A COMPARISON OF STACKING EFFICIENCY FOR VARIOUS STRATEGIES OF SLOT ASSIGNMENT IN CONTAINER YARDS

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Abstract: This paper attempts to divide the containers into two categories--attributes that are known and unknown in advance. Ordered and random stacking strategies are simulated in a yard, which is treated as a single area or divided into twin areas. The simulation results in a single area have shown that random stacking strategy is more efficient than ordered stacking if the departure sequences of all containers are completely unknown. Layer-column-row or layer-row-column is the best ordered stacking strategy that has less unproductive moves than random stacking strategy, provided that all containers attributes are known in advance. Simulations results in twin areas have revealed that ordered stacking is in general superior to random stacking if the ratios of known attributes are not high. The number of unproductive moves for single area random stacking operation is much less than that for twin areas, therefore, dividing the yard into two sub-areas is not recommended.

Key words: simulation, slot assignment, container yard, ordered stacking, random stacking

1. INTRODUCTION

Container transportation is the major manner for the export and import general cargoes in the international trade. The import containers are shipped through vessels, berthed in the piers, unloaded in the port container terminals, temporarily stored at the marshalling yards, assembled and disassembled at the container freight stations, and then delivered to the consignee via land transportation. The export containers generally flow in a similar but reversed direction as shown in Figure 1. Container slot assignment is a preplanning procedure for container stowage both in the vessels and yards. Slot assignment is to allocate container boxes into certain slots. However, most operators assign the slots via experience, thus often cause inefficient usage of slot capacities with unnecessary restowage moves, which are referred to as the "unproductive moves." This represents an increase in operation cost.

Most previous studies on container transportation have emphasized on the economics of the containership or the overall improvement of productivity, loading and unloading of containers between the ships and quaysides in the container terminals. Little attention has been given on container slot management. As to the container stacking operation, the arrival and departure times of individual container should be taken into account. However, pervious related studies have over-simplified the variables that affect the efficiency of container stacking operation. Therefore, their results can only represent the optimization under limited conditions that may neither reduce unproductive moves nor conform to the practical operation.

Studies on container yard operation and management can be classified into three categories:

(1) yard planning and operation strategies; (2) quay crane scheduling and yard crane routing; (3) slot assignment and productivity. Taleb-Ibrahimi et al. (1993) described handling and storage strategies for export containers at marine terminal and quantified their performance according to the amount of space and number of handling moves they required. By using queueing theory their study examined the minimal storage space needed to implement the recommended strategies under given traffic. It was found that to store those containers arrive earlier than their schedule in a dynamic temporary area and to move containers between storage areas in the yard can virtually eliminate the wasted space. Bernardo and Daganzo (1993) developed general expressions for the expected number of moves required to retrieve an import container from storage stacks under two different storage strategies (keep all stack the same size and segregate containers according to arrival time). They suggested that low variability in dwell times of containers favor segregating strategy. Lan and Kao (1998) developed six stacking strategies operated by three kinds of yard equipment (straddle carrier, transtainer, and forklift) and compared their efficiency. The operation times of yard crane includes the time of moving, storing, shuffling and shifting containers. By comparing the average operation times for various stacking strategies, they found equipment moving time has little affect on strategy rankings; while shuffling and shifting time dominates the rankings of stacking strategies.

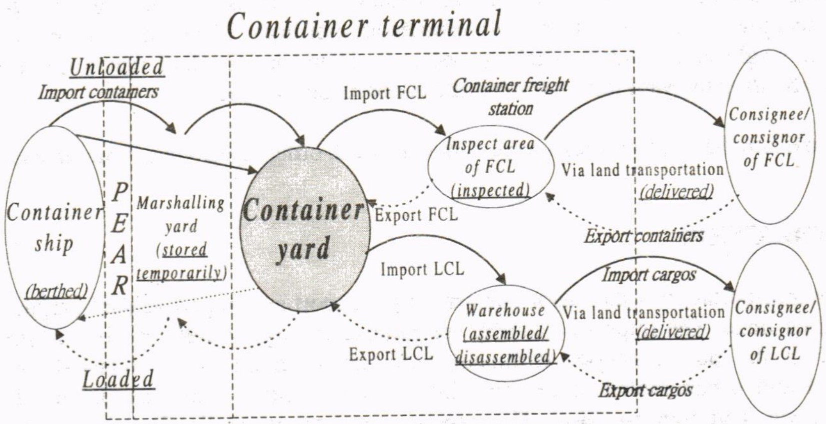

Figure 1. The process of marine container transportation

In the area of crane scheduling and routing, Daganzo (1989), Peterkofsky and Daganzo (1990) suggested that algorithm for assigning quay cranes to container ships is a method that minimize the total delay cost. Their justification is that through the correspondence of yard cranes and quay cranes, the completion time of the individual crane can be about the same. Kim *et al.* (1999) suggested an optimal routing algorithm for a transfer crane during loading operations of export containers at container yard. The routing problem was formulated as a mixed integer programming with objective function to minimize the total handling time of a transfer crane, which included setup time in each yard bay and travel time between yard bays.

Little attention has been given to slot assignment and productivity. Chou *et al.* (1994) tried to construct the intelligent container slot management information system with expert system. Their study provided a more efficient (correct, rapid, reducing container shifting and searching) tool of slot assignment than a rule of thumb method adopted previously. Chen (1999a) classified the operation of container terminal into three sub-systems including ship operation, gate operation, and container storage sub-systems and discussed the unproductive moves in the container yard. He cited that higher container storage did have a serious impact on the number of unproductive moves carried out, and that the major impact was on the operation of container departures. It suggested that terminal operators should maintain a good quality of container information received to reduce the impact of higher container stacking. With the macro point of view, Chen (1999b) compared the land productivity (TEUs/ha) of container yards of the major ports in Asia, Europe and North America and found that the productivity of the port container terminals in Asia was much higher than that in Europe and North America.

This paper attempts to divide the incoming and outgoing containers into two categories--attributes that are known and unknown in advance. Ordered and random stacking strategies are simulated in a container yard that is treated as a single area or divided into twin areas. In order to analyze the influences of ratios of known container attributes on the slot assignment performance, sensitivity scenario analysis is further conducted.

2. SLOT ASSIGNMENT STRATEGIES

In this paper, slot assignment in a single area represents a mixed stacking manner such that all containers are assigned to the same area, ignoring the attributes that are known or not in advance. By contrast, the assignment in twin areas is first to divide the yard into two sub-areas and then to assign the containers of known attributes in one sub-area and assign the ones of unknown attributes in the other. For simplicity, the container attributes are considered only the departure sequence, namely, the departure time of each container. We assume that the initial condition of the yard is empty and that the containers will be assigned on a first-come-first-serve basis. An ordered stacking strategy refers to as stacking the containers in one of the following six orders: column-row-layer, row-column-layer, column-layer-row, row-layer-column, layer-column-row, and layer-row-column. A random stacking strategy indicates stacking containers randomly subject to the condition that any box cannot be stacked in suspension.

Lan and Kao (1998) compared the average operation times for various stacking strategies and found that equipment moving time has little affect on strategy rankings; while box shuffling/shifting time will dominate. In other words, the number of unproductive moves determines the efficiency of a stacking strategy. The number of unproductive moves, in fact, depends upon the containers arrival times, rules of slot selection, and departure times. Among which slot selection is a key factor affecting the stowage efficiency. A general rule of thumb for slot selection is that the containers at upper layers should depart earlier than those at the lower layers to avoid shuffling/shifting moves. However, this criterion very often cannot be met in practice and thus inevitably creates unproductive moves.

2.1 Ordered Stacking Strategy

In this paper, six stacking orders are considered: column-row-layer, row-column-layer, column-layer-row, row-layer-column, layer-column-row, and layer-row-column. The column-row-layer stacking order is to select slots beginning with the first column through the last column in the first row and first layer and ending with the last column in the last row and last layer. This stacking order will first search for the columns holding the row and layer unchanged, and then do the same searches holding the layer unchanged, and then complete the searches until the last layer is reached. The remaining five stacking orders follow the same searching algorithm but vary only with searching orders. The general algorithm of such ordered stacking strategy is shown in Figure 2, which can be explained as the following procedures.

Step 1: Search for all vacant slots that will not cause suspension assignment while container arrives.

Step 2: Sort all the vacant slots according to the reversed sequence of stacking order (e.g. the sorting order for column-row-layer is layer first, then row, then column.)

Step 3: Select a slot in the sorted order.

Step 4: Compare the departure time of designated container with the departure time of lower layer container.

Step 5: If the departure time of upper container is earlier, slot is assigned to the designated container; otherwise, skip the slot and go back to step 3. If there is no suitable slot for arriving container after comparing all the sorted slots, select the slot by using minimum or maximum rule. Stop. The minimum (maximum) rule indicates that summation of the differences between the designated container departure time and the lower-layer departure times are minimized (maximized).

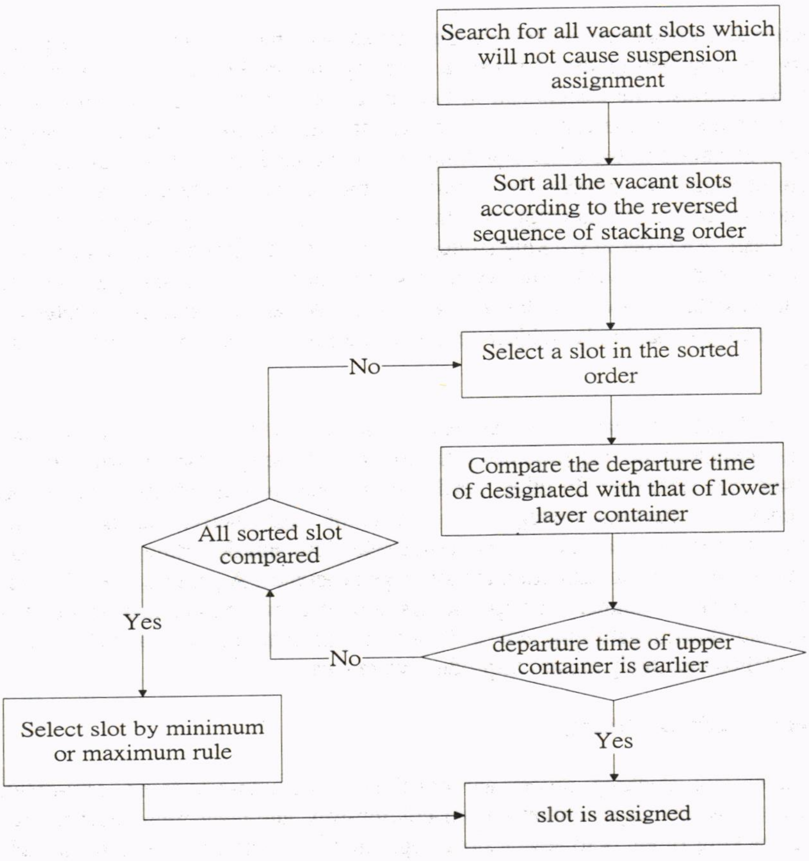

Figure 2. Algorithm of ordered stacking strategy

2.2 Random Stacking Strategy

Unlike ordered stacking strategy that must follow one of the above-mentioned six stacking orders, a random stacking strategy will choose the vacant slots in random as long as any box is not stacked in suspension. The general algorithm of random stacking is shown in Figure 3, which can be explained as the following procedures.

Step 1: Search for all vacant slots while container arrives.
Step 2: Cluster the vacant slots by layer.
Step 3: Select one slot at lower layers in random.
Step 4: Compare the departure time of designated container with the departure time of lower layer container.
Step 5: If the departure time of upper container is earlier, slot is assigned to the designated container; otherwise, go back to step 3. If there is no suitable slot after n iterations, select the slot in random. Stop.

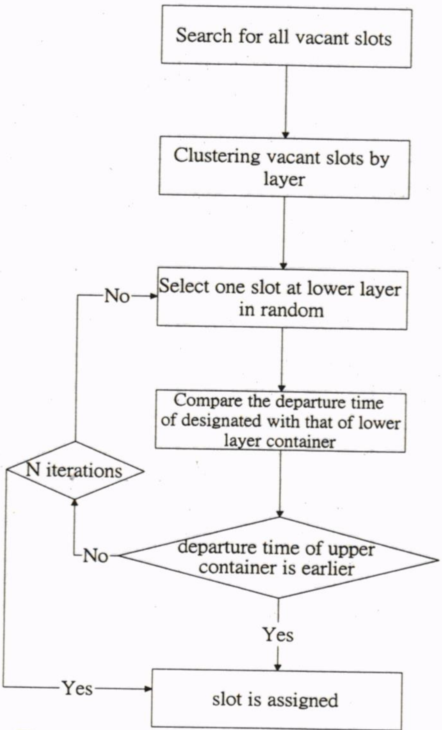

Figure 3. Algorithm of random stacking strategy

3. THE SIMULATION DATA

There are 150 containers to be assigned in the yard. Before they depart, no new containers arrive in this simulation analysis cycle. Each container must arrive and depart during the analysis cycle. The arrival and departure of each container are treated as individual events, thus there will be 300 events in total as illustrated in Table 1. Assume that the container yard has 90 slots with 3 columns, 10 rows, and 3 layers. Also assume that the slots are all vacant initially. Only 20-ft containers are considered and a single transtainer is operated. When shuffling and shifting moves occur, containers are transferred away from the original slot to a temporary space and then restored back to the original row and column. The temporary storage space is assumed always available.

Table1 The simulation data

Container	Sequence		Container	Sequence		Container	Sequence		Container	Sequence		Container	Sequence	
	Arr.	Dep.		Arr.	Dep.		Arr.	Dep.		Arr.	Dep.		Arr.	Dep.
C001	1	41	C031	31	32	C061	76	201	C091	126	257	C121	177	241
C002	2	42	C032	33	142	C062	77	200	C092	127	256	C122	178	240
C003	3	43	C033	34	143	C063	78	199	C093	128	255	C123	179	283
C004	4	44	C034	35	144	C064	79	198	C094	129	269	C124	180	223
C005	5	45	C035	36	145	C065	80	197	C095	130	270	C125	181	222
C006	6	46	C036	37	170	C066	81	196	C096	131	268	C126	182	221
C007	7	66	C037	38	169	C067	82	195	C097	132	267	C127	183	220
C008	8	65	C038	39	168	C068	83	194	C098	133	266	C128	184	219
C009	9	64	C039	40	167	C069	84	193	C099	134	265	C129	185	298
C010	10	63	C040	47	166	C070	85	192	C100	146	264	C130	202	271
C011	11	62	C041	48	165	C071	86	191	C101	147	263	C131	203	300
C012	12	61	C042	49	164	C072	87	141	C102	148	262	C132	204	299
C013	13	60	C043	50	163	C073	88	272	C103	149	261	C133	205	297
C014	14	59	C044	51	162	C074	89	273	C104	150	260	C134	206	218
C015	15	91	C045	52	161	C075	90	277	C105	151	233	C135	207	217
C016	16	92	C046	53	113	C076	101	276	C106	152	232	C136	208	216
C017	17	93	C047	54	114	C077	102	275	C107	153	231	C137	209	215
C018	18	94	C048	55	119	C078	103	274	C108	154	234	C138	210	287
C019	19	97	C049	56	118	C079	104	227	C109	155	236	C139	211	288
C020	20	96	C050	57	117	C080	105	226	C110	156	235	C140	212	289
C021	21	95	C051	58	116	C081	106	225	C111	157	239	C141	213	290
C022	22	100	C052	67	115	C082	107	230	C112	158	238	C142	214	296
C023	23	99	C053	68	120	C083	108	229	C113	159	237	C143	224	295
C024	24	98	C054	69	121	C084	109	228	C114	160	282	C144	244	294
C025	25	135	C055	70	122	C085	110	251	C115	171	281	C145	245	293
C026	26	136	C056	71	186	C086	111	252	C116	172	280	C146	246	292
C027	27	137	C057	72	187	C087	112	253	C117	173	279	C147	247	291
C028	28	138	C058	73	188	C088	123	254	C118	174	278	C148	248	286
C029	29	139	C059	74	189	C089	124	259	C119	175	243	C149	249	285
C030	30	140	C060	75	190	C090	125	258	C120	176	242	C150	250	284

Note: 'Arr.' is the arrival sequence of containers; 'Dep.' is the departure sequence of containers. In this simulation, the arrival or departure times are represented by the sequence.

4. SIMULATION RESULTS IN A SINGLE AREA

4.1 Ordered Stacking Strategy

The simulation results for ordered stacking strategies in a single area are shown in Table 2. It is found that completely known departure sequences has overwhelmed the case that departure sequences are completely unknown in advance, no matter what stacking orders being utilized. Similarly, selecting slots by the "minimum rule" will obtain less unproductive moves than by the "maximum rule" for each of the six stacking orders. In the case of completely known attributes, both layer-column-row and layer-row-column stacking orders obtain the minimum unproductive moves, which agrees to the study of Lan and Kao(1998).

Notice that the numbers of unproductive moves are all the same if one swaps the stacking orders by column and by row without being intervened by layer. This finding indicates that column and row can be viewed as one dimension in the space vector so that one can reduce the dimensions in slot assignment. The above results imply that strategy of "stack as high as possible" should be employed when departure sequences of containers are known in advance and that strategy of "stack the same size" should be used when departure sequences of containers are unknown. This implication also agrees to the suggestions by Bernardo and Daganzo (1993).

Table 2 Unproductive moves for ordered stacking in a single area unit : moves

Container attributes / Stacking orders	Departure sequences known in advance		Departure sequences unknown in advance
	"Minimum rule"	"Maximum rule"	
Layer-column-row	19	44	175
Layer-row-column	19	44	175
Row-column-layer	48	69	84
Column-row-layer	48	69	84
Row-layer-column	52	65	135
Column-layer-row	32	71	107

4.2 Random Stacking Strategy

Random stacking strategy is simulated by comparing the unproductive moves as well as CPU times for different scenarios by varying the ratios of known container attributes from 0%, 30%, 50%, 80%, to 100% and varying the maximum slot selection iterations N from 2, 4, 6, 8, to 10 times. However, in the case of 0% known attributes, there are no departure sequences to be compared, N is thus set equal to 1. Consequently, the total number of scenarios is 21. For each scenario we conduct 50 simulation runs and summarize the average CPU times, the minimum, maximum, average, and standard deviation of unproductive moves as shown in Table 3.

Notice that if the ratios of known attributes increase, the number of unproductive moves will decrease. For instance, the average number of unproductive moves is around 20 for 100% known attributes while it grows as high as 70 for 30% known attributes. We also notice that the unproductive moves decline as the maximum slot selection iterations (N) increase. In the case of 80% known attributes, the average number of unproductive moves is around 60 for 2 iterations while it declines as low as 34 for 10 iterations.

Figure 4 through Figure 7 represent the details of cumulative times occurred for unproductive moves at various maximum slot selection iterations (N) for 100%, 80%, 50%, and 30% known attributes, respectively. We notice that N has the most significant influence on the number of unproductive moves for 100% known attributes; while N becomes less and less significant as the ratios of known attributes decrease.

Table 3 Simulation results for random stacking in a single area (50 simulation runs)

Ratios of known attributes	Max. slot selection iterations (N)	CPU times (seconds/run)	Number of unproductive moves (moves)			
			Minimum	Maximum	Average	Standard deviation
0%	1	11.32	60	89	74.46	6.59
30%	2	11.54	59	86	73.34	7.11
	4	11.68	56	83	71.38	7.06

Ratios of known attributes	Max. slot selection iterations (N)	CPU times (seconds/run)	Number of unproductive moves (moves)			
			Minimum	Maximum	Average	Standard deviation
	6	11.62	58	85	69.66	6.46
	8	11.64	54	81	70.98	6.62
	10	11.78	60	90	70.88	7.33
50%	2	11.48	54	87	69.66	6.84
	4	11.66	45	78	62.50	6.53
	6	11.76	50	71	61.74	5.26
	8	11.90	52	71	59.82	4.36
	10	11.82	45	72	59.20	6.38
80%	2	11.58	50	72	60.96	5.85
	4	11.86	35	63	49.54	6.40
	6	12.10	31	52	41.48	4.42
	8	12.26	24	46	35.98	4.29
	10	12.38	20	44	34.84	4.73
100%	2	11.42	45	70	56.10	6.44
	4	11.76	26	56	38.16	5.47
	6	12.04	19	43	29.26	5.22
	8	12.28	14	36	23.20	4.87
	10	12.58	11	33	20.88	5.14

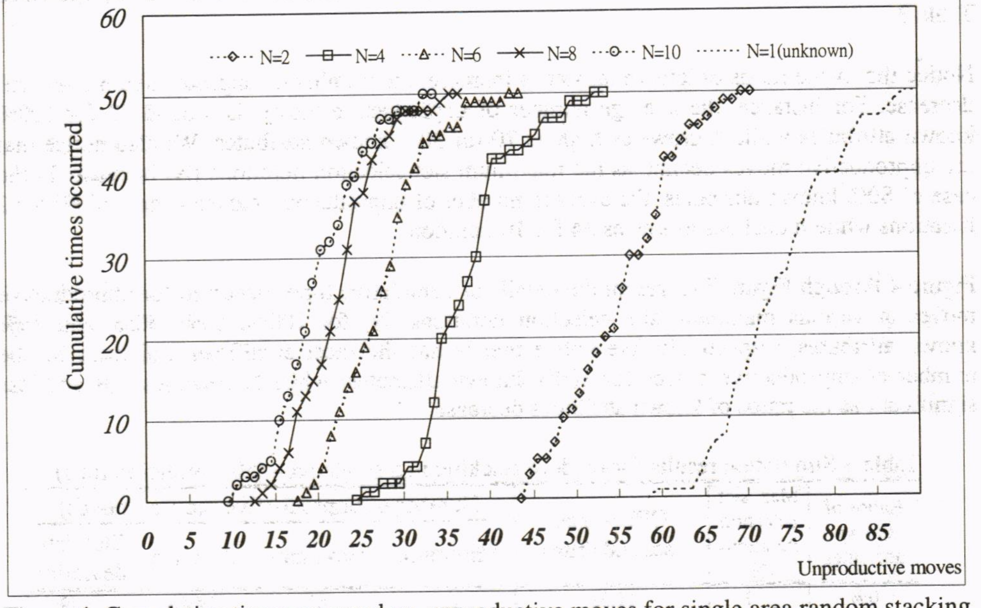

Figure 4. Cumulative times occurred vs. unproductive moves for single area random stacking (100% known attributes)

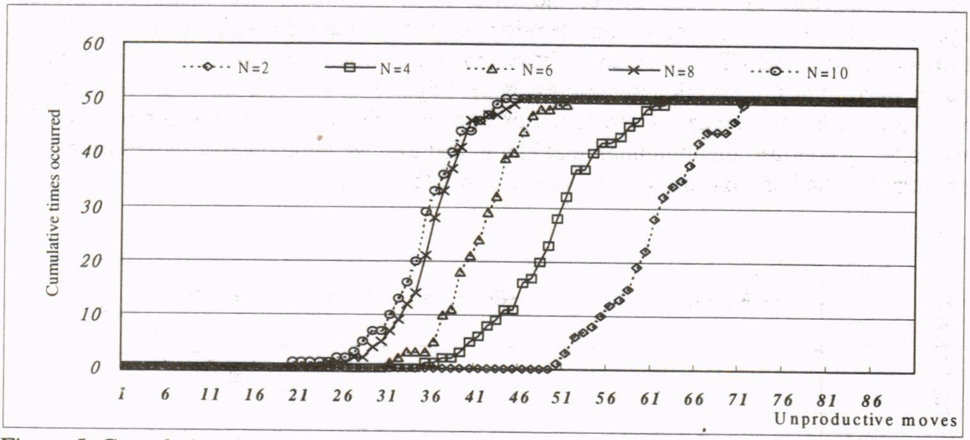

Figure 5. Cumulative times occurred vs. unproductive moves for single area random stacking (80% known attributes)

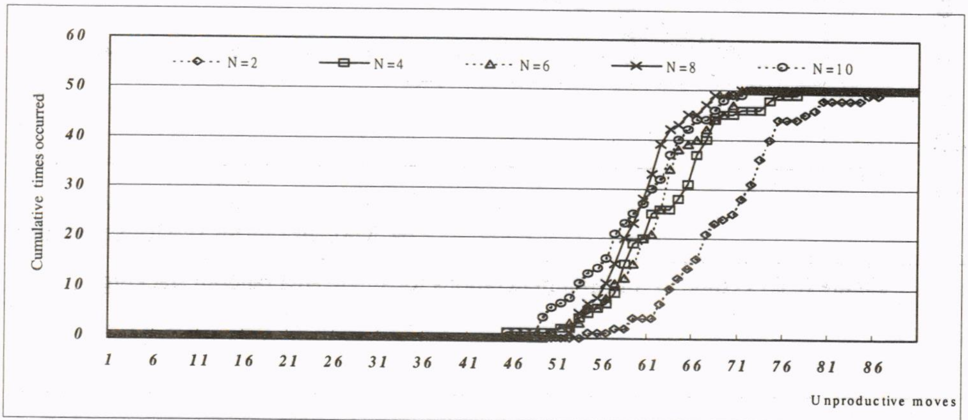

Figure 6. Cumulative times occurred vs. unproductive moves for single area random stacking (50% known attributes)

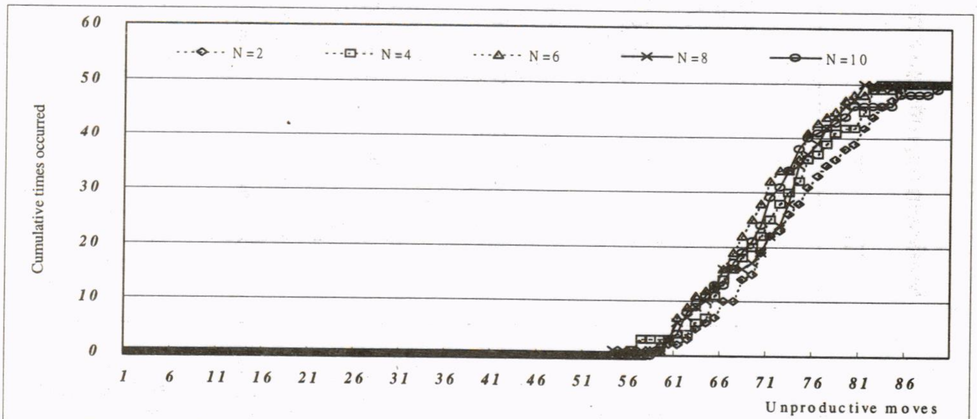

Figure 7. Cumulative times occurred vs. unproductive moves for single area random stacking (30% known attributes)

Figures 8 through 11 further depict the CPU time, minimum, maximum, and average unproductive moves versus maximum iterations of slot selection for various ratios of known attributes. Notice that CPU times do not vary drastically when the ratios of known attributes and the maximum slot selection iterations change. Slightly longer CPU times are required due to more comparisons made, as the ratios of known attributes or the number of iterations increases. By contrast, the minimum, maximum, and average unproductive moves drop more sensitively as the iterations or ratios of known attributes increase.

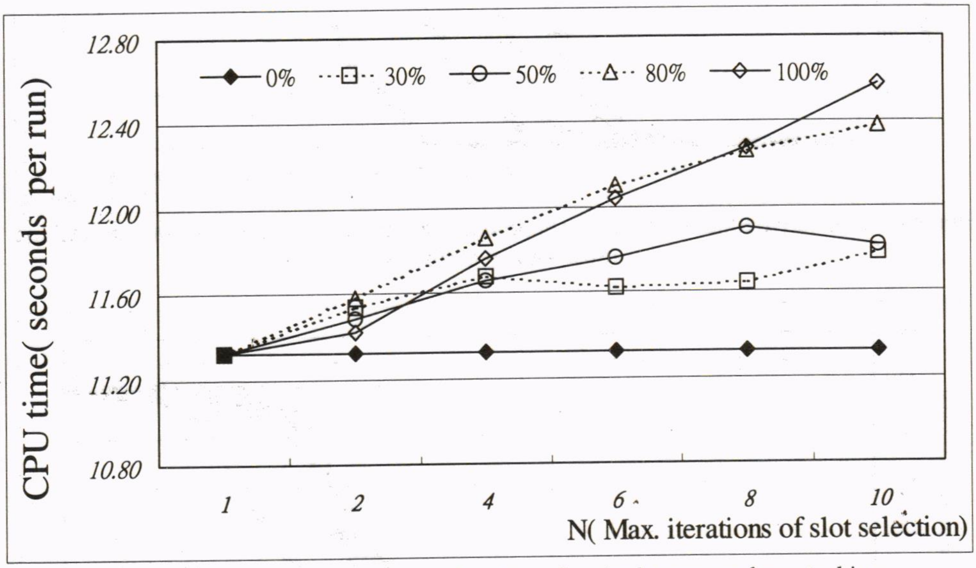

Figure 8. CPU time vs. maximum iterations for single area random stacking

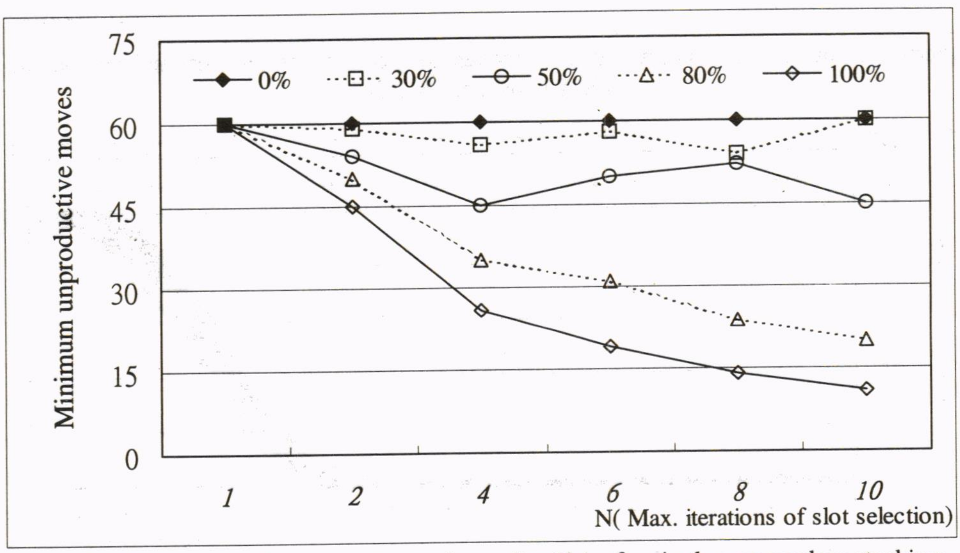

Figure 9. Min. unproductive moves vs. maximum iterations for single area random stacking

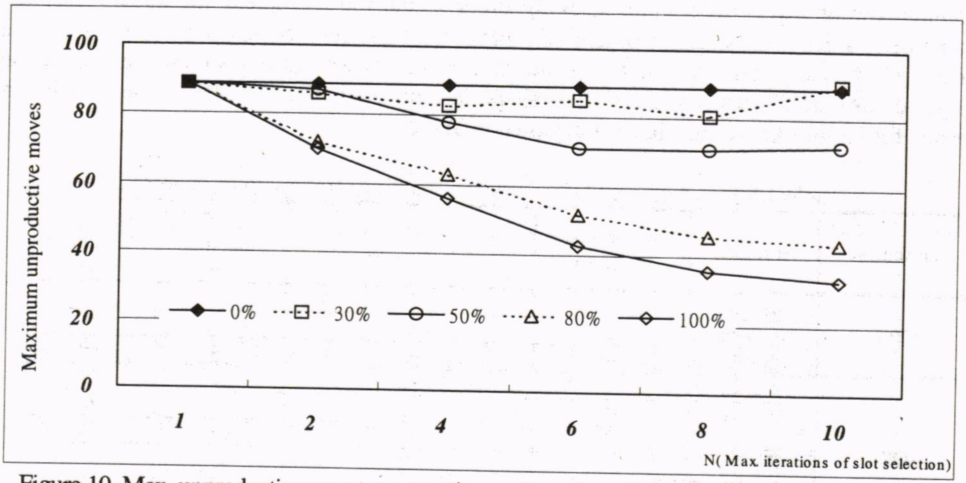

Figure 10. Max. unproductive moves vs. maximum iterations for single area random stacking

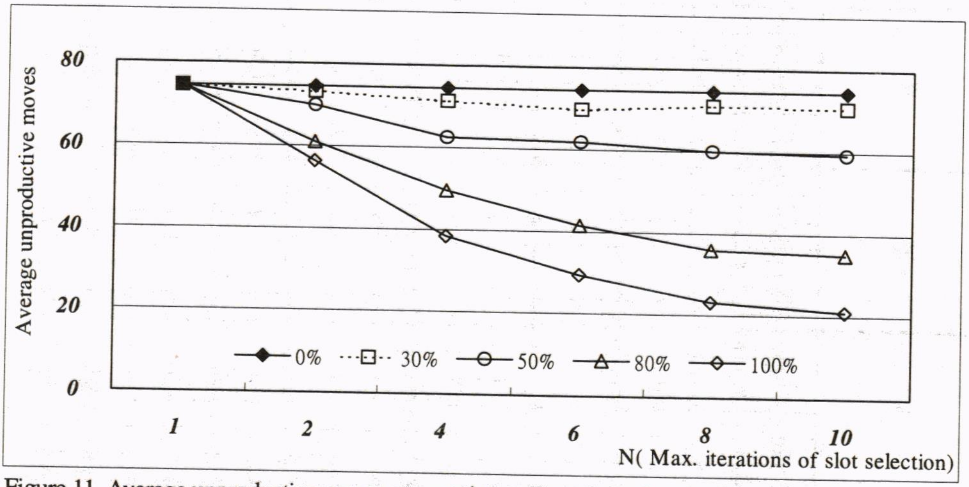

Figure 11. Average unproductive moves vs. maximum iterations for single area random stacking

5. SIMULATION RESULTS IN TWIN AREAS

In order to reduce reposition moves, Taleb-Ibrahimi *et al.* (1993) proposed a concept of "roughpile" to stacking the early arrival containers – those arriving too early to find empty available slots. This paper follows such a concept and attempts to divide the container yard into two sub-areas. Containers with known attributes will be assigned in one sub-area while the other sub-area temporarily accommodates the containers with unknown attributes. The number of slots allocated to both sub-areas is proportional to the ratios of known and unknown attributes.

5.1 Ordered Stacking Strategy

The simulation results for ordered stacking strategy in a single area conclude that layer-column-row or layer-row-column stacking order is the most efficient for known attribute containers, since both stacking orders can leave more unoccupied lower-layer slots for the arriving containers than other stacking orders. For the known attributes containers, only the "layer-column-row" ordered stacking strategy is simulated in twin areas. The simulation results for various known attributes are shown in Table 4.

Table 4 Simulation results for ordered stacking strategy in twin areas

Ratios of known attributes	Attributes	Number of slot allocated	Max. number of containers in the yard	Unproductive moves "Maximum rule"	Unproductive moves "Minimum rule"
100%	Known	90	73	44	19
	Unknown	0	0	0	0
	Total	90	73	44	**19**
90%	Known	78	73	55	29
	Unknown	12	8	6	6
	Total	90	81	61	**35**
	Known	81	73	41	25
	Unknown	9	8	11	11
	Total	90	81	52	36
80%	Known	72	72	65	40
	Unknown	18	14	21	21
	Total	90	86	86	61
	Known	75	72	55	30
	Unknown	15	14	27	27
	Total	90	86	82	**57**
70%	Known	66	65	42	30
	Unknown	24	20	38	38
	Total	90	85	80	68
	Known	69	65	31	24
	Unknown	21	20	42	42
	Total	90	85	73	**66**
60%	Known	57	56	35	26
	Unknown	33	25	42	42
	Total	90	81	77	**68**
	Known	60	56	28	18
	Unknown	30	25	52	52
	Total	90	81	80	70
50%	Known	45	41	38	31
	Unknown	45	38	42	42
	Total	90	79	80	73
	Known	48	41	22	17
	Unknown	42	38	48	48
	Total	90	79	70	**65**
40%	Known	36	34	32	31
	Unknown	54	45	47	47
	Total	90	79	79	78
	Known	42	34	15	14
	Unknown	48	45	62	62
	Total	90	79	77	**76**
30%	Known	21	19	17	16
	Unknown	69	61	73	73
	Total	90	80	90	**89**
	Known	27	19	5	7
	Unknown	63	61	84	84
	Total	90	80	89	91

Ratios of known attributes	Attributes	Number of slot allocated	Max. number of containers in the yard	Unproductive moves	
				"Maximum rule"	"Minimum rule"
20%	Known	15	13	12	4
	Unknown	75	64	95	95
	Total	90	77	107	**99**
	Known	18	13	4	3
	Unknown	72	64	102	102
	Total	90	77	106	105
10%	Known	9	8	8	5
	Unknown	81	68	102	102
	Total	90	76	110	**107**
	Known	12	8	2	3
	Unknown	78	68	110	110
	Total	90	76	112	113
0%	Known	0	0	0	0
	Unknown	90	73	84	84
	Total	90	73	84	**84**

By comparing Tables 2 and 4, we notice that in the two extreme situations (attributes that are completely known and completely unknown), the simulation results in twin areas are just the same as those in a single area. From Table 4 we conclude that as the ratios of known attributes increase the unproductive moves decrease, which is further depicted in Figure 12.

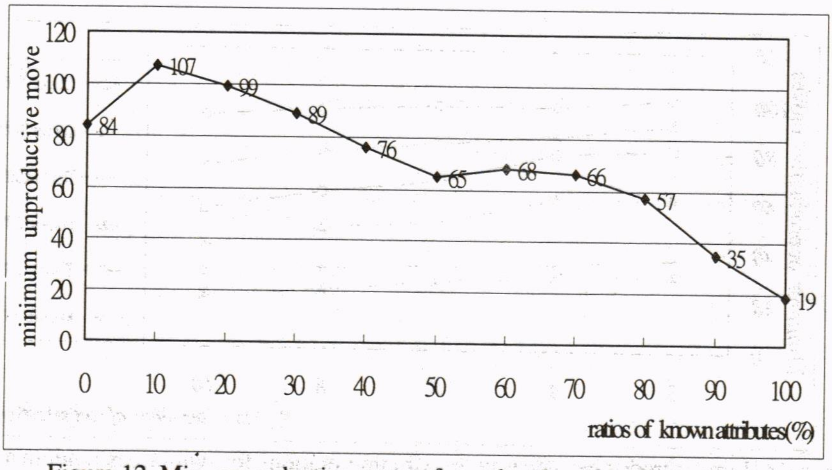

Figure 12. Min. unproductive moves for ordered stacking in twin areas

The simulation also finds that the number of slots allocated to each sub-area would influence the unproductive moves. There is no guarantee that dividing the yard into two sub-areas exactly according to the ratios of known and unknown attributes will obtain the best result. In fact, fine tunes for slots allocation in these two sub-areas may gain efficiency. Figure 13 shows the optimal ratios of slots reserved for known attributes containers. The dotted 45-degree line represents allocating the slots in proportional to the ratios of known attributes; the solid line represents the optimum ratios for allocating the slots in this simulation example. It is found that all the optimum ratios diverge from the 45-degree line except for the 10% known attributes case. While dealing with slots assignment in twin-areas, sketching a chart similar to Figure 13 can be a useful guide for yard planning.

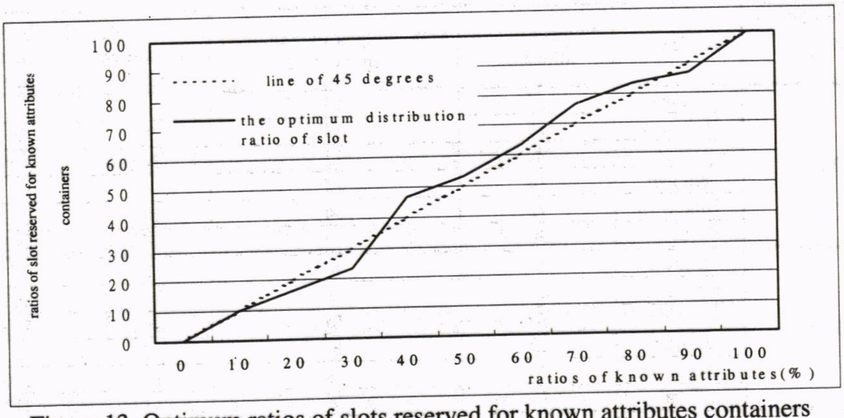

Figure 13. Optimum ratios of slots reserved for known attributes containers

5.2. Random Stacking Strategy

Random stacking strategy in twin areas is simulated as in the single area case, except for the two extremes: attributes completely known in advance (100%) and completely unknown (0%). The total number of scenarios is 15. For each scenario we also conduct 50 simulation runs. The average and minimum unproductive moves for various scenarios are shown in Figure 14 and Table 5.

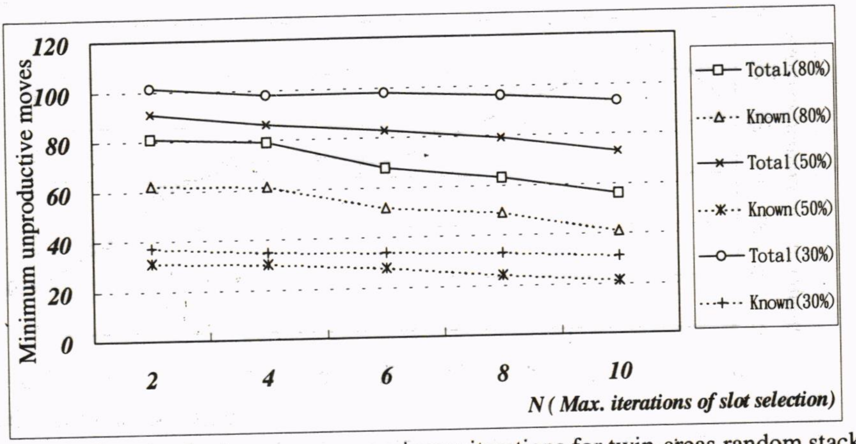

Figure 14. Min. unproductive moves vs. maximum iterations for twin-areas random stacking

Table 5 Simulation results for random stacking strategy in twin areas (50 simulation runs)

Ratios of known attributes	Maximum slot selection iterations (N)	Number of unproductive moves (moves)					
		Average			Minimum		
		Total	Known	Unknown	Total	Known	Unknown
80%	2	85.64	68.68	16.96	81	62	11
	4	84.38	67.84	16.54	79	61	13
	6	74.80	58.12	16.68	68	52	14
	8	71.10	54.36	16.74	63	49	12
	10	67.58	50.46	17.12	**56**	41	13

Ratios of known attributes	Maximum slot selection iterations (N)	Number of unproductive moves (moves)					
		Average			Minimum		
		Total	Known	Unknown	Total	Known	Unknown
50%	2	105.42	38.54	66.88	91	31	50
	4	102.30	34.78	67.52	86	30	49
	6	99.94	33.56	66.38	83	28	48
	8	98.52	32.74	65.78	79	24	49
	10	98.82	31.18	67.64	**73**	21	50
30%	2	113.16	40.82	72.34	101	37	64
	4	110.80	38.92	71.88	98	35	65
	6	106.50	37.14	69.36	98	34	54
	8	105.10	36.38	68.72	96	33	55
	10	104.12	35.98	68.14	**93**	31	59

It is found that total unproductive moves decrease as the ratios of known attributes increase. For higher ratios of known attributes (e.g. 80%), the unproductive moves come mainly from the sub-area with known attributes and the other way around for lower ratios of known attributes such as 30%.

6. COMPARISONS AND CONCLUSIONS

Comparing the results for ordered and random stacking strategies in a single area (Tables 2 and 3), one will find that the best ordered stacking strategy, layer-column-row and layer-row-column stacking orders, is slightly more efficient (has less unproductive moves) than random stacking strategy, provided that all attributes are known in advance. If the departure sequences of all containers are completely unknown in advance, however, random stacking strategy is more efficient than ordered stacking strategy.

Similarly, the simulations results for ordered and random stacking strategies in twin areas (Tables 4 and 5) reveal that ordered stacking is in general superior to random stacking if the ratios of known attributes are not very high. The random stacking strategy may obtain better efficiency only when the ratio of known attributes is more than 80%. This result suggests that random stacking strategy in twin areas be used only when the yard operators have sufficient information about containers in advance.

If one further compares the results of random stacking in a single area and in twin areas (Tables 3 and 5), one will obviously find the performance for single area random stacking is much better than those for twin areas. The main reason is that once the yard is divided into two sub-areas, the freedom of selecting suitable slots for arrival containers will be reduced, as a consequence the unproductive moves increase.

The simulation results for ordered stacking strategies in a single area conclude that selecting slots by the "minimum rule" will obtain more efficiency than by the "maximum rule" for each of the six stacking orders. In the case of completely known attributes, both layer-column-row and layer-row-column stacking orders can obtain the minimum unproductive moves. The numbers of unproductive moves are all the same if one swaps the stacking orders by column and by row without being intervened by layer, implying that column and row can be viewed as one dimension in the slot assignment. For random stacking strategy in a single area, if the ratios of known attributes containers increase, the number of unproductive moves decreases. These results suggest that strategy of "stack as high as possible" be used when departure sequences of more containers are known in advance and that strategy of "stack the same size" be used when departure sequences of more containers are unknown. The number of unproductive moves for single area random stacking operation is much less than that for twin areas, therefore, dividing the yard into two sub-areas is not recommended unless new evidences can be found for further analysis.

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REFERENCES

Bernardo, D.C. and Daganzo, C.F. (1993) Handling strategies for import containers at marine terminal, **Transportation Research -B, Vol. 27, No. 2,** 151-166.

Chen, T. (1999a) Yard operations in the container terminal - a study in the "unproductive moves", **Maritime Policy and Management, Vol. 26, No. 1,** 22-38.

Chen, T. (1999b) Land utilization in the container terminal: a global perspective, **Maritime Policy and Management, Vol. 25, No. 1,** 289-303.

Chou, H.P, Lin, C.H. and Wu, C.T. (1994) The intelligent container slot management information system, **Transportation Planning Journal, Vol. 23, No. 2,** 91-124.

Daganzo, C.F. (1989) The crane scheduling problem, **Transportation Research-B, Vol. 23, No. 3,** 159-175.

Kim, K.H. and Kim, K.Y. (1999) An optimal routing algorithm for a transfer crane in port container terminals, **Transportation Science, Vol. 33, No. 1,** 17-33.

Lan, L.W. and Kao, C.K. (1998) Comparison of stowage efficiency for yard container stacking strategies, **Traffic and Transportation, No. 17,** 69-90.

Peterkofsky, R. I. and Daganzo, C.F. (1990) A branch and bound solution method for the crane scheduling problem, **Transportation Research -B, Vol. 24, No. 3,** 159-172.

Taleb-Ibrahimi, M., Bernardo, D.C. and Daganzo, C.F. (1993) Storage space vs handling work in container terminal, **Transportation Research -B, Vol. 27, No. 1,** 13-32.