</td>
</tr>
<tr>
<td>M1 - L1</td>
<td>11,33</td>
<td>18666</td>
<td>20365</td>
<td>9,10</td>
<td>3484</td>
<td>-81,34%</td>
<td>19602</td>
<td>5,01</td>
<td>7366</td>
<td>-60,54%</td>
</tr>
<tr>
<td>M1 - L4</td>
<td>13,14</td>
<td>18900</td>
<td>23588</td>
<td>24,80</td>
<td>4035</td>
<td>-78,65%</td>
<td>20209</td>
<td>6,93</td>
<td>7366</td>
<td>-61,03</td>
</tr>
<tr>
<td>M1 - L2</td>
<td>13,85</td>
<td>19278</td>
<td>24921</td>
<td>29,27</td>
<td>4326</td>
<td>-77,89%</td>
<td>20333</td>
<td>5,47</td>
<td>7366</td>
<td>-61,79</td>
</tr>
<tr>
<td>M5 - L3</td>
<td>29,18</td>
<td>53766</td>
<td>52335</td>
<td>-2,66%</td>
<td>8725</td>
<td>-83,77%</td>
<td>52444</td>
<td>-2,46%</td>
<td>19217</td>
<td>-64,26%</td>
</tr>
<tr>
<td>M5 - L1</td>
<td>30,66</td>
<td>53334</td>
<td>54987</td>
<td>3,10%</td>
<td>9168</td>
<td>-82,81%</td>
<td>52444</td>
<td>-1,67%</td>
<td>19217</td>
<td>-63,97%</td>
</tr>
<tr>
<td>M5 - L4</td>
<td>35,78</td>
<td>51426</td>
<td>64245</td>
<td>24,93%</td>
<td>10711</td>
<td>-79,17%</td>
<td>53855</td>
<td>4,72%</td>
<td>19217</td>
<td>-62,63%</td>
</tr>
<tr>
<td>M5 - L5</td>
<td>36,92</td>
<td>53244</td>
<td>66087</td>
<td>24,12%</td>
<td>11016</td>
<td>-79,31%</td>
<td>53825</td>
<td>1,09%</td>
<td>19121</td>
<td>-64,09%</td>
</tr>
</tbody>
</table>

Table 3. Empty travel time ($t_e$) and deviations of analytical models from experiment 2
Table 5. Empty travel time ($t_e$) and deviations of analytical models from experiment 4

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Simulation</th>
<th>Beinstein 1</th>
<th>Beinstein 2</th>
<th>Egbelu/Koo-jang</th>
<th>Maxwell-Muckstadt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FTT, s</td>
<td>$t_e$, s</td>
<td>Dev., %</td>
<td>$t_e$, s</td>
<td>Dev., %</td>
</tr>
<tr>
<td>M1 - L3</td>
<td>10.89</td>
<td>17910</td>
<td>9.40%</td>
<td>19594</td>
<td>3352</td>
</tr>
<tr>
<td>M1 - L1</td>
<td>11.31</td>
<td>18018</td>
<td>13.03%</td>
<td>20365</td>
<td>3484</td>
</tr>
<tr>
<td>M1 - L4</td>
<td>13.11</td>
<td>18306</td>
<td>28.85%</td>
<td>23588</td>
<td>4035</td>
</tr>
<tr>
<td>M1 - L2</td>
<td>13.87</td>
<td>18090</td>
<td>37.76%</td>
<td>24921</td>
<td>4263</td>
</tr>
<tr>
<td>M10 - L3</td>
<td>58.35</td>
<td>104616</td>
<td>0.12%</td>
<td>104746</td>
<td>17459</td>
</tr>
<tr>
<td>M10 - L1</td>
<td>61.32</td>
<td>109692</td>
<td>0.30%</td>
<td>110025</td>
<td>18342</td>
</tr>
<tr>
<td>M10 - L4</td>
<td>71.63</td>
<td>108378</td>
<td>18.54%</td>
<td>128476</td>
<td>21414</td>
</tr>
<tr>
<td>M10 - L2</td>
<td>73.95</td>
<td>105930</td>
<td>25.18%</td>
<td>132604</td>
<td>22104</td>
</tr>
</tbody>
</table>

3.2 Experiment 2 – influence of layout design

In experiment 2 three new layouts were made, each defining different distance matrix. Simulation and analytical estimation of empty travel, presented in Table 3 (different layouts are marked L1-L4), were obtained for two selected production volumes, one with lowest vehicle’s utilisation (M1) and one with highest vehicle’s utilisation (M5). Again, as expected, same 3 models as in previous experiment proved useful. However some findings were interesting. According to the simulation results in un-optimized layouts (L2 and L4), increased full travel (in table shown as full travel time, FTT, in percentage of total time) is not followed by the same amount of increased empty travel. So analytical models, where calculation of empty travel is based on full travel, tend to estimate higher amounts of empty travel. However differences are still within several percent, expect BEINSTEINER 1 model where differences (as overestimating empty travel) are up to 30%. So EGBELU and KOO-JANG models are better in “realizing” less empty travel in such layouts than simply estimating it equal as full travel.

3.3 Experiments 3 and 4 – 2 vehicles

Experiments 3 and 4 were extensions of previous two, with added vehicle and corresponding increase of production volume. In experiment 3 production volume was varied in 10 different scenarios (added cases M6-M10). In experiment 4 same four layouts as before were used for two selected production volumes (again representing low and high vehicle’s utilisation). Due to the need of increased product volume for analysis of high utilisation of two vehicles, simulation model had to be slightly reworked by adding additional machines per locations. However this wasn’t affect distance matrices because workplaces were in this case workcentres (same location of pick-up and delivery for all machines in a workcenter). The results are presented in Table 4 and Table 5. The findings are as follows. Increase of production volume increases full travel and empty travel. However analytical models are estimating higher amounts of empty travel compared to the simulation results. The differences in models were also noticed. While BEINSTEINER 1 model always overestimates empty travel (up to 13% in case of extremely low utilisation), EGBELU and KOO-JANG models were more precise, slightly overestimating empty travel in cases of low utilisation while slightly underestimating empty travel in cases of high utilisation of vehicles. While some overestimation of empty travel time in cases of low vehicle’s utilisation has not a risk of potential underestimation of required number of vehicles, underestimation of empty travel time in cases of high utilisation might be a problem. Therefore in those cases designers should be aware of risk of underestimating the required number of vehicles.

Changes in layout confirmed findings from experiment 2. Increased full travel in un-optimized layouts is leading to estimation of higher amount of empty travel in analytical models. BEINSTEINER 1 model again tends to have significant deviations from the simulation results in cases with worst layouts.

4. CONCLUSION

Presented analysis of five analytical models for estimation of empty travel of discrete vehicles has showed that using estimation models without knowledge of assumptions (in this case dispatching rules and control of the system) could lead to heavily underestimated results if one decides to use BEINSTEINER 2 or MAXWELL-MUCKSTADT model. Other presented models quite well estimate empty travel, while EGBELU and KOO-JANG models being more accurate than BEINSTEINER 1 model. The errors (differences between analytical results and simulation results) of three analytical models are usually within several percent (except BEINSTEINER 1 model in some exceptional situations).

A certain influence of production volume and layout design on difference between analytical result and simulation result of estimated empty travel time has been noticed. Increasing full travel of vehicles, analytical models have tendency to estimate higher amounts of empty travel than it was obtained by simulation. However this should be taken with a caution, because only one layout with four variations was analysed in cases with only one and two vehicles.

Since total transport time which leads to the required number of vehicles is composed of full travel time, empty travel time, loading time and unloading time, small overestimations or underestimations of empty travel time are causing even smaller overestimation or underestimation of total transport time. So at least in early stages of internal transport system design estimation models could be used. Analytical methods to calculate (estimate) empty travel time, total travel time and required number of vehicles are fast and easy to use compared to the simulation modelling. But again, analytical models can’t take into
account different dispatching rules and possible blockings and congestions in case of larger fleets. So in this cases, and especially for final verification of chosen transport system, simulation is preferred despite being time consuming. In most of the cases it makes sense to use both methods to solve a problem in order to obtain reliable results [12], while testing on actual system, as a third method of logistics engineering, is here not advisable.

REFERENCES


NOMENCLATURE

- $n$: number of workplaces
- $f_i$: number of loaded trips (full travels) required from workcenter $i$ to workcenter $j$
- $d_{ij}$: distance between workplaces, in meters
- $D_e$: total empty travel distance, in meters
- $g_{ij}$: expected number of empty trips from workcenter $i$ to workcenter $j$
- $fd_k$: number of deliveries to workcenter $k$
- $fs_i$: number of pick-ups at workcenter $i$
- $d_e$: average empty vehicle travel distance per trip, in meters

СИМУЛАЦИОНА АНАЛИЗА МОДЕЛА ЗА ПРОЦЕНУ ПРАЗНОГ ВРЕМЕНОСКОГ ЦИКЛУСА У ВОЗИЛИМА КОД НЕАУТОМАТСКИХ СИСТЕМА ЗА РУКОВАЊЕ МАТЕРИЈАЛИМА

Г. Ђукић, Т. Опетук, Х. Цајнер, М. Јаковљевић

При дизајнирању или редизајнирању објекта као што је производни погон или складиште, интегрални део чини адекватан избор система за руковање материјалима. Упркос бројним альтернативама, укључујући автоматизоване системе за руковање материјалима или аутоматски вођени везилице, већина објеката за руковање материјалима данас користи возила којима управља човек (дискретни неаутоматски систем за руковање материјалима). Одговарајуће проектовање таквих система захтева одређивање потребног броја возила. Дефинисање празног временског циклуса у возилица засновано је на симулацији утрошка времена или приступу без симулације, само коришћењем процене. Главни циљ овог рада је да размотрим и анализира неке од предложених метода за процену празног временског циклуса код неаутоматских дискретних система за руковање материјалима. Резултати добијених методама процене се упоредују са резултатима симулације.