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Efficiencies Of Choosing The Positions In Double Operation Cycle Of Storage And Retrieval Vehicle

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ABSTRACT: Automated storage and retrieval vehicle (ASRV) plays an important role in the goods storage planning of logistics centers and warehouses. The choice between the storage and retrieval positions in the double operation cycle (DOC) is aimed at reducing the required energy and the moving time of ASRV. To find logical choice between the storage and retrieval positions in the system for DOC, the required energy and the moving time of ASRV in DOC are compared with the ones in the single operation cycle (SOC) when the storage and retrieval positions in both DOC and SOC are changed in every compartment of the system. Firstly, the SOC model is created from the theory and the results of the experimental model to simulate the kinematic parameters, the power, the required energy of the driving and lifting units following to the moving time. The energy recovery is included in this model as well. Afterward, the DOC model is developed from the combination of the SOC model. The efficiencies of choosing the storage and retrieval positions to reduce the required energy and the moving time in DOC of the system will be shown by the results of the simulation model and the specific analyses.

KEYWORDS: Storage and retrieval vehicle, Double operation cycle, Storage and retrieval positions, Moving time, required energy.

INTRODUCTION

Due to the requirement for productivity and cost of goods, most industries have become more and more complete in terms of control process, rules and regulations. One of the important stages of the work process is the storage and retrieval phase. Saving the energy and reducing the moving time during the storage and retrieval phase are major factors affecting the productivity and cost of goods [1][2][3][4]. As a result, it is more competitive for enterprises when the transportation cost in the storage and retrieval phase is reduced and the productivity is increased.

Many studies on the moving time of ASRV in the storage system have been focused on the establishment of mathematical models to compute the moving time of ASRV, e.g. the moving time of SOC and DOC were considered in several input/output points [5]; the moving time of SOC was determined when the acceleration and deceleration were taken into account [6]; the average moving time of ASRV was calculated under the random storage conditions [7][8].

Some studies considered both of the moving time and required energy to increase their efficiencies, e.g. cycle time and required energy were computed in every position of the system [3], from which the operating process was changed to increase the time efficiency of about 2.52% and the energy saving of 12.66%; the influence of kinematic parameters on the moving time and the required energy of ASRV [9]; different storage operation strategies were established [10][11], and then the average values of the moving time and the required energy were determined when the speed changed, from which the average values were compared with each other to choose a more logical operation strategy. From the simulation results [10][11], the average required energy per unit load (UL) of DOC saved about 30% compared with the ones of SOC at all speeds. However, the percentage difference in average throughput increases by decreasing the driving unit speed (from about 20.5% at 5m/s to about 36.5% at 1m/s), etc.

Although there have been many studies on the moving time and the required energy of the system, the distance (altitude, length) between the storage and retrieval positions has not been specifically analyzed to reduce the required energy and the moving time in DOC when the storage and retrieval positions are chosen in pairs.

There are some cases for choosing the pairs of the storage and retrieval positions when ASRV runs in DOC. The required energy and the moving time in each case of DOC will be compared to the individual compartments of SOC to find the appropriate method for DOC.

SIMULATION MODEL OF DOC

The automatic small parts warehouse at the Institute of Logistics and Material Handling Systems (ILM) at the Otto-von-Guericke University Magdeburg was built in 2010. The simulation parameters of DOC are verified by this experimental model. The experimental model is constructed by two identical racks on the sides, of which ASRV runs in the middle (Fig. 1). The racks are used to store goods. Each rack has the following main parameters: the length of rack is 10m; the height of rack is about 7.5m including the engine foundation and the top of SRV; each rack has 20 compartments horizontally and 21 compartments vertically. Total compartments of each rack are 420 (20 x 21); the compartment has width of 0.5 m, height of 0.31 m and depth of 0.6 m.

Figure 1. Automatic small parts warehouse (ASPW) at the Institute (ILM).

ASRV is one of the main components of the storage and retrieval system. It has two main movements including the driving unit movement and the lifting unit movement. These movements, which are driven from the independent motors through the transmission systems, are used by the same control system. ASRV is moved in the given orbits. The speeds and the accelerations of the driving unit and the lifting unit can be adjusted independently. Another device on ASRV is the load handling device, which is put on the lifting unit to get goods into or out of ASRV. Storage, retrieval and stock transfer jobs of ASRV are automatically executed and transferred by a control system. It can work to single orders or sequential orders. In addition, the energy can be recovered by using the internal energy recovery system or by providing the released energy to other drives by the direct current intermediate circuit linkage during braking of the driving unit or lowering processes of the lifting unit.

The computational formulas of the kinematic parameters, the power, the required energy, the working cases and the experimental factors of ASRV in DOC are taken as in the simulation model of SOC [1]. And then, the DOC model has similar results as the experimental model when the working conditions of two models are the same.

Description of the simulation model

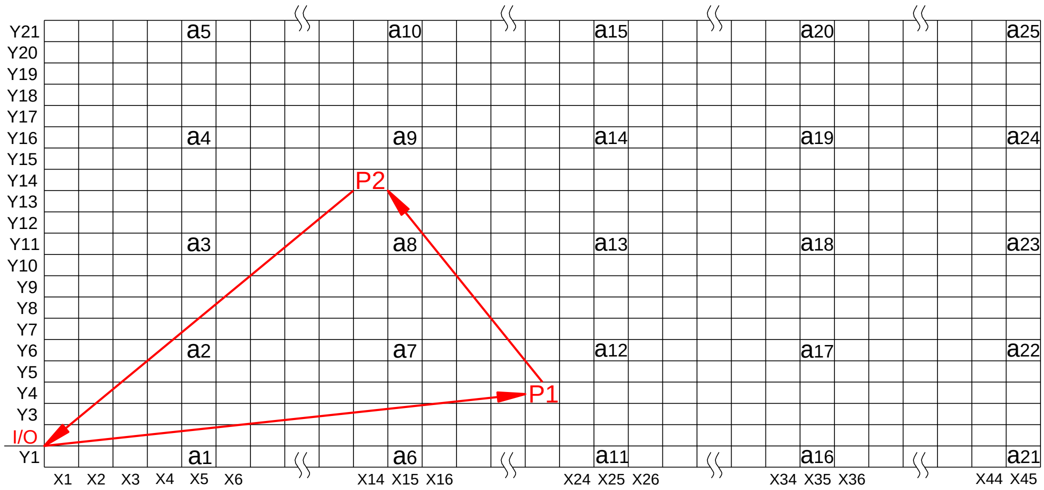

Figure 2. Position of the storage and retrieval compartments

In DOC, ASRV moves from input point (I) to the storage compartment (P1), then to the retrieval compartment (P2) and ends at output point (O) (Fig. 2). The simulation model of ASRV is extended from the experimental model at Institute of Logistics and material handling systems (ILM) at the Otto-von-Guericke University Magdeburg. It is established from the theory and the experimental factors. These factors depend on the structure of ASRV. It means that the storage and retrieval system cannot change vertically when these factors are applied to the simulation model. As the result, when the height of the system changes, the structure of the vehicle has to change to suit with the system and the factors are incorrect in this case. The experimental factors must be redefined. The system can be changed horizontally, then the structure of ASRV is constant and the simulation results are similar to reality.

Table 1. Important parameters of the system

	Configuration parameter	Unit	Value
System	Dimension (L x H)	m	22.5 x 7.5
	Number of the racks		2
	Size of compartment	m	0.5 x 0.31
	Number of compartments		1890
Box	Dimension	m	0.6 x 0.4 x 0.27
Driving unit	Mass	kg	1996
	Maximum speed	m/s	5
	Maximum acceleration	m/s^2	3
	Maximum jerk	m/s^3	6
Lifting unit	Mass	kg	215
	Maximum speed	m/s	4
	Maximum acceleration	m/s^2	4
	Maximum jerk	m/s^3	8
	Maximum loading capacity	kg	100

For more specific analysis of the storage and retrieval positions, the system is extended horizontally as shown in Fig. 2. System has length of 22.5 m and height about 7.5 m including the engine foundation and the top of ASRV. There are two identical racks on the sides, of which ASRV moves in the middle. Each rack has 45 compartments horizontally and 21 compartments vertically. The total of two racks is 1890 compartments. Each compartment has a width of 0.5 m and a height of 0.31 m. The loading capacity in the simulation model is 20 kg. The input/output point (I/O) is located in front of the rack at the height of the second row. ASRV has a total mass of 1996 kg and a height of 7.5 m; the lifting unit has a mass of 215 kg. The specifications of the storage and retrieval system are shown more clearly in Table 1. The compartments denoted from a1 to a25 are illustrated in Fig. 2.

Input and output parameters

The input parameters of the simulation model include: the size and the positions of the storage and retrieval compartments; the requirement of the speed, acceleration and jerk of the driving unit and the lifting unit; the mass of the unit load; the parameters of ASRV with the mass of ASRV and the lifting unit, the diameter of the wheel, the diameter of the wheel gudgeon; the experimental factors of the driving unit and the lifting unit. These experimental factors of ASRV in DOC are taken from the experimental model [1].

The results of the simulation model consist of simulating the moving and lifting distance, the speed, the acceleration and the consumption power by the driving and lifting time from the input point to the storage compartment and then to the retrieval compartment and end at the output point; simulating the recovery power of the driving unit when the vehicle is deceleration or braking; simulating the recovery power of the lifting unit when it lowers the unit load; determining the total required energy and the total moving time when ASRV moves from input point to output point with every input value of the speed and the acceleration.

EFFICIENCIES OF AVERAGE VALUES OF DOC BASED ON COMPARISON WITH SOC

From the simulation models, the average throughput and the average required energy of the operation cycles are calculated to clarify the efficiencies of the selected positions. These values are determined when the chaotic storage is chosen in the whole system, the kinematic parameters of the lifting unit are chosen at maximum values ($v_{l\,inp}=4m/s$, $a_{l\,inp}=4m/s^2$) and the driving unit speed ($v_{d\,inp}$) increases from 2 to 5m/s (Table 2), the driving unit acceleration $a_{d\,inp}=3m/s^2$. The efficient percentages of average throughput ($\overline{\Delta Q_{SC\_DC}}$), average moving time ($\overline{\Delta t_{SC\_DC\,Mo}}$) and average required energy ($\overline{\Delta E_{SC\_DC}}$) of DOC compared with SOC are derived from average throughputs of SOC ($\overline{Q_{SC}}$) with DOC ($\overline{Q_{DC}}$) and average required energy of SOC ($\overline{E_{SC}}$) with DOC ($\overline{E_{DC}}$).

Table 2. Comparison of the average values for chaotic storage in whole system of SOC and DOC

$v_{d\,inp}$ (m/s)	$\overline{Q_{SC}}$ (UL/h)	$\overline{Q_{DC}}$ (UL/h)	$\overline{\Delta Q_{SC\_DC}}$ (%)	$\overline{\Delta t_{SC\_DC\,Mo}}$ (%)	$\overline{E_{SC}}$ (kWs/UL)	$\overline{E_{DC}}$ (kWs/UL)	$\overline{\Delta E_{SC\_DC}}$ (%)
2	150.7	185.1	22.8	31.9	30.0	20.3	-32.3
2.5	163.6	198.0	21.0	31.8	34.1	22.9	-32.8
3	173.2	206.8	19.4	31.3	37.6	25.2	-33.1
3.5	181.0	212.9	17.7	30.2	40.1	27.1	-32.3
4	185.2	217.1	17.2	30.3	43.1	28.8	-33.3
4.5	188.5	219.9	16.7	30.0	45.3	30.1	-33.4
5	190.8	221.5	16.1	29.5	46.7	31.3	-32.9

The average required energy per unit load of DOC saved about 33% compared to the ones of SOC at all speeds and the percentage difference in average throughput increases from 16.1% at 5m/s to 22.8% at 2m/s. If it is only considered to the moving time of ASRV, the percentage difference in average moving time changes less when the driving speed decreases (from 29.5% at 5m/s to 31.9% at 2m/s).

EFFICIENCIES OF DOC COMPARED WITH SOC WHEN THE STORAGE AND RETRIEVAL POSITIONS ARE CHOSEN

Some typical cases of the storage compartment (P1) and the retrieval compartment (P2) are chosen in DOC. After that, the moving time and the required energy of DOC are compared with the ones of SOC to find the most effective when two positions are combined.

Required energy and working time

The required energy and the working time of ASRV consist of the driving unit, the lifting unit and the load handling device. Of which, the load handling device only works when it gets goods into or out at I/O point or at the compartments. The energy recovery is included in total required energy and it is achieved during the deceleration of the driving unit or the lowering process of the lifting unit.

The total working time (t_{TSC}) of ASRV in SOC when it performs both of storage (P1) and retrieval (P2) is calculated by using Eq. (1) at the same time of getting goods into or out of ASRV (t_{IO}). The total working time (t_{DC}) in DOC is calculated by using Eq. (2). The total required energy $(E_{TSC\,Re})$ in SOC when it performs both of storage (P1) and retrieval (P2) is calculated by using Eq. (4) at the same required energy of getting goods into or out of the load handing device (E_{IO}). The required energy $(E_{DC\,Re})$ in DOC is calculated by using Eq. (5).

$t_{O1} = \text{Max}\left\{t_{Dri\,IOP1}; t_{Lift\,IOP1}\right\} = \text{Max}\left\{t_{Dri\,P1IO}; t_{Lift\,P1IO}\right\};\ t_{12} = \text{Max}\left\{t_{Dri\,P1P2}; t_{Lift\,P1P2}\right\};$

$t_{O2} = \text{Max}\left\{t_{Dri\,IOP2}; t_{Lift\,IOP2}\right\} = \text{Max}\left\{t_{Dri\,P2IO}; t_{Lift\,P2IO}\right\}$

t_{Dri} : The moving time of the driving unit; t_{Lift} : the lift time of the lifing unit.

$$t_{TSC} = 2\cdot t_{O1} + 2\cdot t_{O2} + 4\cdot t_{IO} \quad (1)$$

$$t_{DC} = t_{O1} + t_{12} + t_{O2} + 4\cdot t_{IO} \quad (2)$$

$$t_{TSC} - t_{DC} = t_{O1} + t_{O2} - t_{12} \quad (3)$$

$E_{DO1} = E_{Dri\,IOP1} - \left|E_{Dri\,Recu\,IOP1}\right| = E_{Dri\,P1IO} - \left|E_{Dri\,Recu\,P1IO}\right|;\ E_{D12} = E_{Dri\,P1P2} - \left|E_{Dri\,Recu\,P1P2}\right|;$

$E_{DO2} = E_{Dri\,IOP2} - \left|E_{Dri\,Recu\,IOP2}\right| = E_{Dri\,P2IO} - \left|E_{Dri\,Recu\,P2IO}\right|$

E_{Dri} : The required energy of the driving unit when it works in the acceleration and constant phases;

$E_{Dri\,Recu}$: The energy recovery of the driving unit when it works in the deceleration phase.

$E_{LO1} = E_{Lift\,IOP1} - \left|E_{Lift\,Recu\,IOP1}\right|;\ E_{L12} = E_{Lift\,P1P2} - \left|E_{Lift\,Recu\,P1P2}\right|;\ E_{L2O} = E_{Lift\,P2IO} - \left|E_{Lift\,Recu\,P2IO}\right|;$

$E_{L1O} = E_{Lift\,P1IO} - \left|E_{Lift\,Recu\,P1IO}\right|;\ E_{LO2} = E_{Lift\,IOP2} - \left|E_{Lift\,Recu\,IOP2}\right|$

E_{Lift} : The required energy of the lifing unit when it lifts UL

$E_{Lift\,Recu}$: The energy recovery of the lifting unit when it lowers UL.

$$E_{TSC\,Re} = 2\cdot E_{DO1} + 2\cdot E_{DO2} + E_{LO1} + E_{L1O} + E_{LO2} + E_{L2O} + 4\cdot E_{IO} \quad (4)$$

$$E_{DC\,Re} = E_{DO1} + E_{D12} + E_{DO2} + E_{LO1} + E_{L12} + E_{L2O} + 4\cdot E_{IO} \quad (5)$$

$$E_{TSC\,Re} - E_{DC\,Re} = E_{DO1} + E_{DO2} - E_{D12} + E_{L1O} + E_{LO2} - E_{L12} \quad (6)$$

Saving capacities of the working time $(t_{TSC} - t_{DC})$ and the required energy $(E_{TSC\,Re} - E_{DC\,Re})$ in DOC compared to the ones in SOC only depend on the driving unit and the lifting unit, they do not depend on the load handling device, referring to Eq. (3) and (6). Therefore, the next research only considers the required energy and moving time of the driving unit and the lifting unit to find the logical choice of the storage and retrieval positions.

The saving time percentage $PT(\%)$ of DOC compared with SOC is determined by Eq. (7) and the saving energy percentage $PE(\%)$ is determined by Eq. (8) or (9).

$$PT(\%)=\frac{t_{O1}+t_{O2}-t_{12}}{2\cdot(t_{O1}+t_{O2})}\cdot 100(\%)=\left(\frac{1}{2}-\frac{t_{12}}{2\cdot(t_{O1}+t_{O2})}\right)\cdot 100(\%) \quad (7)$$

$$PE(\%)=\frac{E_{DO1}+E_{DO2}-E_{D12}+E_{L1O}+E_{LO2}-E_{L12}}{2\cdot(E_{DO1}+E_{DO2})+E_{LO1}+E_{L1O}+E_{LO2}+E_{L2O}}\cdot 100(\%)$$

$$PE(\%)=\left(\frac{1}{2}-\frac{E_{D12}+E_{L12}+\frac{1}{2}\cdot(E_{LO1}+E_{L2O}-E_{L1O}-E_{LO2})}{2\cdot(E_{DO1}+E_{DO2})+E_{LO1}+E_{L1O}+E_{LO2}+E_{L2O}}\right)\cdot 100(\%) \quad (8)$$

$$PE(\%)=\left(1-\frac{E_{DO1}+E_{DO2}+E_{D12}+E_{LO1}+E_{L2O}+E_{L12}}{2\cdot(E_{DO1}+E_{DO2})+E_{LO1}+E_{L1O}+E_{LO2}+E_{L2O}}\right)\cdot 100(\%) \quad (9)$$

Equations (7), (8) and (9) are to compare the saving of the moving time and the required energy of ASRV when the storage and retrieval positions are chosen differently.

Efficiencies of the values in DOC compared with SOC

In general, the required energy and the moving time in DOC are saved more than the ones in SOC. The required energy does not depend on the input speed (v_{1inp}) and the input acceleration (a_{1inp}) of the lifting unit [11]. Therefore, the kinematic parameters of the lifting unit are chosen at the maximum values $v_{1inp}=4m/s$ and $a_{1inp}=4m/s^2$. Afterward, the lifting time affects a little to the total working time.

To determine the efficiencies of the positions in DOC, the distance (altitude, length) between the storage and retrieval positions P1P2 is specifically analyzed to reduce the required energy and the moving time in DOC. The positions of P1 and P2 are considered in simple cases and then generalized to have general conclusions.

The below cases are indicated to determine the method of choosing the logical positions when the required energy and the moving time in DOC are compared with SOC.

4.2.1 When vehicle moves firstly to one of any two defined positions P1 and P2

The saving efficiencies of the total moving time in DOC are the same when ASRV moves firstly to one of any two defined positions due to ASRV moves on the total constant distances, e.g. when the input speed of the driving unit $v_{dinp}=2m/s$, the input acceleration $a_{dinp}=2m/s^2$ (Table 3) and two chosen cases (P1= a1, P2= a6 and vice versa) then the saving time percentages in two cases of DOC (compared with the ones of SOC) are the same of 25% $(PT(a1a6)=PT(a6a1)=25\%)$.

Table 3. Saving capacities of DOC when ASRV moves firstly to one of any two defined positions

P1	P2	$v_{dinp}=2m/s; a_{dinp}=2m/s^2; v_{1inp}=4m/s; a_{1inp}=4m/s^2$						$v_{dinp}=4m/s; a_{dinp}=3m/s^2; v_{1inp}=4m/s; a_{1inp}=4m/s^2$					
		The required energy (kWs)			The moving time (s)			The required energy (kWs)			The moving time (s)		
		E_{TSCRe}	E_{DCRe}	PE(%)	t_{TSC}	t_{DC}	PT(%)	E_{TSCRe}	E_{DCRe}	PE(%)	t_{TSC}	t_{DC}	PT(%)
a1	a6	23.0	17.0	**-25.9**	15.3	11.5	**-25.0**	29.7	22.2	**-25.2**	12.2	9.2	**-24.3**
a6	a1	23.0	17.0	**-25.9**	15.3	11.5	**-25.0**	29.7	22.2	**-25.2**	12.2	9.2	**-24.3**

a4	a19	53.36	44.46	**-16.7**	25.4	21.6	**-15.3**	75.5	64.5	**-14.6**	17.7	14.4	**-18.5**
a19	a4	53.36	44.46	**-16.7**	25.4	21.6	**-15.3**	75.5	64.5	**-14.6**	17.7	14.4	**-18.5**
a1	a2	11.2	5.88	**-47.5**	10.4	7.03	**-32.1**	11.6	6.1	**-47.6**	9.6	6.6	**-30.8**
a2	a1	11.75	6.09	**-48.2**	10.4	7.03	**-32.1**	12.2	6.7	**-45.3**	9.6	6.6	**-30.8**
a1	a5	13.9	8.8	**-36.2**	11.1	8.6	**-22.6**	14.3	9.1	**-36.6**	10.7	8.4	**-21.6**
a5	a1	16.1	10.6	**-34.2**	11.1	8.6	**-22.6**	16.5	10.8	**-34.6**	10.7	8.4	**-21.6**
a22	a23	110.4	55.3	**-49.9**	50.3	27.0	**-46.3**	170.1	85.2	**-49.9**	29.8	16.8	**-43.9**
a23	a22	111.0	56.3	**-49.3**	50.3	27.0	**-46.3**	170.7	86.2	**-49.5**	29.8	16.8	**-43.9**
a5	a16	52.5	46.5	**-11.5**	26.1	21.9	**-16.2**	74.7	66.5	**-10.9**	18.4	14.8	**-19.6**
a16	a5	50.3	44.8	**-11.1**	26.1	21.9	**-16.2**	72.5	64.8	**-10.6**	18.4	14.8	**-19.6**

The saving efficiencies of the total required energy change a little bit during all the ways of DOC when ASRV moves firstly to one of any two defined positions. If only the two points are far from each other mainly by vertical direction and near the I/O point, the change is clearer, e.g. $v_{dinp} = 2m/s$ and $a_{dinp} = 2m/s^2$ (Table 3), the saving energy percentages $PE(a5a16) = 11.5\%$ and $PE(a16a5) = 11.1\%$; $PE(a1a5) = 36.2\%$ and $PE(a5a1) = 34.2\%$.

The storage compartment is lower than the retrieval compartment and then the required energy is less than the one of vice versa. The reason is that the energy recuperation of the lifting unit is bigger when the retrieval compartment is higher (the unit load is lowered at higher altitude) and the energy consumption of the lifting unit is smaller when the storage compartment is lower (the unit load is lifted at lower altitude).

When P1 and P2 are on the same height and P1 is fixed

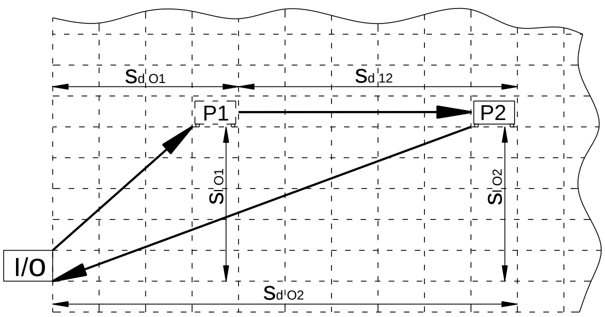

Figure 3. P1 and P2 are on the same height and P2 is farther than P1

When P2 is farther from P1 and I/O point (Fig. 3), the saving capacities of required energy and moving time in DOC are lower and these values are much lower than their average values, e.g. $v_{dinp} = 4m/s$ and $a_{dinp} = 3m/s^2$ (Table 4), the saving energy percentages $PE(a1a6) = 25.2\%$, $PE(a1a11) = 16.5\%$ and $PE(a1a21) = 9.2\%$; The saving time percentages $PT(a1a6) = 24.3\%$, $PT(a1a11) = 20.5\%$ and $PT(a1a21) = 15.3\%$ while the average efficient percentages at these kinematic parameters (Table 2) of the average required energy $\left(\overline{\Delta E_{SC\_DC}} = 33.3\%\right)$ and the average moving time $\left(\overline{\Delta t_{SC\_DCMo}} = 30.3\%\right)$ are much larger. When $v_{dinp} = 2m/s$ and $a_{dinp} = 2m/s^2$ (Table 4), the rule of reducing the saving capacities of the required energy and the moving time is similar to $v_{dinp} = 4m/s$ and $a_{dinp} = 3m/s^2$.

As the result, when the driving distance from P1 to P2 (s_{d12}) increases and P1 is fixed, from Eq. (7), t_{O1} is constant while t_{12} and t_{O2} increase, t_{12} is closer to t_{O2}. It means that the saving time percentage decreases clearly; from Eq. (8), the lifting unit required energy on every distance and E_{DO1} are constant while E_{D12} and E_{DO2} increase, E_{D12} is closer to E_{DO2}. It means that the saving energy percentage decreases significantly.

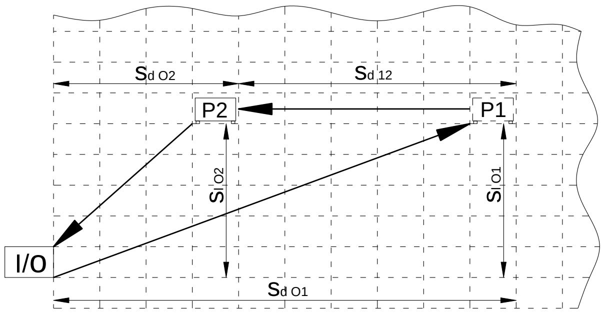

Figure 4. P1 and P2 are on the same height and P1 is farther than P2

When P1 is farther than P2 (Fig. 4) and P2 is closer to I/O point, the saving capacities of the required energy and the moving time in DOC are lower and reduce faster than these values when P2 is farther from P1 (Fig. 3). These saving capacities are much higher than the average values when P2 is close to P1 and they reduce very quickly when P2 is far from P1, e.g. $v_{dinp} = 2m/s$ and $a_{dinp} = 2m/s^2$ (Table 4), the saving energy percentages $PE(a21a16) = 44.2\%$, $PE(a21a6) = 25.3\%$ and $PE(a21a1) = 10.2\%$; The saving time percentages $PT(a21a16) = 41.5\%$, $PT(a21a6) = 25\%$ and $PT(a21a1) = 12.6\%$.

The reason is that when s_{d12} increases and P1 is fixed, from Eq. (7), t_{O1} is constant and t_{O2} decreases while t_{12} increases. It means that the saving time percentage decreases significantly; from Eq. (8), the lifting unit required energy on every distance and E_{DO1} are constant and E_{DO2} decreases while E_{D12} increases. Therefore, the saving energy percentage decreases significantly.

In general, P1 is fixed and P2 changes horizontally, the saving efficiencies of the required energy and moving time of DOC change clearly.

Table 4. Saving capacities of moving time and required energy by horizontal direction of DOC

P1	P2	v_{dinp}=2m/s; a_{dinp}=2m/s^2; v_{linp}=4m/s; a_{linp}=4m/s^2						v_{dinp}=4m/s; a_{dinp}=3m/s^2; v_{linp}=4m/s; a_{linp}=4m/s^2					
		The required energy (kWs)			The moving time (s)			The required energy (kWs)			The moving time (s)		
		E_{TSCRe}	E_{DCRe}	PE(%)	t_{TSC}	t_{DC}	PT(%)	E_{TSCRe}	E_{DCRe}	PE(%)	t_{TSC}	t_{DC}	PT(%)
a1	a6	23.0	17.0	**-25.9**	15.3	11.5	**-25.0**	29.7	22.2	**-25.2**	12.2	9.2	**-24.3**
a1	a11	35.2	29.3	**-16.9**	20.3	16.5	**-18.8**	49.8	41.6	**-16.5**	14.7	11.7	**-20.5**
a1	a21	59.7	53.6	**-10.2**	30.3	26.5	**-12.6**	89.7	81.5	**-9.2**	19.7	16.7	**-15.3**
a3	a8	26.7	18.9	**-29.1**	15.3	11.5	**-25.0**	33.4	24.1	**-27.8**	12.2	9.2	**-24.3**
a3	a23	63.4	55.5	**-12.5**	30.3	26.5	**-12.6**	93.5	83.4	**-10.8**	19.7	16.7	**-15.3**
a21	a16	96.1	53.6	**-44.2**	45.3	26.5	**-41.5**	147.9	81.3	**-45.0**	27.3	16.8	**-38.6**
a21	a6	71.7	53.5	**-25.3**	35.3	26.5	**-25.0**	108.0	80.7	**-25.3**	22.3	16.8	**-25.0**

a21	a1	59.7	53.6	**-10.2**	30.3	26.5	**-12.6**	89.7	81.5	**-9.2**	19.7	16.7	**-15.3**
a5	a10	31.0	21.2	**-31.6**	16.1	11.9	**-26.2**	37.7	26.3	**-30.0**	13.4	9.8	**-26.6**
a5	a25	67.6	57.7	**-14.7**	31.1	26.9	**-13.6**	97.7	85.6	**-12.4**	20.9	17.3	**-17.3**
a6	a11	47.2	29.2	**-38.3**	25.3	16.5	**-34.8**	68.1	41.4	**-39.2**	17.3	11.8	**-31.9**
a16	a21	96.1	53.6	**-44.2**	45.3	26.5	**-41.5**	147.9	81.3	**-45.0**	27.3	16.8	**-38.6**
a8	a13	51.0	31.1	**-39.0**	25.3	16.5	**-34.8**	71.8	43.3	**-39.7**	17.3	11.8	**-31.9**
a10	a15	55.2	33.3	**-39.7**	25.3	16.5	**-34.8**	76.0	45.5	**-40.1**	17.3	11.8	**-31.9**

When P1 and P2 are on the same height and $s_{d\,12}$ is constant (Fig. 3 and Fig. 4)

When the position of s_{d12} is farther from I/O point, the saving efficiencies of the required energy and the moving time are higher and these values are higher than their average values (Table 2), e.g. $v_{dinp}=2m/s$ and $a_{dinp}=2m/s^2$ (Table 4), the saving energy percentages $PE(a1a6)=25.9\%$, $PE(a6a11)=38.3\%$ and $PE(a16a21)=44.2\%$; The saving time percentages $PT(a1a6)=25\%$, $PT(a6a11)=34.8\%$ and $PT(a16a21)=41.5\%$, etc.

As the result, from Fig. 3 and Fig. 4, s_{d12} is constant and the positions P1 and P2 are farther from I/O point, from Eq. (7), t_{12} is constant while t_{O1} and t_{O2} increase. It means that the saving time percentage increases; from Eq. (8), the lifting unit required energy on every distance and E_{D12} are constant while E_{DO1} and E_{DO2} increase. Therefore, the saving energy percentage increases.
The higher the constant distance s_{d12} is, the better the saving energy efficiency is. However, the saving capacity does not change much when two positions are far from I/O point horizontally, e.g. $v_{dinp}=2m/s$ and $a_{dinp}=2m/s^2$ (Table 4), the saving energy percentages $PE(a6a11)=38.3\%$, $PE(a8a13)=39\%$ and $PE(a10a15)=39.7\%$, etc.

The reason is that s_{d12} is constant and the positions of P1P2 are higher from I/O point, from Eq. (8), $E_{L12}=0$ and two positions are far from I/O point horizontally so the driving unit required energy on every distance is constant and quite big. On the other hand, the lifting heights $(s_{lO1}=s_{lO2})$ are equal to the lowering heights $(s_{l1O}=s_{l2O})$ and the energy recovery rate of the lifting unit based on the experimental results is quite high about 70% of the energy consumption on every lifting height and kinematic parameters and then $(E_{L1O}+E_{LO1}+E_{LO2}+E_{L2O})$ increases a little bit and is usually quite smaller than the driving unit's values. It means that the saving energy percentage only increases by the lifting height and these values do not change much.

When both positions are near I/O point, the driving unit required energy is small and the saving capacity changes more about 5÷6%, e.g. when $v_{dinp}=2m/s$, $a_{dinp}=2m/s^2$ then $PE(a1a6)=25.9\%$, $PE(a5a10)=31.6\%$, etc. In this case, the moving time efficiency may be equal or bigger. When the driving time is more than the lifting time on each distance, t_{12}, t_{O1} and t_{O2} are constant, from Eq. (7), the moving time efficiency is equal, e.g. when $v_{dinp}=2m/s$, $a_{dinp}=2m/s^2$ (Table 4) then $PT(a6a11)=34.8\%$, $PT(a8a13)=34.8\%$ and $PT(a10a15)=34.8\%$, etc. Besides, when both positions are near I/O point horizontally, the driving time is smaller than the lifting time, t_{O1} and t_{O2} increase, from Eq. (7), the moving time efficiency is higher. However, saving capacity does not change much due to the kinematic parameters of the lifting unit are big, e.g. when $v_{dinp}=2m/s$, $a_{dinp}=2m/s^2$ then $PT(a1a6)=25\%$, $PT(a5a10)=26.2\%$; when $v_{dinp}=4m/s$, $a_{dinp}=3m/s^2$ then $PT(a1a6)=24.3\%$, $PT(a5a10)=26.6\%$.

When P1 and P2 are on the same length and P1 is fixed

When P2 is higher from P1 (Fig. 5), the saving efficiencies of the required energy and the moving time in DOC are lower. These efficiencies are much higher than their average values (Table 2) and reduce a little bit when two positions are far from I/O point horizontally, e.g. $v_{dinp}=2m/s$ and $a_{dinp}=2m/s^2$ (Table 5), the saving energy percentages PE(a21a22) =49.7%, and PE(a21a25) =48.3%; the saving time percentages PT(a21a22) =46.3%, and PT(a21a25) =43.9%, etc.

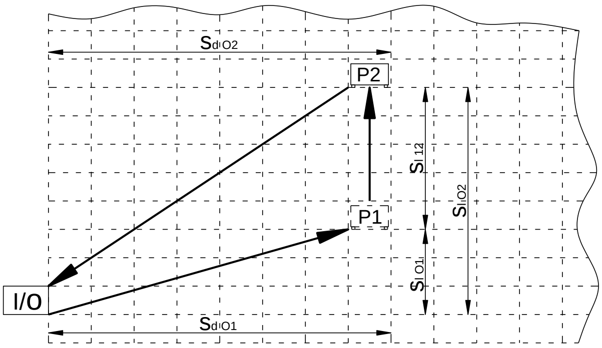

Figure 5. P1 and P2 are on the same length and P2 is higher than P1

Due to P2 is higher and higher from P1 and P1 is fixed, the lifting distance s_{l12} increases. When two positions are horizontally far from I/O point, the driving time is bigger than the lifting time on the distances IP1 and P2O and then t_{O1} and t_{O2} is constant and big. While the kinematic parameters of the lifting unit are big and the maximum lifting height is only about 6.5 m then t_{12} increases but quite smaller than t_{O1} and t_{O2}. From the above reasons and Eq. (7), the saving efficiency of the moving time in DOC is lower but only changes a little bit when P2 is higher and higher from P1; from Eq. (9) E_{DO1} and E_{DO2} are constant, $E_{D12} = 0$, E_{LO1} and E_{L1O} are constant whereas E_{L12} and E_{LO2} increase and E_{L12} is closer to E_{LO2}. Furthermore, the lifting unit energy recovery is about 70% of the energy consumption on every lifting height so $(E_{L12}+E_{L2O})$ is closer to $(E_{LO2}+E_{L2O})$ and they are quite smaller than $(E_{DO1}+E_{DO2})$. Therefore, the saving efficiency of the required energy in DOC is lower but only changes a little bit when P2 is higher and higher from P1.

These efficiencies decrease much more when two positions are near I/O point horizontally, e.g. when v_{dinp}= 2m/s and a_{dinp}= 2m/s^2 then PE(a1a2) =47.5% and PE(a1a5) =36.2%; PT(a1a2) =32.1% and PT(a1a5) =22.6%, etc. The reason is that two positions are near I/O point horizontally then t_{O2} increases when the driving time is smaller than the lifting time, t_{O1} is fixed and small, t_{12} and t_{O2} increase and t_{12} is closer to t_{O2} and then from Eq. (7), the saving efficiency of the moving time decreases more clearly; from Eq. (9), E_{DO1} and E_{DO2} are constant and small, $E_{D12} = 0$, E_{LO1} and E_{L1O} are constant while E_{L12} and E_{LO2} increase, $(E_{L12}+E_{L2O})$ is closer to $(E_{LO2}+E_{L2O})$. It means that the saving efficiency of the required energy decreases more clearly.

When P1 is higher from P2, the saving efficiencies of the required energy and the moving time in DOC are lower. These values are also much higher than their average values and the reason is explained similarly when P2 is higher than P1.

In general, P1 is fixed and P2 changes vertically, the saving efficiencies of the required energy and the moving time of DOC change a little bit and these values are quite high.

Table 5. Saving capacities of moving time and required energy by vertical direction of DOC

P1	P2	v_{dinp}=2m/s; a_{dinp}=2m/s^2; v_{linp}=4m/s; a_{linp}=4m/s^2						v_{dinp}=4m/s; a_{dinp}=3m/s^2; v_{linp}=4m/s; a_{linp}=4m/s^2					
		The required energy (kWs)			The moving time (s)			The required energy (kWs)			The moving time (s)		
		E_{TSCRe}	E_{DCRe}	PE(%)	t_{TSC}	t_{DC}	PT(%)	E_{TSCRe}	E_{DCRe}	PE(%)	t_{TSC}	t_{DC}	PT(%)

a1	a2	11.2	5.9	**-47.5**	10.4	7.0	**-32.1**	11.6	6.1	**-47.6**	9.6	6.6	**-30.8**
a1	a3	12.3	6.9	**-43.6**	10.4	7.5	**-27.4**	12.7	7.1	**-43.8**	9.6	7.1	**-25.5**
a1	a5	13.9	8.8	**-36.2**	11.1	8.6	**-22.6**	14.3	9.1	**-36.6**	10.7	8.4	**-21.6**
a11	a12	59.7	30.1	**-49.5**	30.3	17.0	**-43.9**	88.4	44.5	**-49.7**	19.8	11.8	**-40.8**
a11	a15	62.3	33.1	**-46.9**	30.3	18.2	**-39.9**	91.1	47.4	**-47.9**	19.8	13.0	**-34.6**
a15	a14	66.7	34.0	**-49.0**	30.3	17.0	**-43.9**	95.4	48.3	**-49.3**	19.8	11.8	**-40.8**
a15	a11	64.5	34.8	**-46.1**	30.3	18.2	**-39.9**	93.3	49.2	**-47.3**	19.8	13.0	**-34.6**
a21	a22	108.6	54.6	**-49.7**	50.3	27.0	**-46.3**	168.3	84.4	**-49.8**	29.8	16.8	**-43.9**
a21	a25	111.2	57.5	**-48.3**	50.3	28.2	**-43.9**	170.9	87.4	**-48.9**	29.8	18.0	**-39.8**
a3	a4	15.5	8.0	**-48.3**	10.5	7.1	**-32.4**	16.0	8.2	**-48.4**	10.1	6.9	**-31.7**
a4	a5	17.7	9.2	**-47.7**	11.2	7.5	**-33.6**	18.1	9.5	**-47.8**	11.2	7.5	**-33.6**
a13	a14	64.0	32.3	**-49.6**	30.3	17.0	**-43.9**	92.7	46.6	**-49.7**	19.8	11.8	**-40.8**
a14	a15	66.1	33.5	**-49.4**	30.3	17.0	**-43.9**	94.9	47.8	**-49.6**	19.8	11.8	**-40.8**
a23	a24	112.9	56.7	**-49.8**	50.3	27.0	**-46.3**	172.6	86.6	**-49.8**	29.8	16.8	**-43.9**
a24	a25	115.0	57.9	**-49.6**	50.3	27.0	**-46.3**	174.7	87.8	**-49.8**	29.8	16.8	**-43.9**
a6	a8	36.3	18.9	**-47.8**	20.3	12.5	**-38.5**	49.2	25.4	**-48.4**	14.8	9.8	**-34.3**
a8	a10	40.3	21.2	**-47.4**	20.3	12.5	**-38.5**	53.2	27.7	**-48.1**	14.8	9.8	**-34.3**

When P1 and P2 are on the same length and $s_{l\,12}$ is constant (Fig. 5)

The saving efficiencies of the required energy and the moving time are significantly unchangeable when the position of P1P2 changes vertically.

In this case, t_{12} is constant and when the driving time is bigger than the lifting time in the distances of IOP1 and P2IO, t_{O1} and t_{O2} are constant. Therefore, from Eq. (7), the saving efficiency of moving time is equal, e.g. $v_{d\,inp} = 2m/s$ and $a_{d\,inp} = 2m/s^2$ (Table 5) then $PT(a11a12) = 43.9\%$, $PT(a13a14) = 43.9\%$ and $PT(a14a15) = 43.9\%$, etc. when the driving time is smaller than the lifting time in the distances of IOP1 and P2IO (P1 and P2 are at high positions and near I/O point horizontally), t_{O1} and t_{O2} increase. Therefore, from Eq. (7), the saving efficiency of the moving time is higher. This saving efficiency does not change much due to the kinematic parameters of the lifting unit are big and the maximum lifting height is not high, e.g. $v_{d\,inp} = 2m/s$ and $a_{d\,inp} = 2m/s^2$ (Table 5) then $PT(a1a2) = 32.1\%$, and $PT(a4a5) = 33.6\%$, etc.

Besides, the driving unit required energy on every distance and E_{L12} are constant, the lifting unit energy recovery is about 70% of the energy consumption on every lifting height and then the remaining lifting unit required energy in Eq. (9) affects a little bit to the total value and the saving efficiency of the required energy is significantly unchangeable, e.g. v_{dinp} = 2m/s and a_{dinp} = 2m/s^2 (Table 5) then PE(a11a12) =49.5%, PE(a13a14) =49.6% and PE(a14a15) =49.4%, etc.

The farther the constant distance s_{l12} at the same height is, the higher the saving efficiencies of the required energy and the moving time are. These efficiencies are much higher than their average values, e.g. v_{dinp} = 2m/s and a_{dinp} = 2m/s^2 (Table 5) then PE(a1a2) =47.5%, PE(a11a12) =49.5% and PE(a21a22) =49.7%; PT(a1a2) =32.1%, PT(a11a12) =43.9% and PT(a21a22) =46.3%; etc. The reason is that the lifting heights are constant in every driving distance. Therefore, from Eq. (7), t_{12} is constant while t_{O1} and t_{O2} increase. It means that the saving time efficiency increases; from Eq. (8), $E_{D12} = 0$, E_{DO1} and E_{DO2} increase while the lifting unit required energy is constant in every moving distance. Therefore, the saving efficiency of the required energy in DOC increases.

4.2.6 When P1&P2 are located on a tilt line with the constant distance of P1P2

When the position of P1P2 is farther from I/O point, the saving efficiencies of the required energy and the moving time are higher, e.g. v_{dinp} = 2m/s and a_{dinp} = 2m/s^2 (Table 6) then PE(a1a7) =25%, PE(a7a13) =38.6%, and PE(a19a25) =44.2%; PT(a1a7) =25%, PT(a7a13) =34.8%, and PT(a19a25) =41.5%, etc.

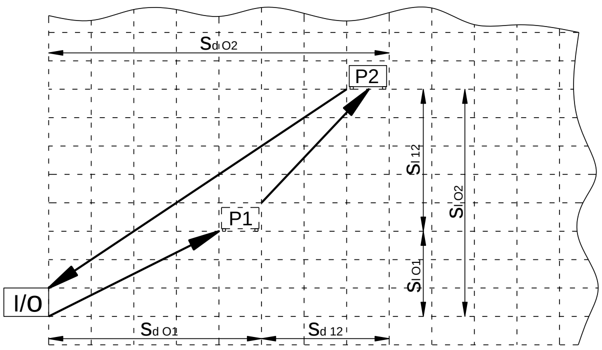

Figure 6. P1 and P2 are on any position

The result is explained by a combination of Section 4.2.3 and Section 4.2.5 of changing the constant distances in both directions (Fig. 6).

When P1 is fixed and P2 changes (Fig. 6)

P2 is farther from P1 horizontally, the saving efficiencies of the required energy and the moving time are lower, and these values decrease quite a lot, e.g. when v_{dinp} = 2m/s and a_{dinp} = 2m/s^2 (Table 6) then PE(a13a15) =48.4%, PE(a13a10) =37.5% and PE(a13a5) =18.7%; PT(a13a15) =42.3%, PT(a13a10) =34.8% and PT(a13a5) =20%. The reason is that the lifting heights are constant in every distance and the driving distances change as Section 4.2.2 then it is explained as the above Section.

The remaining positions P2 are symmetric following vertical direction of P1. After that, P2 is farther from I/O point, the saving efficiencies of the required energy and the moving time of DOC are better, e.g. v_{dinp} = 2m/s and a_{dinp} = 2m/s^2 then PE(a13a5) =18.7% and PE(a13a25) =35.8%; PT(a13a5) =20% and PT(a13a25) =34.3%, etc. The reason is that the lifting heights are constant in every distance and the driving distances are explained as the same as Section 4.2.3.

When P2 changes on the same lengths and then P2 is farther from P1 vertically, the saving efficiency of the required energy is lower. However, the saving capacity does not change much, e.g. when $v_{dinp}=2m/s$ and $a_{dinp}=2m/s^2$ then PE(a13a18)=42.6%, PE(a13a19)=42.4% and PE(a13a20)=41.5%, etc.

Table 6. Saving capacities of moving time and required energy in the general cases of DOC

P1	P2	v_{dinp}=2m/s; a_{dinp}=2m/s^2; v_{1inp}=4m/s; a_{1inp}=4m/s^2						v_{dinp}=4m/s; a_{dinp}=3m/s^2; v_{1inp}=4m/s; a_{1inp}=4m/s^2					
		The required energy (kWs)			The moving time (s)			The required energy (kWs)			The moving time (s)		
		E_{TSCRe}	E_{DCRe}	PE(%)	t_{TSC}	t_{DC}	PT(%)	E_{TSCRe}	E_{DCRe}	PE(%)	t_{TSC}	t_{DC}	PT(%)
a1	a7	23.2	17.4	**-25.0**	15.3	11.5	**-25.0**	29.9	22.6	**-24.5**	12.2	9.2	**-24.3**
a7	a13	49.3	30.3	**-38.6**	25.3	16.5	**-34.8**	70.1	42.5	**-39.4**	17.3	11.8	**-31.9**
a19	a25	102.8	57.4	**-44.2**	45.3	26.5	**-41.5**	154.6	85.1	**-45.0**	27.3	16.8	**-38.6**
a5	a9	30.2	21.3	**-29.5**	16.1	11.9	**-26.2**	36.9	26.5	**-28.3**	13.4	9.8	**-26.6**
a9	a13	52.3	32.4	**-38.1**	25.3	16.5	**-34.8**	73.2	44.6	**-39.0**	17.3	11.8	**-31.9**
a17	a21	96.9	54.6	**-43.7**	45.3	26.5	**-41.5**	148.7	82.3	**-44.7**	27.3	16.8	**-38.6**
a13	a5	40.5	32.9	**-18.7**	21.1	16.9	**-20.0**	55.1	45.3	**-17.8**	15.9	12.3	**-22.7**
a13	a10	52.5	32.8	**-37.5**	25.3	16.5	**-34.8**	73.4	45.1	**-38.6**	17.3	11.8	**-31.9**
a13	a15	64.8	33.4	**-48.4**	30.3	17.5	**-42.3**	93.5	47.8	**-48.9**	19.8	12.3	**-38.3**
a13	a20	77.0	45.1	**-41.5**	35.3	21.5	**-39.1**	113.3	65.1	**-42.6**	22.3	14.3	**-36.0**
a13	a25	89.2	57.3	**-35.8**	40.3	26.5	**-34.3**	133.4	84.4	**-36.7**	24.8	16.8	**-32.6**
a13	a6	49.7	31.7	**-36.1**	25.3	16.5	**-34.8**	70.5	44.0	**-37.6**	17.3	11.8	**-31.9**
a13	a11	61.9	32.3	**-47.8**	30.3	17.5	**-42.3**	90.6	46.7	**-48.5**	19.8	12.3	**-38.3**
a13	a3	38.9	31.2	**-20.0**	20.3	16.5	**-18.8**	53.5	43.5	**-18.7**	14.7	11.7	**-20.5**
a13	a18	75.4	43.3	**-42.6**	35.3	21.5	**-39.1**	111.7	63.3	**-43.4**	22.3	14.3	**-36.0**
a13	a17	74.3	43.6	**-41.4**	35.3	21.5	**-39.1**	110.6	63.5	**-42.6**	22.3	14.3	**-36.0**
a13	a19	76.2	43.9	**-42.4**	35.3	21.5	**-39.1**	112.5	63.9	**-43.2**	22.3	14.3	**-36.0**

Besides, the saving efficiency of the moving time is usually equal or changes a little bit, e.g. PT(a13a18)=39.1% and PT(a13a20)=39.1%, etc. The reason is that the driving distances are constant, when P2 changes vertically. When the driving time is bigger than the lifting time in P1P2 and then the saving efficiency of the moving time is equal. When the driving time is smaller than the lifting time in P1P2 then t_{12} increases and it is explained as the same as Section 4.2.4.

The remaining positions P2 are symmetric following horizontal direction of P1. After that, P2 is upper the horizontal direction of P1, the saving efficiency of the required energy is better and the saving efficiency of moving time is equal or higher. Their saving capacities do not change much, e.g. $v_{dinp} = 2m/s$ and $a_{dinp} = 2m/s^2$ (Table 6) then PE(a13a17) =41.4% and PE(a13a19) =42.4%; PT(a13a17) =39.1% and PT(a13a19) =39.1%, etc. The reason is that the driving distances are constant and the lifting heights change as Section 4.2.5 and then it is explained as the same as this Section.

When P2 changes on a tilt line and P2 is farther from P1, the saving efficiencies of the required energy and the moving time are lower. It is explained by a combination of Section 4.2.2 and Section 4.2.4.

SUMMARY AND OUTLOOK

The simulation model of DOC is created. After that, the required energy and the moving time of ASRV in DOC at every position are compared to the ones of SOC. From Section 4.2, there are some results when a storage position and a retrieval position are chosen in a pair to achieve the high saving efficiencies of the required energy and the moving time of DOC compared with the ones of SOC, as below:

The farther from I/O point a storage position and a retrieval position are and the nearer to each other by horizontal direction they are, the higher the saving efficiencies of the required energy and the moving time in DOC are. These values are much higher than their average values.

When ASRV moves firstly to one of any two defined positions P1 and P2, the saving efficiencies of the total moving time in DOC are the same and the saving efficiencies of the total required energy change a little bit during all the ways of DOC.

When the storage and retrieval positions are far from each other mainly by vertical direction, the saving efficiency of the required energy in DOC changes a little bit and the saving efficiency of moving time is equal or also changes a little bit (the smaller the driving unit speed is, the less the change of the saving efficiency is). Therefore, when the logical choice between a storage compartment and a retrieval compartment is performed, the vertical of the storage and retrieval positions can be ignored. However, this result is only applied when ASRV has an energy recovery system (the energy recovery of the lifting unit is about 70% of the energy consumption on every lifting height) and the system's height is average.

The general method of logical choice between the storage and retrieval positions of DOC could be developed by directly comparing the pairs of DOC in order to analyze the flexible pairs of DOC and their impact on ASRV-strategies to achieve the best efficiency of the required energy and the moving time.

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