An Efficient Heuristic Method for Dynamic Berth Allocation Problem

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Abstract

The bottle neck of Maritime transportation is the time spent by vessels at a Container Terminal (CT). Time is money for the logistic business and hence the time spent by a vessel at the CT results in major part of losses for the customer: transport companies. As a result, they strive for shorter stay time at CT. In order to survive in the competition by satisfying their customers every CT works on minimizing the Turnaround Time of Vessel (TTV). The TTV varies across all berths. Therefore, allocation of vessel to berth in order to minimize the TTV is the prime objective of the CT. Thus, this study focuses on dynamic Berth Allocation Problem (BAP), considering discrete berth layout. A mixed integer linear programming (MILP) model is proposed with the objective of minimizing the total finish time of all vessels. Further, a simple heuristic method (HM), based on early-to-finish strategy, for generating a feasible solution is developed. Finally, the quality of the solution obtained from the proposed HM is compared with the exact solution obtained from the proposed MILP model on 10 problem instances and observed empirically that the proposed HM provides efficient/optimal solutions in almost all the 7 instances.

Keywords
Container Terminal, Turnaround Time of Vessel, Berth Allocation Problem, Mixed Integer Linear Programming Model, Heuristic Method

1. Introduction

Transportation of goods over long distances is the need of the hour. Among all the means of transport, waterway transport of goods is considered the most effective means across global markets though it has longer transportation times (TGAL,2021). A container terminal (CT) is a facility which acts as an interface for transport of goods in the form of standardized containers between water and land. The transport companies act as customers to the CT. Every CT strives to increase its performance to attract maximum customers. To achieve higher performance level, optimal usage of resources (like berths, quay cranes, transport vehicles etc.), reduction in operational cost and minimizing the handling time are necessary for the CT.

The decision of berth allocation to the vessel has a major role in improving the performance of the CT (Ursavas, 2015). The reason to this is that the duration of stay of the vessel at CT highly depends on the allocation of the berth to the vessel. In addition to this, if the available berths are utilized efficiently then the capacity of the berth will increase without physically constructing extra berth (Park and Kim,2003). Theoretically, the berth allocation problem (BAP) is proved to be NP hard. Hence, use of other solution approaches like greedy heuristics or metaheuristics is an alternative approach for BAP. With this, the aim of this study is to propose an efficient heuristic method for Berth Allocation Problem (BAP) to minimize the total finish time to of all vessels arriving at CT.

The remainder of this paper is organised as follows. Section 2 reviews the closely related literature pertaining to BAP. In Section 3, problem configuration, the assumptions, and the calculation of expected handling time are discussed. Section 4 presents the proposed mathematical model. Further, a simple heuristic is presented in Section 5. A computationalexperiment displaying the comparison between the mathematical model and proposed heuristic is provided in Section 6. Finally, the concluding remarks are presented in Section 6.

2. Related Review

There are number studies addressing BAP. The BAP problems can be classified based on (a) berth-layout, (b) arrival pattern of the vessel, (c) handling time of the vessel, and (d) performance measure. Based on the layout of berth, BAP can be classified as discrete, continuous or hybrid. In discrete berth layout, each berth serves one vessel at a time and there is partition among different berths. The continuous berth layout signifies that there is no specific boundary or partition that separates different berths and they are arranged on a continuous space (Dulebnets et al.,2018). In hybrid layout, two vessels can be accommodated at one berth, or one large vessel can occupy two berths (Umang et al., 2013).

The second classification is about arrival pattern of the vessels viz. static, dynamic, cyclic and stochastic. When the vessels to be served have already arrived at the terminal before berth planning starts is termed as static BAP (Emde et al.,2014). In a dynamic situation, some vessels may arrive during the planned horizon (Dulebnets et al., 2018). If the arrival of vessels repeats at equal interval of time, then the arrival pattern is assumed to be cyclic (Zhen and Chang, 2012). In the case of stochastic interval time, the arrival pattern of the vessel follows a distribution (Ursavas and Zhu, 2016).

The handling time of vessel depends on allocation of berth to that vessel, but it also serves as one of the major inputs to a BAP problem. The handling time of the vessel is assumed to be either deterministic or stochastic. Many studies have assumed deterministic handling time and very few have considered uncertainty in handling time and propose a robust model for BAP (Ursavas and Zhu, 2016). Another way of classifying BAP is based on the performance measure. Accordingly, there are various studies consider either single performance measure or multiple performance measures while deciding the berth allocation. It can be broadly classified as time related (for e.g. completion time of vessel) or cost related performance measures (for e.g. cost occurred due to departure delay) and CT related (for e.g. handling time of vessel) or transport company related (for e.g. satisfaction regarding berthing order).

The solution methods used to solve BAP in literature can be summed up into three categories viz. exact methods, heuristics, and metaheuristics. Exact methods are computationally hard to solve but they provide optimal solutions. In exact method, solution approaches used to solve BAP are Lagrangian Relaxation, Branch and Bound method, etc. Whereas both heuristics (Boile et al., 2006, Xu et al., 2012, Lin et al., 2014) and metaheuristic apply rules to achieve decent quality solutions with satisfactory computation time. Various metaheuristics such as genetic algorithm, particle swarm optimization, simulated annealing etc. are used to solve BAP.

In this study, we intend to consider BAP with handling time (which is dependent on berth position), discrete berth layout, and dynamic arrival pattern. The objective of the study is the minimization of finish time of all vessels. We derive handling time of vessel from available data for modelling purpose. We propose a Mixed Integer Linear Programming Model (MILP) model for the BAP. Due to computational intractable reason, we develop a simple heuristic for addressing BAP. From the analysis of the literature, to the best of our knowledge, it is observed that the problem configuration considered in this study is not studied so far.

3. Problem Statement

This study considers discrete berthing positions that are allocated to the arriving vessels.We are given total 'NV' vessels and 'NB' berths that are available for the service. Each vessel is allocated to exactly one berth k. The vessels arrive at expected arrival time denoted as EATV(i) and is known well in advance. The expected handling time of the vessel (EHTV(i,k)) is known and can be computed. The vessel starts its service at STV(i) and finishes at FTV(i). The objective of allocation of berth to the vessel is to minimize the finish time of all vessels. Furthermore, the decision on berth allocation considered in this study has the following assumptions:

- There is no delay in the arrival of the vessel.
- All the berths are available at time t=0.
- The processing of the vessel happens at only one berth. The vessel cannot be shifted to another berth amid service.
- The vessel leaves the CT only after completion of the service.
- The expected handling time of the vessel depends on the position of the berth assigned.

- We do not consider any disruption or breakdown of the handling equipment during the service.
- A vessel may arrive at any time during the planning horizon but is serviced only after its arrival.
- All vessels are eligible for allocation at any berth.

The expected handling time of vessel is one of the important parameters in the solution methodology as it has a major influence on the finish time of the vessel. From the literature review, we observe that the studies related to BAP have used the expected handling time of the vessel as a known parameter. Contrary we propose a method to calculate the handling time with the help of various vessel related data available in the real-life scenarios. The details on the derivation of the handling time of the vessel are as follows:

3.1 Derivation of the handling time

The vessel's expected handling time (EHT) is the total time taken at the CT to unload and load the containers. Therefore, expected handling time is computed by breaking it down into several components and added at the end. In practice, the unloading process and the loading process happens one after the other. The containers' unloading process consists of lifting the containers using quay cranes (QC) from the vessel and transferring them to the transport truck (TT). Further, the TT carries the container to the yard area. The straddle carrier (SC) lifts the container from the TT and stacks the containers in the yard area. The containers' loading process is in the reverse order. Hence, the unloading/loading process constitutes three major tasks viz. EHT associated with I. QC, II. TT and III. SC. The systematic representation of HT components is shown in Figure 1.

The time taken to transport the container from berth to yard/ yard to berth requires the distance travelled by the TT. The CT layout shown in Figure 2 is used for the calculation of distance travelled by TT. It gives a rough idea of the movement of TT. We consider that every CT has such a layout, which is useful to calculate the distance travelled by the TT. The layout consists of 3 berths and 10-yard positions. The dimensions of the CT layout are in meters. We assume that the container handling equipment viz. QC, TT and SC work at their actual capacity. For simplicity, we assume each berth is equipped with one QC and infinite TT. The later part ensures no idle time at the berth/yard area.The flow of TT is as per the CT layout and has to be maintained strictly.The TT's speed is assumed lesser while handling a container compared to an empty truck.

In the unloading process the containers which belong to a particular yard are grouped together as the number of unloading containers from vessel 'V' to yard 'Y' (NUC_{VY}). Similarly, for the loading process, the number of loading containers from yard 'Y' to vessel 'V' is referred as NLC_{YV}. The capacities of the TT with and without carrying containers are denoted as AST and ASTE. The flow of TT is in one direction. Hence, the distances from berth 'B' to yard 'Y' (D_{BY}) and distance from yard 'Y' to berth 'B'(D_{YB}) are different. Actual Speed of QC at berth 'B' ($ASQC_B$) and Actual Speed of SC at yard 'Y' ($ASSC_Y$) are calculated as percentage of design capacities. The expression for expected HT of vessel 'V' at berth 'B'($EHTV_{VB}$) is as follows:

$$\mathrm{EHTV}_{VB} = \frac{\sum_{\mathrm{Y}} \mathrm{NUC}_{\mathrm{VY}}}{\mathrm{ASQC}_{\mathrm{B}}} + \frac{\sum_{\mathrm{Y}} \mathrm{NUC}_{\mathrm{VY}} * \mathrm{D}_{\mathrm{BY}}}{\mathrm{AST}} + \frac{\sum_{\mathrm{Y}} \mathrm{NUC}_{\mathrm{VY}} * \mathrm{D}_{\mathrm{YB}}}{\mathrm{ASTE}} + \sum_{\mathrm{Y}} \frac{\mathrm{NUC}_{\mathrm{VY}}}{\mathrm{ASSC}_{\mathrm{Y}}} + \sum_{\mathrm{Y}} \frac{\mathrm{NLC}_{\mathrm{YV}}}{\mathrm{ASSC}_{\mathrm{Y}}} + \frac{\sum_{\mathrm{Y}} \mathrm{NLC}_{\mathrm{YV}} * \mathrm{D}_{\mathrm{BY}}}{\mathrm{ASTE}} + \frac{\sum_{\mathrm{Y}} \mathrm{NLC}_{\mathrm{YV}} * \mathrm{D}_{\mathrm{YB}}}{\mathrm{AST}} + \frac{\sum_{\mathrm{Y}} \mathrm{NLC}_{\mathrm{YV}}}{\mathrm{ASQC}_{\mathrm{B}}}$$

4. Proposed Mathematical Model

In this section, we develop a mathematical model for the underlying BAP problem. As the number of berths is fewer than number of vessels, some vessels have to wait in the queue. The mathematical model uses expected arrival time of vessel and expected handling time of the vessel as input parameters. The output of the model provides information about the allocation of berth to the vessel, starting time of service of vessel. The mathematical model is the basic discrete dynamic BAP model.

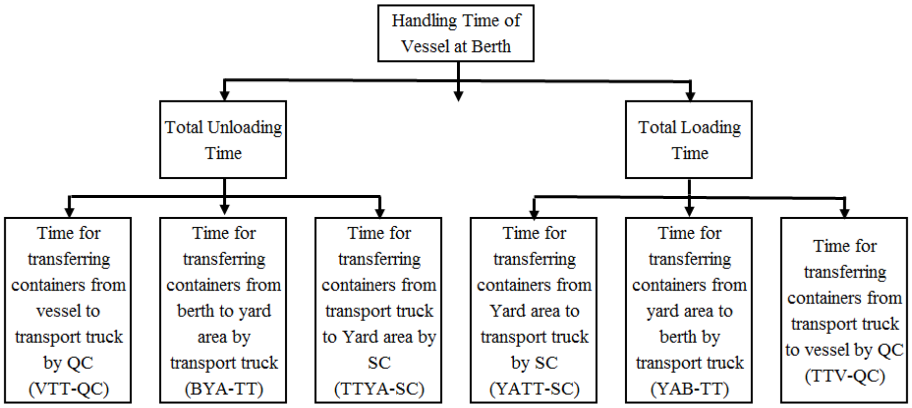

Figure 1 Components of HT

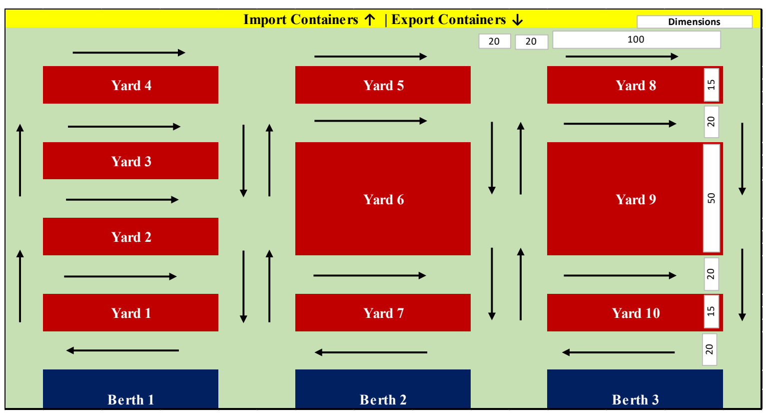

Figure 2 A CT Layout

4.1 Mathematical Model

$$\text{Minimize FT} = \sum_{i} \text{STV(i)} + \sum_{i}\sum_{k} \text{EHTV(i, k)} * \text{AVB(i, k)} \qquad \text{... (1)}$$

$$\sum_{k} \text{AVB(i, k)} = 1 \qquad \forall\, i \in \text{NV} \qquad \text{... (2)}$$

$$\text{STV(i)} \geq \text{EATV(i)} \qquad \forall\, i \in \text{NV} \qquad \text{... (3)}$$

$$\text{STV(j)} \geq \text{STV(i)} + \text{EHTV(i)} - \text{BIG M} * \{1 - \text{SOTVB(i, j, k)}\} \qquad \forall\, i, j \in \text{NV} \cap i \neq j, \forall\, k \in \text{NB} \qquad \text{... (4)}$$

$$\text{SOTVB(i, j, k)} + \text{SOTVB(j, i, k)} \leq 0.5 * \{\text{AVB(i, k)} + \text{AVB(j, k)}\} \qquad \forall\, i, j \in \text{NV} \cap i < j, \forall\, k \in NB \qquad \text{... (5)}$$

$$\text{SOTVB(i, j, k)} + \text{SOTVB(j, i, k)} \geq \{\text{AVB(i, k)} + \text{AVB(j, k)} - 1\} \qquad \forall\, i, j \in \text{NV} \cap i < j, \forall\, k \in NB \qquad \text{... (6)}$$

$$\text{SOTVB(i, j, k)} = \{0,1\} \qquad \forall\, i, j \in \text{NV} \cap i < j, \forall\, k \in NB \qquad \text{... (7)}$$

$$\text{AVB (i, k)} = \{0,1\}, \text{STV (i)} \geq 0$$

Where,

AVB (i,k)	=1	if Allocation of Vessel 'i' at berth 'k'
	=0	otherwise
SOTVB (i,j,k)	=1	if vessel 'i' is assigned before vessel 'j' at berth 'k'. It is Sequence Of Two Vessels at Berth.
	=0	otherwise

Objective (1) minimizes the summation of total finish time of all the vessels. Constraint (2) ensures that each vessel should be allocated to exactly one berth. Constraint (3) makes sure that the service of a vessel starts only after its arrival. Constraint (4) ensures that the service of a vessel should start only after the completion time of immediately previous vessel allocated to that berth. Constraint (5) and (6) are used to decide the sequence of the two vessels allocated at the same berth. Constraint (7) assigns binary values to the variable that decides the sequence of the two vessels at same berth.

A LINGO set Code is developed to generate the above proposed MILP model for any given data. Due to the brevity of the paper size the LINGO set code is not presented in the paper.

5. Proposed Heuristic Algorithm

The main idea behind the heuristic is that it allocates the vessel on a first-to-finish basis. The heuristic first calculates the possible finish time of vessels at all the berths.Further it searches for the least possible finish time and allocates the berth to the vessel. However, if there is a tie, then it checks for the difference between the two smaller finish time of the vessel and chooses the vessel with maximum difference. The next step is to calculate the start time of the vessel, finish time of the vessel and next available time of the berth. Finally, it increases the possible finish time of allocated vessel as a large number to avoid repeated allocations. The step-by-step procedure of the proposed heuristic is as shown in Figure 3 and the same is implemented in Python.

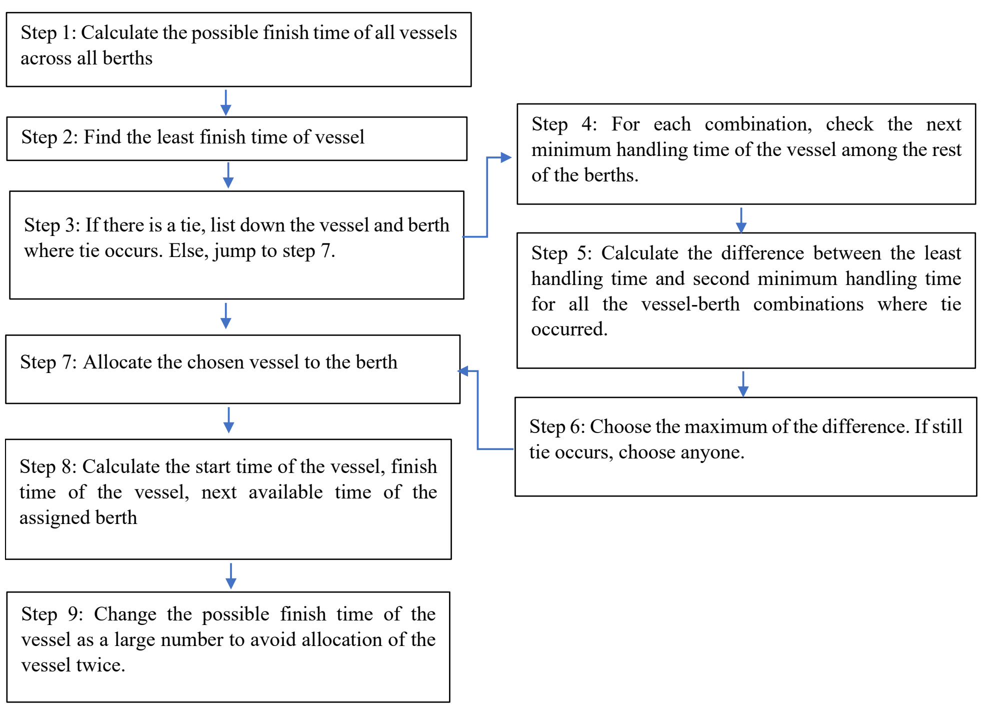

Figure 3 The procedure for proposed heuristic

6. Computational Experiment

We randomly generated 10 small scale problem instances for the BAP defined in this study. Due to the brevity of the paper size, one of the complete numerical examples is presented in Annexure 1 along with the given data for the numerical example.Furthermore, the walkthrough of the proposed heuristic is given in Annexure 2, considering the numerical example presented in Annexure 1. The optimal solution and the heuristic solution obtained for the numerical example presented in Annexure 2. In addition, optimal solution and the heuristic solution obtained for each of the 10 problem instances using the proposed MILP model and the proposed heuristic method are given in

Table 1, respectively. For each of the 10 problem instance, the obtained results are presented in Table 1. From Table 1, it is observed that out of 10 instances, the proposed heuristic method yielded optimal solution for 7 instances.

Table 1 Comparison of result obtained by 10 problem instances

Sr no.	LINGO Solution	Heuristic Solution	Relative % Deviation
1	95	95	0
2	90	90	0
3	89	90	1.12
4	90	90	0
5	83	83	0
6	90	92	2.22
7	76	76	0
8	108	108	0
9	87	87	0
10	90	91	1.11

7. Conclusion

Almost all the studies on BAP assume that the expected handling time is given. In this study a method for estimating the handling time of the vessels is proposed. Considering the estimated handling time of vessels,a MILP model and a simple heuristic method are proposed at address BAP. There are 10 numerical examples are randomly generated to reflect the problem configuration defined in this study. Each of the 10 instances are solved using both the proposed MILP and heuristic method. Out of 10 instances, the proposed heuristic method yielded optimal solution for 7 instances. When the number of vessels and number of berths increase, it is difficult to use the proposed MILP model as benchmark procedure. So, developing a lower bound is one of the immediate research directions for the problem considered in this study. Furthermore, proposing a few more simple heuristics to meta heuristics are additional interested future research issues for the problem considered in this study.

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Biographies

Ms. Ankita is pursuing integrated PhD in Department of Management Studies at Indian Institute of Science (IISc), Bangalore, after completing BE mechanical. Her research interest focuses on Container Terminal (CT) Logistics in general, particularly on operational decisions in Container Terminals. Her on-going research is focused on development of a new and efficient methodology for Berth Allocation Problem of CT Logistics.

M. Mathirajan obtained his PhD in Operations Management and MS degree by research in Applied Operations Research (OR) from IISc, Bangalore. He also received his MSc in Mathematics from Madurai Kamaraj University and Postgraduate Diploma in OR from College of Engineering, Guindy, Anna University. He has been working as faculty of IISc Bangalore since 1986 and currently serving as a Chief Research Scientist since 2013. He is a Fellow of Operational Research Society of India (FORSI). His areas of research interest include mathematical/heuristic optimization and research methods for operations and supply chain management, sequencing and scheduling, personnel scheduling, routing and scheduling of logistics, urban road transport, and container terminal logistics problems.

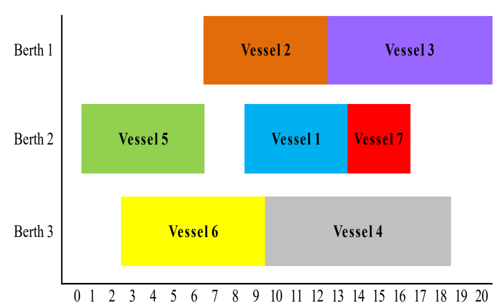
Annexure 1: A Numerical Example

Vessel	EATV	EHTV		
		Berth		
		1	2	3
1	9	5	4	9
2	7	5	10	10
3	12	8	10	9
4	4	9	9	9
5	1	10	5	12
6	3	10	6	6
7	12	12	3	7

Annexure 2

Solution obtained for the Numerical example using MILP and the Proposed Heuristic Algorithm

Vessel	EATV	STV	Allocated Berth	EHTV	FTV
2	7	7	1	5	12
3	12	12	1	8	20
5	1	1	2	5	6
1	9	9	2	4	13
7	12	13	2	3	16
6	3	3	3	6	9
4	4	9	3	9	18



A Graphical Representation of Berth Allocation obtained from the MILP and the Proposed Heuristic Algorithm

Annexure 2: A Walkthrough of the Proposed Heuristic Algorithm for the numerical example presented in Annexure 1

#	Possible Finish Time			Least Value	Tie occurred?	CV	Allocation Matrix			STV [CV]	FTV [CV]	FT [B]	Crossing out the Chosen Vessel		
Step	1			2	3	7				8			9		
	14	13	18				0	0	0	0	0		14	13	18
	12	17	17				0	0	0	0	0		12	17	17
	20	22	21				0	0	0	0	0	0	20	22	21
1	13	13	13	6	No	5	0	0	0	0	0	6	13	13	13
	11	6	13				0	1	0	1	6	0	M	M	M
	13	9	9				0	0	0	0	0		13	9	9
	24	15	19				0	0	0	0	0		24	15	19
	14	13	18				0	0	0	0	0		14	13	18
	12	17	17				0	0	0	0	0		12	17	17
	20	22	21				0	0	0	0	0	0	20	22	21
2	13	15	13	9	No	6	0	0	0	0	0	6	13	15	13
	M	M	M				0	1	0	1	6	9	M	M	M
	13	12	9				0	0	1	3	9		M	M	M
	24	15	19				0	0	0	0	0		24	15	19
	14	13	18				0	0	0	0	0		14	13	18
	12	17	19				1	0	0	7	12		M	M	M
	20	22	21				0	0	0	0	0	12	20	22	21
3	13	15	18	12	No	2	0	0	0	0	0	6	13	15	18
	M	M	M				0	1	0	1	6	9	M	M	M
	M	M	M				0	0	1	3	9		M	M	M
	24	15	19				0	0	0	0	0		24	15	19
	17	13	18				0	1	0	9	13		M	M	M
	M	M	M				1	0	0	7	12		M	M	M
	20	22	21				0	0	0	0	0	12	20	22	21
4	21	15	18	13	No	1	0	0	0	0	0	13	21	15	18
	M	M	M				0	1	0	1	6	9	M	M	M
	M	M	M				0	0	1	3	9		M	M	M
	24	15	19				0	0	0	0	0		24	15	19
	M	M	M				0	1	0	9	13		M	M	M
	M	M	M				1	0	0	7	12		M	M	M
	20	23	21				0	0	0	0	0	12	20	23	21
5	21	21	18	16	No	7	0	0	0	0	0	16	21	21	18
	M	M	M				0	1	0	1	6	9	M	M	M
	M	M	M				0	0	1	3	9		M	M	M
	24	16	19				0	1	0	13	16		M	M	M
	M	M	M				0	1	0	9	13		M	M	M
	M	M	M				1	0	0	7	12		M	M	M
	20	26	21				0	0	0	0	0	12	20	26	21
6	21	25	18	18	No	4	0	0	1	9	18	16	M	M	M
	M	M	M				0	1	0	1	6	18	M	M	M
	M	M	M				0	0	1	3	9		M	M	M
	M	M	M				0	1	0	13	16		M	M	M
	M	M	M				0	1	0	9	13		M	M	M
	M	M	M				1	0	0	7	12		M	M	M
	20	26	27				1	0	0	12	20	20	M	M	M
7	M	M	M	20	No	3	0	0	1	9	18	16	M	M	M
	M	M	M				0	1	0	1	6	18	M	M	M
	M	M	M				0	0	1	3	9		M	M	M
	M	M	M				0	1	0	13	16		M	M	M