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Simulation-based performance evaluation of transport vehicles at automated container terminals

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Abstract. Significant unproductive and costly waiting occurs during AGV (Automated Guided Vehicle) use, both under the CC (Container Crane) and in the blocks compared to that of a manual yard tractor. A possible solution to this problem is that, in the design of ACT (Automated Container Terminals), ALV (Automated Lifting Vehicles), which can load and unload their own containers, be considered as an alternative. In this paper, the objective is to analyze how increases in the use of ALVs rather than AGVs affects the productivity of ACTs. We derived four inferences regarding the cycle time of vehicles and verified their validity in a simulation. A simulation model of an ACT with perpendicular layout was developed and is described in this paper. From the results of the simulation analysis, we determined the savings effect by cycle time and the required number of vehicles. We demonstrated that the ALV is superior to the AGV in both productivity and efficiency principally because the ALV eliminates the waiting time in the buffer zone.

Keywords: AGV (Automated Guided Vehicle) – ALV (Automated Lifting Vehicle) – ACT (Automated Container Terminal) – Simulation model – Productivity

1 Introduction

The age of automated container handling systems has commenced with them having been adopted in several ports and harbors in the world, such as the ECT (Europe Combined Terminal) in Rotterdam, Thamesport in London, the CTA (Container Terminal Altenwerder) in Hamburg, and the PPT (Pasir Panjang Terminal) in Singapore. Furthermore, management engaged in container operations all over the world has begun to take a keen interest in automated container handling systems.

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To solve problems such as the increase in operation time due to larger and wider vessels, high personnel expenses, lack of qualified manpower, and for the higher efficiency of land utilization, modern port facilities generally and ACT (Automated Container Terminals) specifically have become the foci of interest around the world. In some advanced countries, ideas promoting efficiency in response to the above maladies, have been practically implemented. ECT, the most modern ACT in the world, honed the concept of ACT 10 years ago; in 1997, they started operating the second generation ACT while currently they are testing technologies for the third generation ACT.

Van der Meer has studied the performance of several well-known on-line dispatching rules and some case-specific dispatching rules for container transshipments in terms of pre-arrival information [9]. Bish theoretically analyzed operation problems in container terminals such as the vehicle dispatching problem, the vehicle scheduling location problem, and the vehicle routing problem [2].

Evers and Koppers proposed the distributed traffic control technique for AGVs (Automated Guided Vehicles), which led to the development of the conceptual model [4]. Vis et al. discussed a method for determining the minimum number of AGVs needed for completing a given set of delivery tasks without causing a delay in semi-automated container terminals. To determine the minimum number of AGVs, they suggested a dispatching method that utilized the maximum flow problem technique [10]. Kim and Bae discussed a dispatching method for AGV to minimize delays during containership operations [7]. Lim et al. proposed a dispatching method for AGVs based on a bidding concept and discussed the theoretical rationale behind the distributed dispatching method. And the performance of the method is compared with that of a popular dispatching rule using simulation [8]. Grunow et al. discussed a priority rule based algorithm for the dispatching of multi-load vehicles in automated container terminals [5].

Most research has focused on equipment allocation and dispatching problems and its results set limits on the particular operational situation based upon port properties, and it is not sufficient to analyze the vehicle operations of a specific ACT equipped with newly sophisticated container handling equipment. Regarding vehicle dispatching in container terminals, in studies to minimize the delays of ship operations, the works of Bish, Van der Meer, and Vis et al. failed to explore the characteristics of loading/unloading operations or the strategies of equipment allocation.

The objective of this study is to determine the extent to which an increased number of ALVs (Automated Lifting Vehicles), compared with AGVs, improves the productivity of ACTs. To determine the number of transport vehicles needed to transport containers between seaside (berth apron) and landside (yard) in an ACT, we compare the required number of ALVs and AGVs at a given service level and their impact on cycle time. This study investigates both the seaside and landside operations and tries to synchronize the goal productivity of CCs (Container Cranes) and the delivery tasks of these transport vehicles.

Because a simulation analysis reflects the characteristics of a system more precisely than a mathematical analysis does, we analyze the effect of vehicle operations using a simulation. Therefore, we develop the simulation model taking into con-

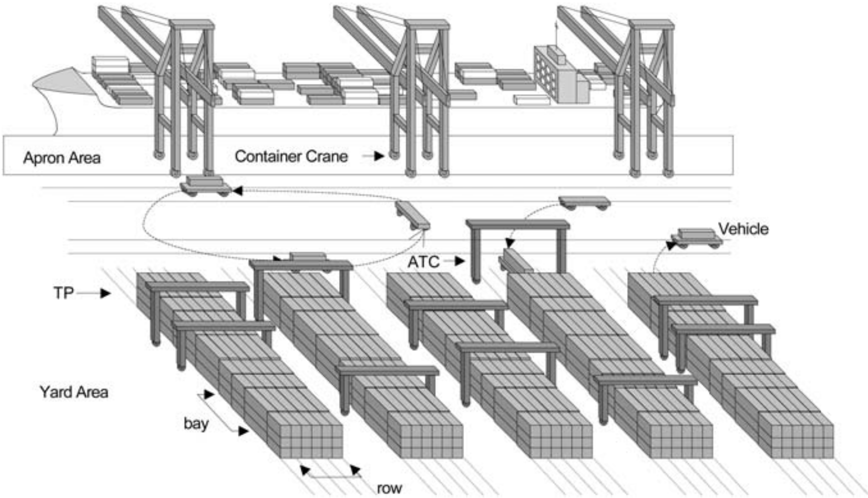

Fig. 1. Container operations in an automated container terminal

sideration the characteristics of an ACT. In this simulation model, we assume that the cycle time of transport vehicles consists of the moving time between apron and yard, the waiting time in buffer zones, both apron and yard, and the waiting time for loading and unloading by the CC and the ATC (Automated Transfer Crane). These time elements are used to define the state transition model and are utilized as performance measures.

2 Automated container terminal

The container handling operations in an ACT, generally, consist of seaside (or apron) and landside (or yard) operations, as shown in Figure 1.

Seaside operations are divided into three kinds of operations, that is to say, container handling with ships at the apron, container shifting between apron and yard and container handling in the yard. The first operation, container handling with ships at the apron, is performed by CCs, excepting roll on/roll off operations. AGVs are used for the shifting of containers between apron and yard. Container handling in the yard is performed by ATCs.

The work to shift containers between apron and yard has been automated by using AGVs. But, special devices, such as a chassis-loader system used at ECT, are required for the container handling duties of the AGV in cooperation with CCs at seaside.

The proposed operation system of the Kwangyang ACT in Korea is partially modified from the system adopted by ECT and CTA. In flow planning, the access of trucks to the yard has been minimized and the intersecting of trucks and AGVs has also been prohibited in the yard. AGVs are used for the transport of containers between apron and yard, and ATCs are used for any work done in the yard. By providing for rails that go inside the yard, the amount of transport equipment used for bringing in and out containers has been minimized [11].

A yard that is located next to a quay stores outbound containers while they are waiting for a ship or other inbound containers, until a vehicle arrives and transports them. Containers are stored in a yard formation, called a “block”. A stack is a group of containers on top of each other. A bay is a group of container side by side. A tier is a layer of containers.

The layouts of ACTs include blocks in a yard, the paths of AGVs, and the locations of pickup and drop-off points (P/D points). Terminal layouts can be categorized according to perpendicular and parallel layouts, depending on the direction of an ATC’s movement. Terminal layouts can vary in their characteristics and in their requirements of operation. In the case of a perpendicular layout, AGVs and outside trucks do not enter a storage area in a terminal due to their TPs (Transfer Points) located at the both ends of the blocks. Containers are placed end to end in long blocks. In the case of a discharging or a receiving operation, an ATC receives containers at the TPs, and then moves them to the designated storage position. In the case of a loading or a delivery operation, an ATC brings containers from storage, then transfers them to AGVs or outside trucks at the TPs. The flow of containers and the operation of equipment in a terminal are simple, but ATCs are expensive to purchase and maintain [1].

In this study, it is assumed that the container terminal is automated, in which the yard crane is an ATC such as an automated stacking crane, as exists at the ECT, and the prime mover is an AGV or an ALV. The terminal layout used in the simulation is a perpendicular layout such as the ECT and CTA.

3 Transport equipment model

3.1 Vehicle model

A vehicle as transport equipment is a component that can transport containers from the loading point (apron/yard) to their destination (yard/apron). Every vehicle possesses data relating to its speed and states such as the loaded state and the empty state, its pickup and delivery points of origin and destination, and its load. In some cases, vehicle speed may be considered a decision variable in the design of the transport equipment, and the vehicle speed is specified by the user of the simulation model. A vehicle has a process description in which the trip between two types of cranes and its activations are defined. In this study, we consider two types of vehicles: AGV and ALV. We assume that the AGV must wait for lifting to be performed by the crane, but the ALV can load and unload its own containers.

The ALV system combines the best of both worlds, and which aims to enable the full potential of CC productivity to be exploited. The ALV system is essentially a small transporter SC (Shuttle Carrier), an integral part of port operation, which has been in existence since the 1950’s, but now updated with modern technology and performance to find its place in high throughput container terminals and to more efficiently bridge the gap between CCs and ATCs [3].

ALVs are used for transporting containers between apron and yard and for loading and unloading trucks. In this case, an ATC is used only for stacking. Therefore, the ALV improves the productivity of CCs and the utilization of the buffer zone under a CC. It also improves the productivity of the ATC, and TPs under the ATC are used as buffer zones both at the seaside and at the landside of the yard [6].

The ALV is a vehicle that can both load and unload containers and travels from the loading point to its destination under its own power. In this study, the control activates an idle ALV. The ALV loads a container at its origin, then it travels to the destination of the container, unloads the container and is idle again. In this case the idle ALV is sent to a destination unloaded.

The ALV has an independent work cycle from that of the CC and does not need to wait for a transport vehicle. This factor can reduce both the cycle time and the number of transport vehicles. The loading and unloading of a ship's containers operate under a CC portal within a buffer zone, but when using an AGV it operates under a backreach with no buffer. Therefore, it can reduce the work cycle of the CC. Through these improvements with the ALV, ship turnaround time can be reduced.

3.2 State transition model

An AGV is a vehicle that is loaded and unloaded by both a CC and an ATC, but a vehicle that can also travel from the loading point to its destination under its own power. In this study, the control assigns an idle AGV to respond to the needs of the loading/unloading equipment such as the CC or the ATC, which load the AGV. Then the crane activates the AGV, which moves to the destination with a user-determined speed. At the destination, the AGV activates the crane and waits until unloading is completed. Then the AGV is empty again and the empty AGV is sent to a destination unloaded.

The AGV model utilizes state transition, a system consisting of six states, which is shown in Figure 2; it also contains two conditions in order to check the availability of the buffer zone. At the end of the AGV's task, the state of AGV transitions from a moving state to an idle state. The time interval between the start time and the end time of a relevant event is defined as the transition time of a state.

The ALV model also utilizes state transition, as shown in Figure 3. It includes eight conditions: the upper four conditions represent situations of the yard and the lower four conditions represent situations of the apron. From those conditions, we know that the ALV model is different from the AGV model. In addition, the ALV model divides the waiting time of the operation into loading and unloading periods.

From Figure 2 and Figure 3, Table 1 summarizes the state-transition systems of the AGV and the ALV mentioned above, and shows the relationship between these and the elements of cycle time proposed in this study.

In the case of the AGV model, the basic element is moving time ($\overline{G_3}+\overline{G_6}$) without considering crashing, the fixed element is waiting time for loading/unloading ($\overline{G_2}+\overline{G_5}$), and the reducible element is waiting time in the buffer zone ($\overline{G_1}+\overline{G_4}$). In case of the ALV model, similarly, the basic element is moving time ($\overline{L_3}+\overline{L_6}$) without considering crashing, the fixed element is loading/unloading time ($\overline{L_2}+\overline{L_5}$),

Table 1. Organization of state transition for transport vehicles

AGV		ALV	
$\overline{G_1}$	Mean waiting time in buffer of apron	$\overline{L_1}$	Mean waiting time in buffer of apron
$\overline{G_2}$	Mean waiting time for loading/unloading by CC	$\overline{L_2}$	Mean loading/unloading time by CC or itself
$\overline{G_3}$	Mean moving time from apron to yard	$\overline{L_3}$	Mean moving time from apron to yard
$\overline{G_4}$	Mean waiting time in buffer of yard	$\overline{L_4}$	Mean waiting time in buffer of yard
$\overline{G_5}$	Mean waiting time for loading/unloading by ATC	$\overline{L_5}$	Mean loading/unloading time by ATC or itself
$\overline{G_6}$	Mean moving time from yard to apron	$\overline{L_6}$	Mean moving time from yard to apron
CT_G(Cycle Time) = $\sum_{i=1}^{6} \overline{G_i} / N_G$		CT_L(Cycle Time) = $\sum_{j=1}^{6} \overline{L_j} / N_L$	
N_G : Average number of transported containers per AGV		N_L : Average number of transported containers per ALV	
$\overline{G_1} + \overline{G_4} =$ Mean waiting time in buffer zone		$\overline{L_1} + \overline{L_4} =$ Mean waiting time in buffer zone	
$\overline{G_2} + \overline{G_5} =$ Mean waiting time for loading/unloading		$\overline{L_2} + \overline{L_5} =$ Mean loading/unloading time	
$\overline{G_3} + \overline{G_6} =$ Mean moving time between apron and yard		$\overline{L_3} + \overline{L_6} =$ Mean moving time between apron and yard	

Table 2. Patterns of traffic lane selection

Task / Traffic area			Traveling lane from apron to yard			Block	Traveling lane from yard to apron		
No	Origin	Destination	Apron	Change	Yard	TP	Yard	Change	Apron
1	CC1	A block	A1	C1→C1	Y1	assigned TP	Y1	C1→C1	A1
2	CC2	C block	A2	C2→C3	Y3	assigned TP	Y1	C1→C2	A2
3	CC3	E block	A3	C3→C5	Y5	assigned TP	Y1	C1→C3	A3

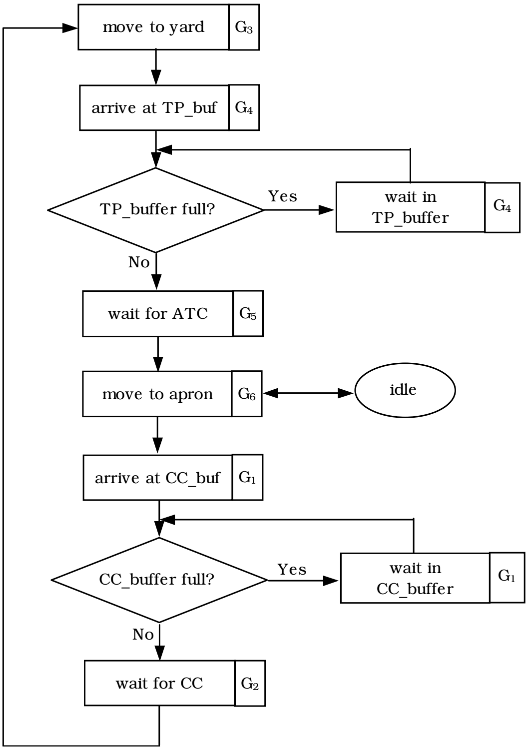

Fig. 2. AGV model by state transition

and the reducible element is waiting time in the buffer zone $(\overline{L_1} + \overline{L_4})$. The loading/unloading time of the ALV is selected according to a small value between the CC work time and the ALV work time. The sum of the cycle time of the AGV, $\sum_{i=1}^{6} \overline{G_i}$ means that the sum of the state transition times (i.e. $\overline{G_i}$) is equal to the completion time of all the tasks, while the sum of the cycle of the ALV, $\sum_{j=1}^{6} \overline{L_j}$ includes the six state- transition times.

We expect that the cycle time of the AGV is longer than that of the ALV and that the waiting time of the ALV is shorter than that of the AGV under the same conditions because the buffer zone of the ALV is more flexible. We assume that the speed of the transport vehicle is identical in both cases; however, it may be different due to the performance of the CC and the ATC.

Therefore, we derive the following four inferences.

1) $\overline{G_1} + \overline{G_4} \quad \leq \quad \overline{L_1} + \overline{L_4}$

   The ALV can lift a container by itself without the help of cranes, and the loading/unloading time is reduced and the length of waiting time in the buffer is also reduced. Therefore, the ALV arrives early at the next buffer where it may encounter more downtime, waiting in the buffer.

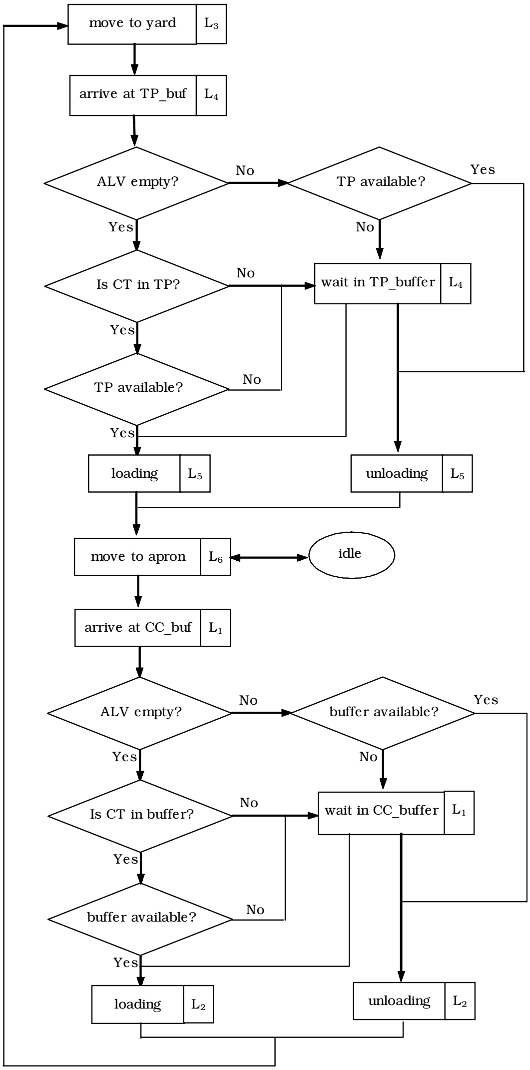

Fig. 3. ALV model by state transition

2) $\overline{G_2} + \overline{G_5} \geq \overline{L_2} + \overline{L_5}$
In most cases, the loading and unloading of containers is performed by the CC and the ATC. However since the ALV performs the loading/unloading of containers by itself, this time is reduced.

3) $\overline{G_3} + \overline{G_6} = \overline{L_3} + \overline{L_6}$
If vehicles are assigned the same task, the travel distance is equal, both for the AGV and the ALV. Therefore, an equality of moving time is realized.

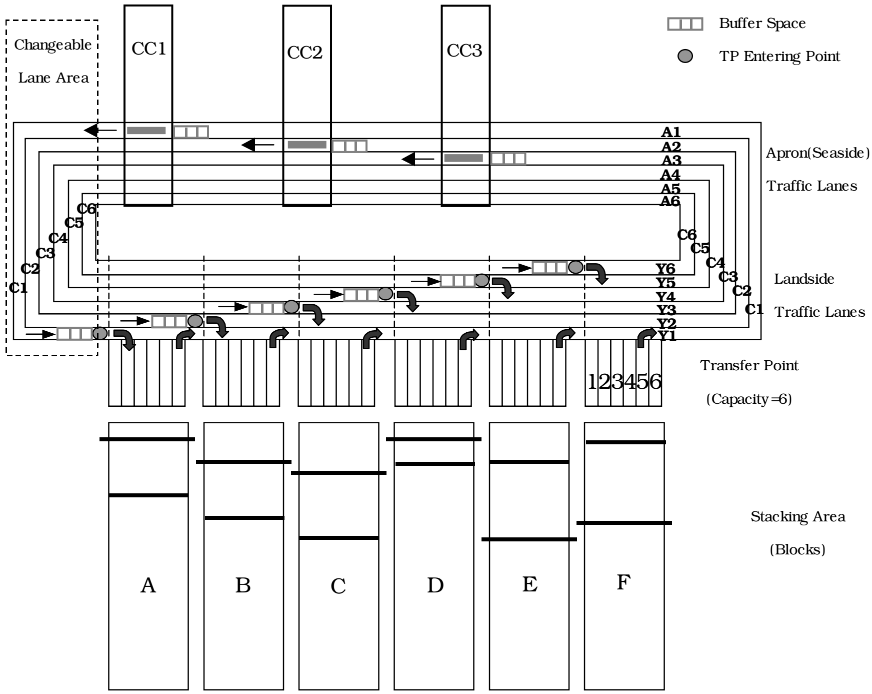

Fig. 4. Traffic patterns of transport vehicles

4) $\sum_{i=1}^{6} \overline{G_i} \geq \sum_{j=1}^{6} \overline{L_j}$

It is possible to reduce the waiting time and the loading/unloading time of the AGV. After all, the cycle time of the ALV is smaller than that of the AGV. If $\sum_{i=1}^{6} \overline{G_i}$ dose not equal $\sum_{j=1}^{6} \overline{L_j}$, then the difference, $\sum_{i=1}^{6} \overline{G_i} - \sum_{j=1}^{6} \overline{L_j}$, represents a savings effect that reduces the number of ALVs.

The above four inferences show the effectiveness of analysis through simulation results.

3.3 Vehicle traffic model

For the setup of traffic control systems, two concepts have to be taken into consideration: central traffic control and distributed traffic control. Although there are many forms and combinations of control in use today, the most popular form of zone control is that in which the zones are individually controlled for movements within the zones and centrally controlled to interface with other zones in the system. The general rule is that only one vehicle can occupy a zone [12]. In this paper, a setup is described in which several vehicles may access an intersection area at the same time so the priority in the area has to be that no vehicles collide within the area. A basic entity is a zone (in the form of an intersection of lanes), which is controlled via mutual exclusion. This implies that at any time only one vehicle is allowed to pass through the zone, even when the layout of a terminal may show zones with several adjacent lanes which could guarantee a high usage of the predetermined capacity.

According to the above definition, we use the state transition model for vehicle traffic control and apply the waiting and moving rules or criteria to activate waiting vehicles. It is possible to define a number of activation criteria, like sequencing rules or priority rules.

As depicted in Figure 4, we designed the two types of traffic lanes as the exclusive lane and the changeable lane in the terminal layout. In the apron area, vehicle traffic lanes are fixed for each CC. In the landside area, vehicle traffic lanes are fixed in terms of each block. In the case of traveling from CC (block) to block (CC), vehicles are able to change traffic lanes within the changeable lane area. In the landside traffic lanes, vehicles traveling straight are given precedence over those making right-hand turns when vehicles access the intersection point at the same time.

To illustrate the performance of the task of transporting a container, the patterns for the selection of traffic lanes are given in Table 2. A task consists of the origin and the destination. To travel to the destination, vehicles have to select both a traveling lane from the apron and to the yard and one from the yard to the apron for the given task. To change the lane, it is possible to use the changeable lanes. In the landside area, the waiting area consists of a buffer space from which to enter the transfer point, and the transfer point has a capacity of 6. In front of the transfer point, vehicles enter in an assigned order. Therefore, Task No. 3 of Table 3 performs the sequence of A3-C3-C5-Y5- assigned TP-Y1-C1-C3-A3 in one cycle.

4 Simulation and analysis

4.1 Simulation model

The simulation model was developed using Visual BASIC, a general-purpose language. Figure 5 shows the configuration of our simulation model as displayed by user input.

Figure 5 describes the behavior of the ACT in the simulation model. Before the simulation run, the user can input parameters and information through the user interface to construct an experimental simulation model. During the simulation, the model can interface with the state transition model and the vehicle traffic model, and displays a 2D animation.

We used a reduced-size model, which represents a part of the ACT, to show an example of model building by simulation, because the real container terminal requires a massive amount of data for terminal operation and planning. However, this model considers the values of the various parameters of facility operations and some measures are used to evaluate the effectiveness of the transport vehicle model.

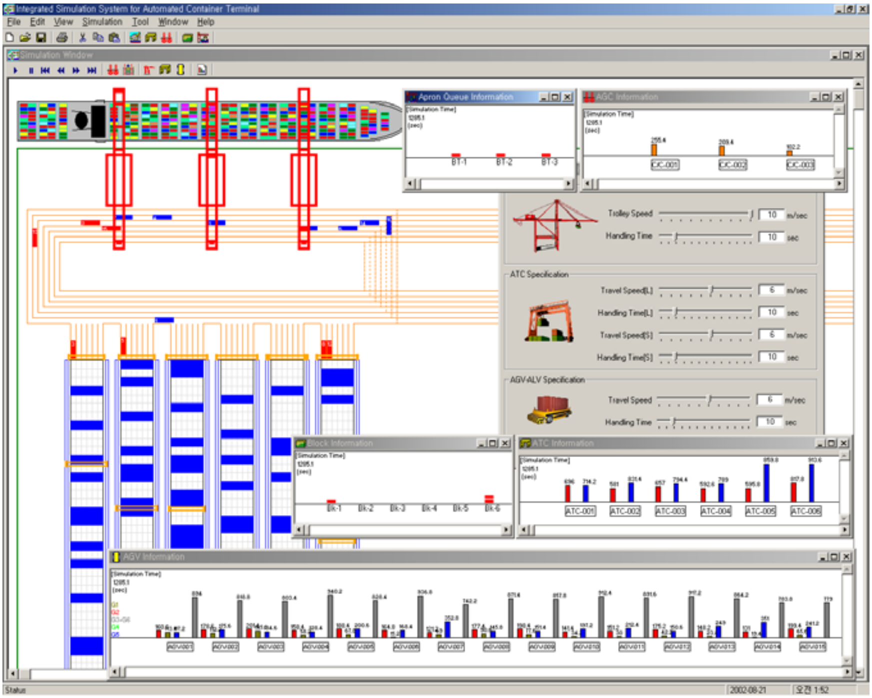

Fig. 5. User interface of the developed simulation model

4.2 Experiment design

The scope of our experiment's model is as follows. The container yard has 6 blocks and 2 ATCs per block. A block includes 40 bays, each bay consisting of 10 rows by 5 tiers. The berth has a quay and 3 CCs.

Table 3 shows the equipment characteristics. The operation of cranes such as the CC and the ATC involves trolley speed and loading/unloading time. Similarly, the ALVs have travel speed and loading/unloading time as characteristics, but the AGVs have only travel speed. The loading/unloading time of the ALVs is shorter than that of cranes. The number of cranes is fixed at 3 CCs and 12 ATCs. The number of vehicles is a decision variable determining the level of more efficient performance.

We start the simulation exercise by generating the ship arrivals at the berth. Upon berthing, equipment (CC, ATC, and AGV or ALV) is assigned to the ships according to the experiment conditions, and the discharging operations start at time 0. Loading operations follow the discharging operations. When all the container operations (discharging and loading) are finished, we terminate the simulation run. In our model, we complete all the discharging operations before starting the loading operations. In reality, however, the discharging and loading operations may be alternated to suit the stowage plan. It should be realized that the total time for container operations is mostly determined by the number of import and export

Table 3. Characteristics of equipment

Item	Number or equipment	Characteristics
CC	3	Trolley speed = 3m/second, Loading/unloading time = 30 second
ATC	12	Travel speed = 2m/second, Loading/unloading time = 30 second
AGV	N	Travel speed = 3m/second
ALV	N	Travel speed = 3m/second, Loading/unloading time = 20 second

containers to be handled, and not so much by the sequencing of handling the import and export containers. Therefore, the main assumption in a model (i.e., starting the loading operations only after completing all the unloading operations) will not significantly affect the model outputs in terms of performance measures.

For the simulation experiment, we used a terminating simulation that runs for the duration of time T_E, where E is a specified event which stops the simulation. The stopping time T_E is generally unpredictable in advance, and, in fact, T_E is probably the response variable of interest, as it represents the completion time of the task. One of the decision variables in our simulation is the estimated $E(T_E)$, the mean time to task completion. The task is to handle 300 lifts per CC, 900 lifts in total including the number of import and export containers.

The two alternative models have the same equipment and the same operation flows except for the transport vehicle. Therefore, the operation strategies used the same parameters as input.

4.3 Experiment results

Since one of the important factors that affect the turn-around time of ships is the productivity of the CCs at the apron, we use productivity of the CCs as an evaluation measure and determine the vehicle speed through a preliminary test.

Until the simulation terminates, we use a given travel speed for vehicles. The results produced by simulation, Table 4 and Table 5, are provided. The productivity limit of the CCs is 27.60 lifts/hr as shown in Table 4 and Table 5. We consider that 27.60 lifts/hr is the productivity limit of a CC.

In Table 4 and Table 5, the gray areas show that the feasible solutions are satisfied by the goal productivity of the CCs. In the case of 1m/second travel speed, a high productivity of a CC working with an AGV is infeasible. The savings effect of the vehicles does not effect the efficiency at the speed of over 4m/second. In most cases, when the travel speeds of the two vehicles are the same, fewer ALVs than AGVs are required.

With constraints on the productivity of the CCs, the speed of the vehicle is a necessary determinant in order to maximize the difference of the number of assigned vehicles and to minimize the number of allocated vehicles. Due to the fact that both

Table 4. CC productivity by AGV travel speed

Number of AGVs	AGV travel speed						
	1m/second	2m/second	3m/second	4m/second	5m/second	6m/second	7m/second
3	5.24	9.59	13.16	16.14	18.61	21.07	22.40
6	10.47	18.92	25.59	27.21	27.23	27.38	27.48
9	15.65	26.68	27.57	27.60[a]	27.60[a]	27.60[a]	27.60[a]
12	20.59	27.59	27.60[a]	27.60	27.60	27.60	27.60
15	25.18	27.60[a]	27.60	27.60	27.60	27.60	27.60
18	27.55	27.60	27.60	27.60	27.60	27.60	27.60
21	27.57	27.60	27.60	27.60	27.60	27.60	27.60

[a] The minimum number of vehicles among feasible solutions

Table 5. CC productivity by ALV travel speed

Number of ALVs	ALV travel speed						
	1m/second	2m/second	3m/second	4m/second	5m/second	6m/second	7m/second
3	5.39	10.12	14.26	17.87	21.03	24.20	26.52
6	10.77	20.20	27.60[a]	27.60[a]	27.60[a]	27.60[a]	27.60[a]
9	16.12	27.60[a]	27.60	27.60	27.60	27.60	27.60
12	21.46	27.60	27.60	27.60	27.60	27.60	27.60
15	26.77	27.60	27.60	27.60	27.60	27.60	27.60
18	27.60[a]	27.60	27.60	27.60	27.60	27.60	27.60
21	27.60	27.60	27.60	27.60	27.60	27.60	27.60

[a] The minimum number of vehicles among feasible solutions.

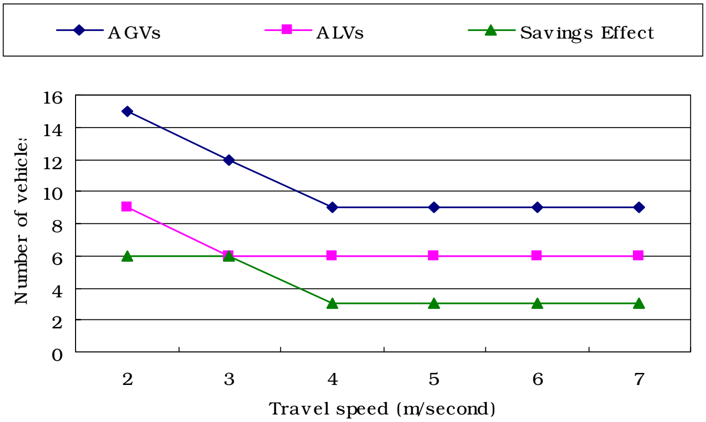

Fig. 6. The required number of vehicles for a given CC productivity

the 2m/second and 3m/second speeds are suitable for the purpose of determining the difference between the two types of transport vehicles, both speeds are possible, as shown in Figure 6. Here we select the 3m/second travel speed to show the savings effect of the vehicles due to the higher-percent decrease in the number of required vehicles (i.e., 2m/second: 15→9 (40%), 3m/second: 12→6 (50%)).

From the results, we determine the number of vehicles with the completion time constraint. We also consider the goal productivity of the CC for 27.60 lifts/hr at a 3m/second travel speed. Consequently, Table 6 shows that 6 ALVs (2 ALVs per CC) and 12 AGVs (4 AGVs per CC) satisfy constraints including the completion time, the goal productivity of the CCs, and the travel speed of vehicles, at the same time.

4.4 Results implementation

Cause analysis of cycle time The completion time, $\sum_{i=1}^{6} \overline{G_i}$ (or $\sum_{j=1}^{6} \overline{L_j}$), consists of 6 $\overline{G_i}$(or $\overline{L_i}$) and the cycle time of a vehicle, $\sum_{i=1}^{6} \overline{G_i}/N_G$ (or $\sum_{j=1}^{6} \overline{L_j}/N_L$), consists of each $\overline{G_i}/N_G$ (or $\overline{L_i}/N_L$). Using the cycle time, it is not easy to analyze the effect of the differences. So, we analyze it using $\sum_{i=1}^{6} \overline{G_i}$ and $\sum_{j=1}^{6} \overline{L_j}$(=T$_E$), but they include all the elements of the cycle time.

The simulation results of the AGV and the ALV cases are presented in Tables 7 and 8, respectively. In Tables 7 and 8, positive values of $\overline{G_1}$ and $\overline{L_1}$ are possible due to the buffer size of the apron being 1, but $\overline{G_4}$ and $\overline{L_4}$ are 0 because the buffer size in a block is sufficient at six. We expect a savings effect by the reduction of the waiting time. In fact, as must happen, $\overline{G_4}$ and $\overline{L_4}$ are 0 due to sufficient buffer size, and $\overline{G_3} + \overline{G_6}$ is equal to $\overline{L_3} + \overline{L_6}$.

Table 6. Comparison of CC productivity between AGVs and ALVs

Number of vehicles	AGV (3m/second)			ALV (3m/second)		
	Completion time (sec.)	CC Waiting time (sec.)	CC productivity (lifts/hr)	Completion time (sec.)	CC waiting time (sec.)	CC productivity (lifts/hr)
3	82,060.00	42,752.00	13.16	75,760.00	36,281.33	14.26
6	42,204.00	3,501.67	25.59	39,130.00	178.33	27.60[a]
9	39,168.00	135.33	27.57	39,130.00	0.00	27.60
12	39,130.00	9.00	27.60[a]	39,130.00	0.00	27.60
15	39,130.00	9.00	27.60	39,130.00	0.00	27.60
18	39,130.00	8.67	27.60	39,130.00	0.00	27.60
21	39,130.00	8.67	27.60	39,130.00	0.00	27.60

[a] The minimum number of vehicles among feasible solutions.

Table 7. Cycle time of AGVs

Number of vehicles	AGV (3m/second)					
	$\overline{G_1}$	$\overline{G_2}$	$\overline{G_3}+\overline{G_6}$	$\overline{G_4}$	$\overline{G_5}$	$\sum_{i=1}^{6}\overline{G_i}$ (=T_E)
3	0.00	8,986.00	63,200.33	0.00	9,873.67	82,060.00
6	40.50	5,338.00	31,149.83	0.00	5,675.67	42,204.00
9	1,684.33	12,308.22	21,012.33	0.00	4,163.11	39,167.99
12[a]	10,458.33	9,757.33	15,816.17	0.00	3,098.17	39,130.00
15	16,165.93	7,809.07	12,676.40	0.00	2,478.60	39,130.00
18	19,978.50	6,507.78	10,577.61	0.00	2,066.11	39,130.00
21	22,699.19	5,578.10	9,083.14	0.00	1,769.57	39,130.00

[a] The minimum number of vehicles among feasible solutions.

Table 8. Cycle time of ALVs

Number of vehicles	ALV (3m/second)					
	$\overline{L_1}$	$\overline{L_2}$	$\overline{L_3}+\overline{L_6}$	$\overline{L_4}$	$\overline{L_5}$	$\sum_{j=1}^{6}\overline{L_j}$ (=T_E)
3	0.00	6,218.00	63,348.67	0.00	6,193.33	75,760.00
6[a]	8.50	4,703.33	31,360.50	0.00	3,057.67	39,130.00
9	2,998.44	13,012.89	21,068.00	0.00	2,050.67	39,130.00
12	12,008.59	9,761.33	15,822.08	0.00	1,538.00	39,130.00
15	17,409.46	7,809.07	12,681.07	0.00	1,230.40	39,130.00
18	21,015.33	6,507.78	10,581.56	0.00	1,025.33	39,130.00
21	23,586.66	5,578.10	9,086.38	0.00	878.86	39,130.00

[a] The minimum number of vehicles among feasible solutions.

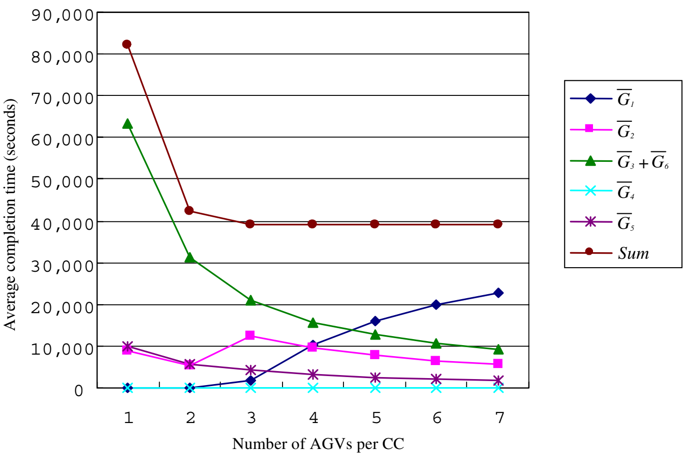

Fig. 7. The elements of the cycle time of AGVs at 3m/second speed

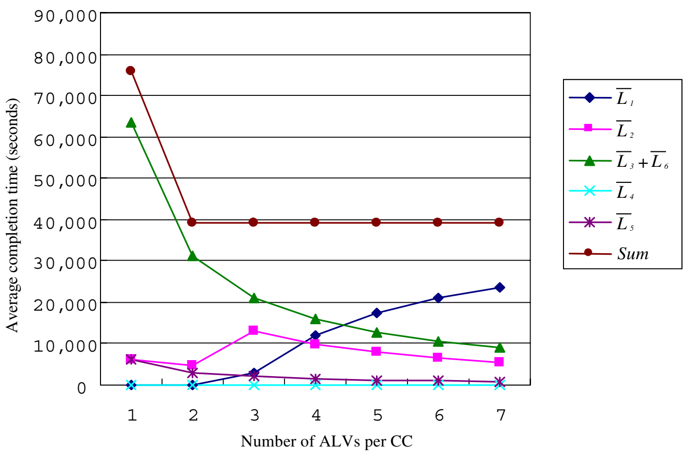

Fig. 8. The elements of the cycle time of ALVs at 3m/second speed

From Tables 7 and 8, we validate the above-mentioned four inferences within the feasible solutions.

Though these inferences are obvious, they each include all the variable effects. An illustration of the cycle time for AGVs in Table 7 is shown in Figure 7. And an illustration of Table 8 is shown in Figure 8. Figures 7 and 8 show how to compose time elements related to the cycle time for vehicles based on the assigned number of vehicles per CC.

The performance measures for vehicles after the termination of the simulation time are listed in Table 9. The $\overline{G_1}$ of the AGVs during the T$_E$ is more than 26.73% compared with the ALVs because, occasionally, the AGVs have to wait for the CCs. The $\overline{G_2}$ of the AGVs based on the mean waiting time for loading and unloading by CC is on the increase. The difference between $\overline{G_3}+\overline{G_6}$ and $\overline{L_3}+\overline{L_6}$ is due to the assigned number of vehicles, and in the case of the ALVs, the total routing distance

Table 9. Observed performance of vehicles

AGV(No = 12)			ALV(No = 6)		
Measures	Time (unit: second)	% cycle	Measures	Time (unit: second)	% cycle
$\sum_{i=1}^{6} \overline{G_i}$	$39,130.00$	100.00	$\sum_{j=1}^{6} \overline{L_j}$	$39,130.00$	100.00
$\overline{G_1}$	$10,458.33$	26.73	$\overline{L_1}$	8.50	0.02
$\overline{G_2}$	$9,757.33$	24.94	$\overline{L_2}$	$4,703.33$	12.02
$\overline{G_3} + \overline{G_6}$	$15,816.17$	40.42	$\overline{L_3} + \overline{L_6}$	$31,360.50$	80.14
$\overline{G_4}$	0.00	0.00	$\overline{L_4}$	0.00	0.00
$\overline{G_5}$	$3,098.17$	7.92	$\overline{L_5}$	$3,057.67$	7.81

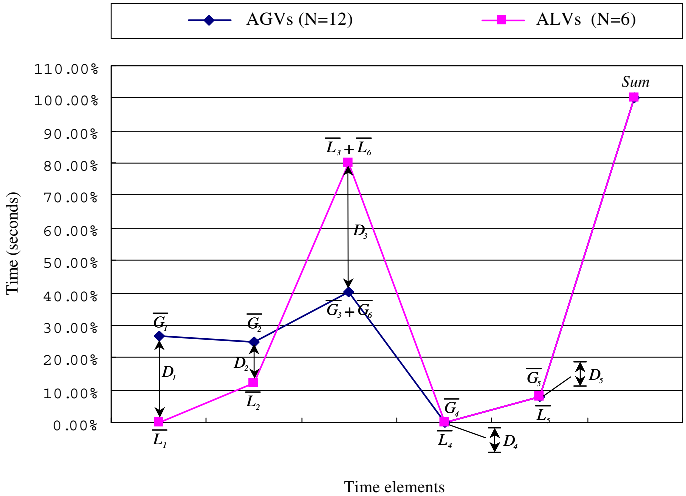

Fig. 9. Comparison of time elements between 12 AGVs and 6 ALVs

is increased by a factor of 2. The mean waiting time for loading and unloading by ATCs, $\overline{G_5}$ and $\overline{L_5}$, provides almost the same results. The zero value of $\overline{G_4}$ and $\overline{L_4}$ means that the waiting time in the buffer was not due to the sufficient buffer size of the block. In the case of the ALVs, 80% of the cycle time was spent on moving because the ALV has a shorter waiting time and a longer travel distance compared with the AGV.

In Figure 9, we know that the difference between $(\overline{L_3} + \overline{L_6})$ and $(\overline{G_3} + \overline{G_6})$ can cover the sum of $(\overline{G_1} - \overline{L_1})$ and $(\overline{G_2} - \overline{L_2})$. Therefore, it is possible to reduce the number of ALVs to 6.

5 Replacement range

We discover the measure to determine the replacement range by savings effect.

Table 10. Savings effect of D'

AGV \ ALV	6	9	12	15	18	21
12	81.0	2,095.0	3,211.0	3,736.9	4,147.9	4,440.5
15	−1,158.1	855.9	1,822.9	2,497.7	2,908.8	3,201.4
18	−1,983.1	30.9	1,057.9	1,672.8	2,083.8	2,376.4
21	−2,576.2	−562.2	464.8	1,079.7	1,490.7	1,783.3

Gray area : positive savings effect for waiting at seaside.

Using the above-mentioned four inferences, the notations are defined as follows:

$$D_1 = \overline{G_1} - \overline{L_1} \quad (1)$$
$$D_2 = \overline{G_2} - \overline{L_2} \quad (2)$$
$$D_3 = (\overline{L_3} + \overline{L_6}) - (\overline{G_3} + \overline{G_6}) \quad (3)$$
$$D_4 = \overline{G_4} - \overline{L_4} \quad (4)$$
$$D_5 = \overline{G_5} - \overline{L_5} \quad (5)$$
$$D' = D_3 - (D_1 + D_2) + (D_4 + D_5) \quad (6)$$
$$D'' = D_3 + (D_1 + D_2) - (D_4 + D_5) \quad (7)$$

In notations (1)–(5), D_i indicates the different effects of an AGV and an ALV on the set of time elements. In notations (6) and (7), we let D' denote the savings effect of waiting at seaside and D'' denote the savings effect of waiting at landside. Let $D' \times D''$ denote the savings effect of waiting in the buffers. By using $D' \times D''$, it is a rather simple calculation to derive an expression for the savings effect of assigning vehicles.

Comparing Table 10 with Table 11, a common savings effect, $D' \times D''$, can be determined, as shown in Table 12. Note that positive values are used to determine the savings effect in order to be able to assign between an AGV and an ALV.

In reference to the above notation, we see that if $D' \times D'' > 0$, then there is a positive savings effect and the number of vehicles is reducible until $D' \times D''=0$. Hence, $D' \times D''$represents a savings effect determining the required number of vehicles. But if $D' \times D'' < 0$, then there is a negative savings effect and the number of vehicles is irreducible.

Figure 10 shows that the contour of the savings effect was divided into 4 degrees. From the above-mentioned results, we know that the gray area in Figure 9 indicates a positive savings effect. Within the positive savings effect, it is possible to assign any combination of AGVs and ALVs while maintaining the balance of productivity. For example, as shown in Figures 10, 9 ALVs can replace 18 AGVs.

The results of the application of this simulation model have been encouraging. Our model has demonstrated how the use of a replaceable range can reduce the number of vehicles by assigning ALVs in the places of AGVs.

Table 11. Savings effect of D''

AGV \ ALV	6	9	12	15	18	21
12	31,007.7	8,408.7	−3110.2	−10,007.1	−14,617.1	−17,900.1
15	38,526.7	15,927.3	4,408.5	−2,488.4	−7,098.4	−10,381.4
18	43,548.9	20,949.9	9,431.1	2,534.2	−2,075.9	−5,358.9
21	47,130.9	24,531.9	13,013.1	6,116.2	1,506.1	−1,776.9

Gray area : positive savings effect for waiting at landside.

Table 12. Savings effect of $D' \times D''$

AGV \ ALV	6	9	12	15	18	21
12	2.51E+06	1.76E+07	−9.7E+06	−3.74E+07	−6.06E+07	−7.95E+07
15	−4.46E+07	1.36E+07	8.30E+06	−6.22E+06	−2.06E+07	−3.32E+07
18	−9.64E+07	6.47E+05	9.98E+06	4.24E+06	−4.33E+06	−1.27E+07
21	−1.21E+08	−1.38E+07	6.05E+06	6.60E+06	2.25E+06	−3.17E+06

Gray area : positive savings effect between AGV and ALV.

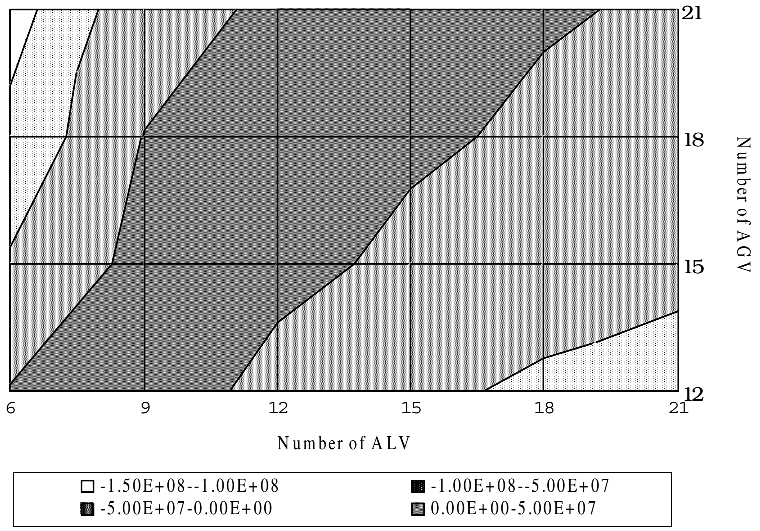

Fig. 10. Contour of savings effect comparing the AGV and the ALV

6 Conclusion

This paper presents a simulation model and a procedure governing transport vehicles of ACTs; the state transition model and the traffic model were proposed for the purpose of vehicle modeling. Using the simulation model developed for an ACT, we analyzed the travel speed of the vehicle with constraints on the productivity of the CC, and obtained the required number of vehicles and a savings effect by cycle time. Using a vehicle speed of 3m/second, we found that the number of ALVs is reducible while maintaining the same service level. This was due to the AGVs spending more time than the ALVs waiting in the ATC and CC buffer zones, respectively. This means that the ALV applied the wasteful waiting time of an AGV to its additional moving time.

As for the results, we demonstrated that the ALV is superior to the AGV in productivity because it reduces the waiting time in the buffer zones. In addition, we know that there are savings effects by assigning a vehicle mix between AGVs and ALVs.

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