

## Sorting multi-bay block stacking storage systems<sup>☆</sup>

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### ABSTRACT

Autonomous mobile robots (AMRs) are increasingly deployed in intralogistics to automate warehouse operations. A key advantage of AMRs is their continuous availability, enabling them to operate during off-peak hours. This work addresses the multi-bay unit-load pre-marshalling problem (MUPMP), an extension of the unit-load pre-marshalling problem to larger, more realistic warehouse environments with multiple bays. Unit-load pre-marshalling leverages off-peak time intervals to sort a block stacking warehouse in anticipation of future orders. These larger warehouse configurations require not only the minimization of the number of moves but also the consideration of time when making sorting decisions. Our step-based approach first determines the access direction for each stack, then finds a sequence of short-time moves to sort the warehouse. For the move search, we compare a time-efficient A\* algorithm with a solution-optimal constraint programming approach. Further, we extend the multi-bay unit-load pre-marshalling problem to multiple AMRs. We introduce an additional routing step that assigns the pre-marshalling moves to a fleet of AMRs, minimizing either travel time or makespan. The results demonstrate that the presented approach is able to efficiently find and allocate the necessary reshuffling moves to transfer a multi-bay block stacking system into a blockage-free state using multiple AMRs.

### 1. Introduction

Block stacking storage systems are a very simple and widely used type of warehouse. Unit loads like pallets, boxes, containers, or movable shelves are placed on the ground and may be stacked on top of each other. The advantage of block storage is that it does not require high investments in infrastructure, is highly flexible, and easily scalable. Fig. 1 shows an example of a block stacking warehouse with four bays separated by aisles for traveling. Each bay contains unit loads. Dependent on the available access directions and the properties of the unit load, access to the outermost stacks from up to four cardinal directions is possible.

The use of autonomous mobile robots (AMRs) for material handling allows to increase the storage density by utilizing a shared storage policy and rearrangement operations that are difficult to implement by human operators. The reason is the high availability of AMRs, also during off-peak hours, and their accurate information on the storage system state. AMRs could rearrange the storage during idle time and prepare it for a future demand sequence that may be derived from

a production schedule or truck loading time slots. For example, a supplier receives orders from customers until late at night. Based on these orders the truck loading times for the next day are calculated. A fleet of AMRs sorts the warehouse the same night to speed up the loading process the next morning.

In Pfrommer et al. (2024), we introduced this problem as unit-load pre-marshalling problem (UPMP). This work is the continuation of this paper, extending the problem to a larger multi-bay setup and hence to a much wider range of applications. Extending the scope to multiple bays requires not only a highly efficient solution approach but also additional features like the consideration of travel times of the AMRs. To solve the multi-bay unit-load pre-marshalling problem (MUPMP) we propose a two-step approach. First, a network flow model determines the access direction of each slot in the warehouse minimizing the number of misplaced unit loads. Second, an A\* algorithm searches for short-time moves to sort the warehouse.

One of the key characteristics of block-stacking warehouses is that pre-marshalling operations are typically carried out by a fleet of AMRs

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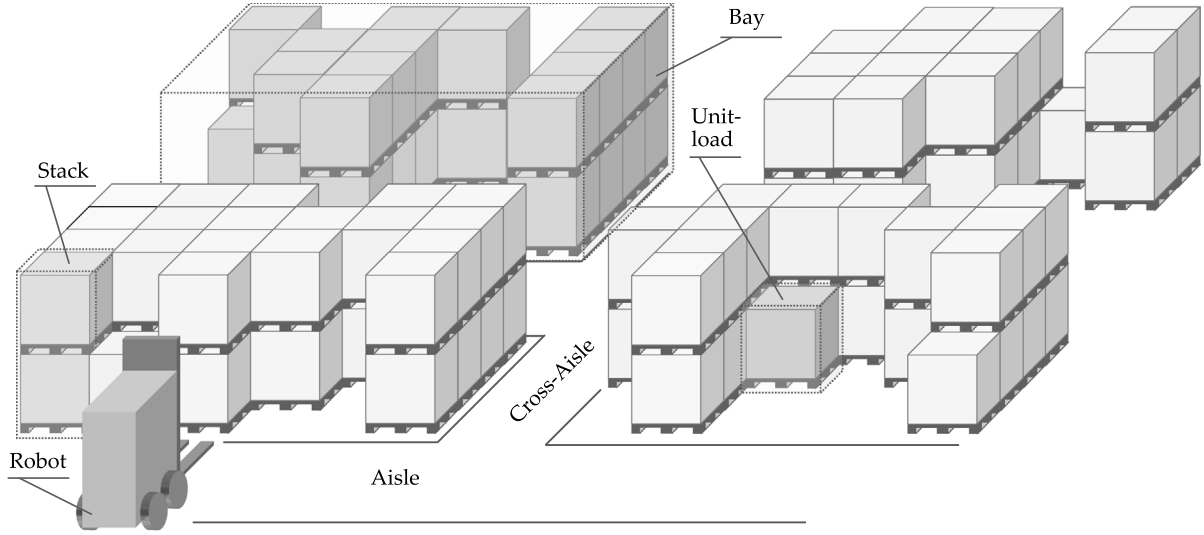


Fig. 1. Example of a block stacking warehouse with a robotic forklift.

rather than a single AMR. To address this, we introduce an additional routing step that assigns the pre-marshalling moves to multiple AMRs. To solve the resulting multi-robot and multibay unit-load pre-marshalling problem (MR-MUPMP), we employ a mixed-integer programming model that allocates the moves to the AMRs with the objective of minimizing either total travel time or makespan. This model was originally introduced in preliminary form in the conference proceedings by Bömer et al. (2024). In this paper, we provide a more comprehensive description and extended analysis of the routing step.

The main contributions of this paper are:

1. We formally introduce the MUPMP and MR-MUPMP with up to four access directions.
2. We show that our two-step solution approach for the UPMP can be applied to solve the MUPMP with little modifications.
3. We further introduce an optimal constraint programming (CP) approach for the second step to evaluate our heuristic tree search approach.
4. We introduce an additional third routing step to efficiently assign the moves to a fleet of AMRs while avoiding collisions to solve the MR-MUPMP.
5. We show that the approaches can solve real-world size instances and publish the benchmark datasets.

This paper is structured in the following main sections. We commence this paper with an introduction of the MUPMP and MR-MUPMP in Section 2 followed by a brief literature review in Section 3. Subsequently, we introduce the step-based solution approach in Section 4 and conduct a series of experiments presented in Section 5. Finally, we provide a summary and outlook in Section 6.

## 2. The multi-bay unit-load pre-marshalling problem

This section presents a formal description of the MUPMP. The MUPMP is about sorting a block stacking warehouse of multiple bays until all blockages are resolved. In addition, we introduce an extension of the problem, the MR-MUPMP, which includes the assignment of pre-marshalling moves to multiple AMRs. Similar to the UPMP for a single bay, we assume that the AMRs are idle and that no unit loads are entering or leaving the storage system.

Fig. 2 shows the state representation of a block stacking warehouse. The warehouse consists of a set of bays  $B = \{1, \dots, |B|\}$ . The bays are interconnected via aisle space for traveling. Let  $\mathcal{Y}$  be the set of access directions. Each bay  $b \in B$  can be accessed from up to four access directions. For the four access direction case  $\mathcal{Y} = \{\text{north}, \text{east}, \text{south}, \text{west}\}$ .

Let  $C = \{1, \dots, |C|\}$  be the set of columns,  $\mathcal{R} = \{1, \dots, |\mathcal{R}|\}$  be the set of rows, and  $\mathcal{T} = \{1, \dots, |\mathcal{T}|\}$  be the set of tiers per bay  $b$ . Unit loads are stored in slots. The slots are located within a bay  $b$  in a three-dimensional grid with columns  $c \in C$ , rows  $r \in \mathcal{R}$ , and tiers  $t \in \mathcal{T}$ . A slot can be identified by  $s_{b,r,c,t}$ . The slot  $s_{b,r,c,t+1}$  can only be occupied if  $s_{b,r,c,t}$  is occupied to prevent floating unit loads.

Let  $Q = \{0, 1, \dots, |Q|\}$  be the set of priority classes. Each unit load is assigned to a specific priority class. The priority class of the unit load in slot  $s_{b,r,c,t}$  is  $g_{b,r,c,t} \in Q$ . A priority class of zero is assigned to empty slots. The priority class is derived based on a known (e.g., planned truck arrivals or production schedule) or predicted (e.g., based on material supply precedence graph or demand forecast) future retrieval time. A unit load with a smaller priority class will be retrieved before a unit load with a larger priority class. Hence, we refer to a smaller priority number as a higher priority class (1 is the highest priority class).

Slots are accessed from access points, which form entry points to the bay. Let  $\mathcal{P} = \{1, \dots, |\mathcal{P}|\}$  be the set of access points. The access point  $p \in \mathcal{P}$  is located in the aisle space in front of a bay. Only slots in a straight line can be reached from an access point. Turning inside a bay is not possible. This representation with access points is more detailed than just defining the allowed access directions, as also partial access via one access direction can be modeled, which may be necessary due to pillars, for example.

Fig. 3 shows an example of a warehouse with access points. The purple dots indicate possible access points from aisle space to the bay. This example allows access from all four cardinal directions. The distance between the access points is calculated as the Manhattan distance. A downside of using such a static Manhattan distance matrix between all access points is that possible diagonal shortcuts through unused storage space in case of low fill levels are not considered, as it may lead to overestimated travel distances. Travel times are assumed to be proportional to these distances, with acceleration and deceleration effects being neglected.

The objective of pre-marshalling is to reach a state in which each unit load can be accessed from at least one access point without encountering a blocking unit load. Only unit loads accessed from the same access point can hinder access to each other. In the following, we assume unit loads that are accessed from the access point as pictured in Fig. 4. Unit loads are *blocking* when they have a lower priority class (higher number) compared to the unit loads that are placed underneath or behind. Further, unit loads are *indirectly blocking* when they are placed on top or in front of a blocking unit load regardless of their priority class. Indirectly blocking unit loads must be relocated to access blocking unit loads. Blocking and indirectly blocking unit loads are

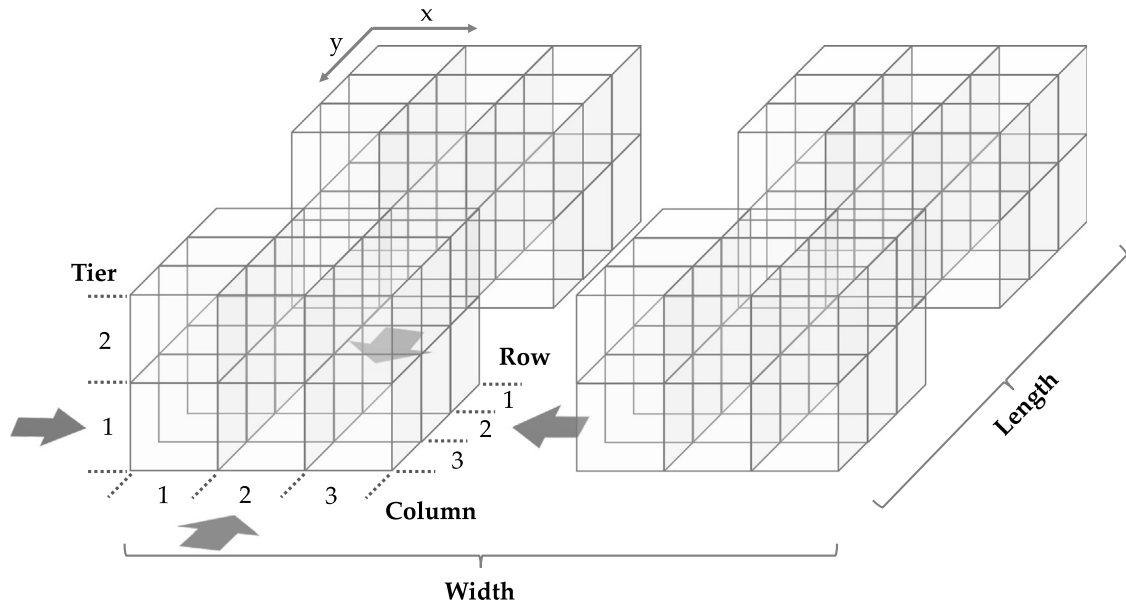


Fig. 2. State representation with four bays of the multi-bay block stacking warehouse.

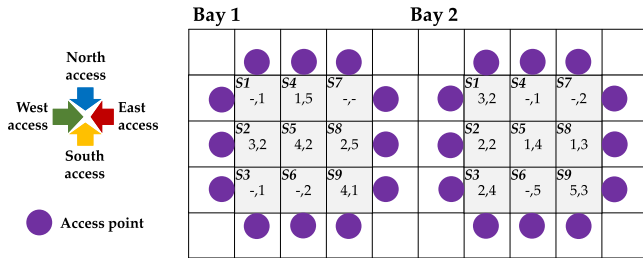


Fig. 3. Example of a warehouse configuration with two bays and possible access points.

referred to as *misplaced* unit loads. Fig. 4 displays an example for two three-tier stacks filled with the priority classes:  $[[0, 5, 1][3, 2, 2]]$ . Both stacks are accessed from the same access point. The unit loads with priority classes five and three are blocking. The unit load with priority class one is indirectly blocking. All misplaced unit loads need to be moved if no other access point assignment with fewer misplaced unit loads is available.

To resolve blockages reshuffling *moves* must be performed. A move defines the process of picking up a unit load from one slot and dropping it off in another slot. The moves are operated by forklift type AMRs. This restricts the moves as follows: Firstly, an AMR can only move one unit load at a time. Secondly, only the unit load in the outermost and then uppermost occupied slot can be picked up. Unit loads placed below or behind another unit load are not accessible (see Fig. 5(a)). Thirdly, the unit load can only be dropped off in the innermost and then lowermost unoccupied slot assigned to an access point. It is not allowed to leave an empty slot between the outermost unit load and the newly placed unit load if both slots are accessed from the same access point (see Fig. 5(b)).

The example in Fig. 6(a) shows a warehouse configuration containing two square bays of the same size with  $|R| = 3$ ,  $|C| = 3$ , and  $|T| = 1$  that can both be accessed from all four directions. It is filled with unit loads of priority classes from one to five that are specified on top of each load. Fig. 6(b) switches the perspective to the top view with white tiles for empty/aisle space and dark gray tiles for unit loads. The bold red digits are the unit loads that are potentially misplaced and blocking the center unit load of the bottom bay depending on the access

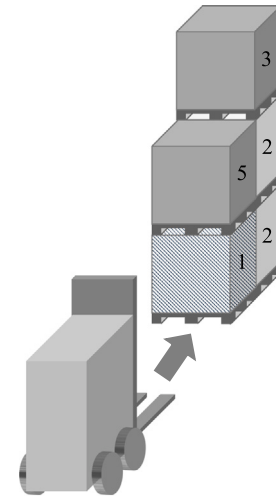


Fig. 4. Representation of two stacks accessed from the same access point. The coloring highlights blocking (dark gray) and indirectly blocking (hatched) unit loads.

direction of the center unit load. The decision to access the center unit load with priority class one from the north leaves the unit load with priority class three as the only misplaced unit load. A red-dotted arrow indicates a possible move to resolve the blockage. Relocating one of the other potentially misplaced unit loads would also be possible, but it requires a longer loaded move time. Fig. 6(c) shows the resulting sorted configuration.

Each reshuffling move operated by an AMR consists of: unloaded move time, handling time (pick-up), loaded move time, handling time (drop-off), and (optional) waiting time. The *loaded move time* is the time required to travel the distance from the pick-up access point to the drop-off access point; the *unloaded move time* is the time required to travel to the next move's pick-up access point; the *handling time* is the time it takes for the pick-up or drop-off process; and the *waiting time* is the time a robot has to wait for another robot to finish a process to respect dependencies between moves. Dependencies between moves exist if two reshuffling moves contain the same access point for pick-up or drop-off. To avoid collisions only one AMR can access point to

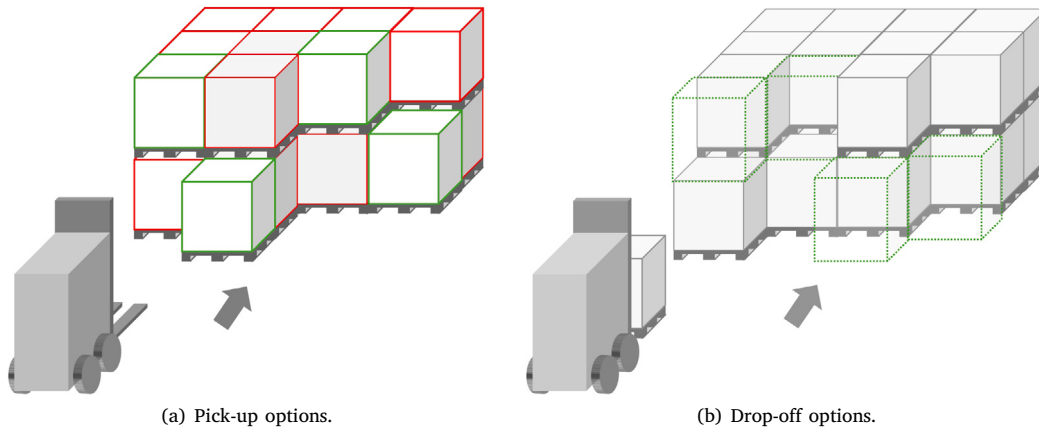


Fig. 5. Pick-up and drop-off slot options for a two-tier single bay marked in green if all slots are accessed from the south access direction.

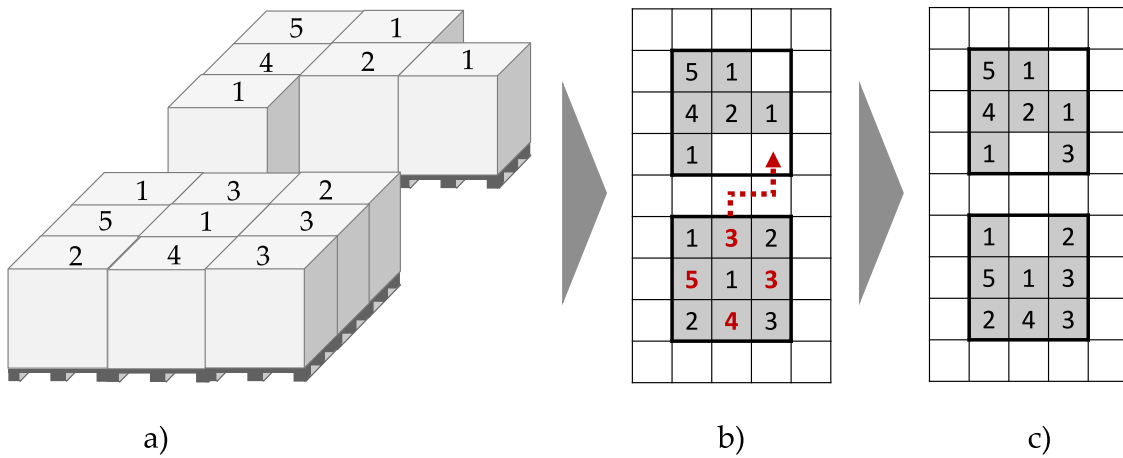


Fig. 6. Example configuration in (a), top view of the grid-based layout and red arrow for a possible move in (b) and solution in (c).

perform a reshuffling move. The aisles are assumed to be wide enough for bidirectional traffic.

Whereas in case of the UPMP, the goal was solely to find a minimum number of moves to sort a bay such that there is no blockage, in case of large warehouses in the MUPMP time must be considered. The MUPMP follows the primary objective to sort the warehouse with the minimum number of moves and as the secondary objective, the loaded move time is minimized. To handle complexity we solve the MUPMP in two steps: First, we select a fixed access direction for each slot minimizing the number of misplaced unit loads. Second, we search for the minimal number of reshuffling moves with a short loaded move time.

In industry, warehouses are often operated by multiple AMRs. When the reshuffling moves required to solve the MUPMP are executed by multiple AMRs, we refer to this as the MR-MUPMP. The primary objective of the MR-MUPMP, as in the MUPMP, is to minimize the total number of reshuffling moves. In this study, we consider two secondary objectives: travel time and makespan. The travel time objective promotes a resource-efficient reshuffling process, while the makespan objective seeks to return the warehouse to a sorted state as quickly as possible. The assignment of AMRs to reshuffling moves must satisfy the constraint that only one AMR can access a given unit load from a specific access point at any time, in order to avoid collisions. Consequently, handling times for pick-up or drop-off operations involving the same access point may not overlap. Aisles are assumed to be wide enough for two AMRs to pass each other without interference.

The MUPMP and MR-MUPMP increase the scope to a variety of storage applications considering not only a single bay but larger multi-bay

warehouses. Hence, the MUPMP and MR-MUPMP are a generalization of the UPMP in [Pfrommer et al. \(2024\)](#). In the case of bays that can only be accessed from one access direction and are one-tier high, the MR-MUPMP can be reduced to the container pre-marshalling problem (CPMP) and is thus also NP-hard ([Caserta et al., 2011](#)). Bays with more than one access direction require further investigation on the complexity.

### 3. Related work

The literature review presents related publications focusing on rearrangement activities for multi-bay setups as well as the minimization of crane travel time. For an overview of single-bay pre-marshalling literature, we refer to [Pfrommer et al. \(2024\)](#).

#### 3.1. Multiple bays

In maritime transportation, the rearrangement of containers across multiple bays is known as the remarshalling problem (RMP). Similar to unit-load pre-marshalling, the goal is to sort the scattered containers based on their retrieval priority with a minimum number of moves until all blockings are resolved ([Caserta et al., 2011](#)). Different problem definitions exist for RMP, which the following literature review shows. It is important to note that, in maritime transportation, a bay corresponds to a lane in the warehouse context, while a block in maritime settings is equivalent to a bay in the warehouse context.

An early publication by [Kim and Bae \(1998\)](#) deals with the RMP and converting the current configuration of multiple bays into a target configuration. Instead of the exact position of each container, the bay configuration is defined simply as the number of containers per group that are located within each bay. The group is a collection of containers going to the same destination on the same vessel. The problem is divided into two sub-problems: (1) bay matching and move planning and (2) sequencing the moving tasks. In the first step, dynamic programming and an approach referred to as “transportation algorithm” are used to determine the flow and movement between bays to reach the target configuration. Second, the task sequencing problem is modeled as a traveling salesperson problem (TSP) with precedence constraints to consider space availability at the destination bay, with the goal of minimizing travel time. Because the exact positions of the containers are neglected in the bay configuration, the rehandling of containers within a bay is not addressed in this work.

Later publications take exact container positions into account and investigate the intra-block RMP where containers are sorted based on categories and retrieval priorities. In successive publications, [Kang et al. \(2006\)](#) and [Choe et al. \(2011\)](#) investigate the RMP where, starting from a source, bay containers are relocated to an empty target bay so that no rehandling is necessary either during the rearrangement process or later in the ship loading process. Interference between multiple cranes is taken into account. Both publications present a similar two-phase solution approach that couples a simulated annealing algorithm for finding a target configuration and partial order graph with crane scheduling to determine a minimum-time re-marshalling plan.

[Park et al. \(2009\)](#) study the RMP in a container terminal with two cranes. Whereas one crane is used for loading containers from the storage yard on the vessel (seaside), the second crane is used to carry in containers from external trucks (landside). The goal of their solution is to bring containers from the landside of the storage yard to the seaside where the ship loading happens and, at the same time, sort the containers based on their retrieval priority. Therefore, the authors propose a two-step algorithm: First, potential stacks where the containers will be moved are selected heuristically. Second, an algorithm is used to conduct an alternating search to solve the two sub-problems of determining target slots that are assigned to each container as well as the order of container movements.

Further approaches deal with rearrangement activities to improve the location of containers whenever one of the cranes is temporarily idle (called “housekeeping” ([Kemme, 2012](#), p 148) or “iterative rescheduling”), where the re-marshalling jobs that most reduce future loading times are selected with the objective of minimizing current delay times as well as the overall makespan ([Choe et al., 2015](#)). Besides re-marshalling before a ship is loaded (export terminal), re-marshalling activities may also be performed after unloading a ship (import terminal) before containers are retrieved (e.g., to external trucks). The works of [van Asperen et al. \(2013\)](#) and [Covic \(2017\)](#) investigate this type of re-marshalling problem where container departure times are reported by a truck announcement system.

The presented research for the RMP with multiple bays deals with a variety of use-case-specific problems (e.g., moving containers to an empty target bay) using relaxing assumptions to simplify the problems. As a result, these solutions are not directly applicable to our problem.

A recent study by [Jiménez-Piqueras and Tierney \(2025\)](#) bridges this gap by proposing a CPMP extension that allows for limited inter-bay relocations via an auxiliary bay. This new variant, CPMP-AB, enables containers to be moved to a neighboring bay during the pre-marshalling process. A constraint programming model is introduced to solve the CPMP-AB. Their experiments demonstrate that CPMP-AB significantly reduces relocations, while remaining adaptable to yard constraints. This study represents a first step toward extending classical pre-marshalling methods into multi-bay environments without requiring crane mobility across the entire block. However, the assumptions, such as restricting relocations to a single adjacent bay and disregarding crane travel times, limit the applicability to warehouse settings. In block-stacking warehouses, unit loads can be moved freely between any bays, making the CPMP-AB model less directly transferable to such environments.

### 3.2. Minimization of crane times

Besides the aforementioned publications that specifically address rearrangement operations between multiple bays, there are also solution approaches of the CPMP considering crane times for the rearrangement of containers in a single bay. Instead of minimizing moves, [Parreño-Torres et al. \(2020\)](#) address the minimization of crane times for the pre-marshalling of containers. The authors propose an integer linear model that builds upon ([Parreño-Torres et al., 2019](#)) as well as a branch and bound algorithm, which is set up as an iterative deepening search. Besides the lower bound from [Tanaka et al. \(2019\)](#), a novel lower bound incorporating the travel time, as well as a heuristic algorithm for an upper bound for the number of moves, are also introduced. The heuristic algorithm is executed at each iteration of the search, and the algorithm stops when the depth level reaches the upper bound. The novel time-based lower bound extends the lower bound for the number of moves. Each move is multiplied by a minimum time that consists of the travel time unloaded and loaded, crane lowering and lifting times, and twistlock time. Further variants of the time-based lower bound also consider the position of the blocking container and the highest positions they can be moved to. The time-based lower bound is used as a secondary tie-breaking criterion. Overall, the branch and bound algorithm outperforms the integer programming models in terms of solved instances and runtime. In a recent publication, [Parreño-Torres et al. \(2022\)](#) propose a beam search algorithm that is able to find all previously found optimal and more improved solutions (not necessarily optimal). For the tree search procedure, the authors use several tie-breaking criteria based on the move type (bad-bad (BB), bad-good (BG), good-bad (GB) and good-good (GG); see [Pfrommer et al. \(2024\)](#)), develop a global evaluation heuristic to obtain the most promising nodes, and present new dominance rules for eliminating nodes that cannot result in a better solution. The research on the minimization of crane times by [Parreño-Torres et al. \(2022\)](#) uses a lower bound based on minimum travel times multiplied by the number of moves. In single-bay scenarios, this approach is feasible. However, in larger multi-bay warehouses, a similar lower bound based on minimum move time becomes less effective due to the greater variability in move times.

[Jiménez-Piqueras et al. \(2024\)](#) introduce the CPMP under limited crane time (CPMP-LCT), where only a partial bay rearrangement is possible due to crane availability constraints. The authors propose constraint programming models that minimize the number of inaccessible containers within a given time limit, prioritizing early-retrieval containers. Their approach outperforms existing integer programming models and reliably produces high-quality solutions, making it suitable for both exact and heuristic use.

### 3.3. Warehousing

The warehousing literature contains numerous studies addressing reshuffling problems. However, only a few studies are related to the unit-load pre-marshalling problem, which specifically considers the priority class assigned to each unit load. While some storage location assignment strategies are based on the duration-of-stay (DOS) introduced by [Goetschalckx and Ratliff \(1990\)](#) — a metric that can be translated into a priority classification — existing research utilizing DOS or priority-based approaches for reshuffling typically assumes warehouse configurations without deep lanes like Automated Storage and Retrieval Systems (see, e.g. [Pazour and Carlo \(2015\)](#)). In such settings, unit loads are always directly accessible, which differs fundamentally from environments where deep-lane storage restricts access and necessitates additional reshuffling considerations. In the context of block stacking warehouses, [Maniezzo et al. \(2021\)](#) are the only ones to address pre-marshalling, focusing on stochastic pre-marshalling with uncertain retrieval sequences. Using historical data, they estimate future SKU requests to optimize moves. In contrast to this work, they assume direct access to all stacks, considering only blockages within individual stacks while disregarding move times or travel distances, and movements between multiple bays.

#### 4. Solving the MUPMP and MR-MUPMP

In this section, we provide an overview of our adapted step-based solution approach for the MUPMP, which builds on a previously established network flow model and tree search procedure introduced in Pfrommer et al. (2024). Additionally, we extend the approach with a routing step to address the MR-MUPMP. This routing component is formulated as a mixed-integer optimization model, originally presented in preliminary form in the conference proceedings by Bömer et al. (2024). In the present paper, we offer a more detailed formulation and comprehensive analysis of this model. Our main extensions are:

- Multiple outputs when solving the network flow model for each bay applying the advanced lower bound as an additional tie-breaking rule.
- An improved tree search procedure
  - with an incremental calculation of the lower bound heuristics,
  - a new tie-breaking rule that includes the total loaded move time,
- An exact CP approach to validate the results of the tree search procedure.
- Two efficient mixed-integer programming models to plan routes between the reshuffling moves.

The process flow of our sequential step-based approach is shown in Fig. 7.

##### 4.1. Step-based sequential approach

We start this section by giving an overview and briefly describing the steps of our solution approach based on a network flow model and a tree search procedure that has been presented in Pfrommer et al. (2024). Fig. 7 shows the two-step approach to solve the MUPMP and an additional third step to solve the MR-MUPMP. The approach requires the bay representation and travel time matrix as described in Section 2 as input.

In the first step, we use the network flow model to determine the access directions for each stack. The objective is to minimize the misplaced unit loads. Based on the access directions, we can transform the configuration into a state representation of virtual lanes. Each virtual lane consists of a sequence of 1 to  $\max(|\mathcal{R}|, |\mathcal{C}|)$  stacks in a row/column that can be accessed one after the other. The access direction for each virtual lane is defined by an access point, and the length of the lane may be different. In the second step, we use the virtual lane representation to find a solution for sorting the warehouse with a minimum number of short-time moves. Therefore, we present an adapted tree search procedure as well as a CP approach. To solve the MR-MUPMP an additional third step is necessary. The third step performs the routing between the moves aiming for the minimal travel time or makespan while considering dependencies between moves. In the following subsections, we explain our solution approach in detail and focus on the newly added adaptations.

##### 4.2. Step 1: Access direction fixing

In this step, we want to define the access direction for each stack. This is necessary to make the application of our lower bound - which estimates the number of required moves - valid, and also because we want to avoid crossing AMRs when accessing a bay. Fixing the access directions at the beginning of our approach may lead to additional moves, as discussed in Pfrommer et al. (2024). To calculate the access direction for each stack that minimizes the number of misplaced unit loads, we use the network flow model from Pfrommer et al. (2024). The result is used to determine a virtual lane representation that defines

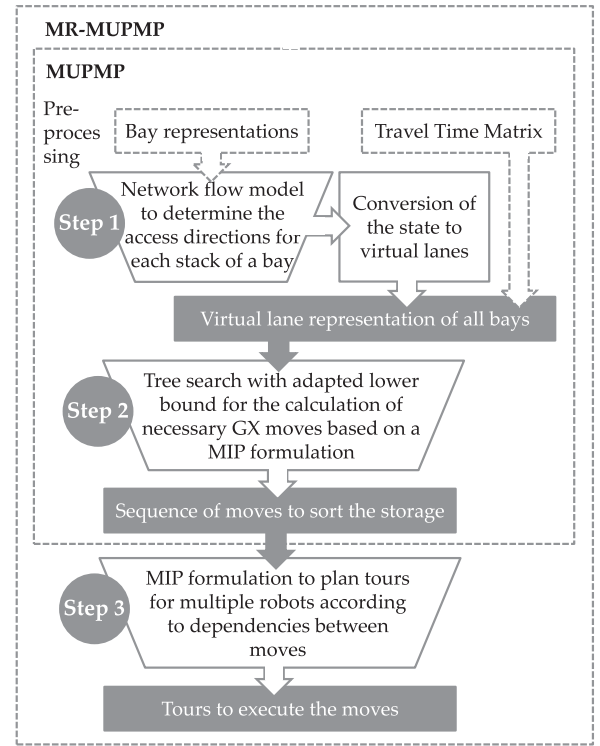


Fig. 7. Illustration of the main components of our extended solution approach based on Pfrommer et al. (2024).

how each stack is accessed via a defined access point. In our previous version, we obtained only a single optimal solution, even when many symmetrical solutions were available. Now, by leveraging the solution pool functionality of standard mathematical solvers, we return multiple optimal access direction solutions for each bay, allowing us to better utilize the symmetry in the problem. We then compare up to 10 solutions with our more advanced lower bound heuristic, which does not merely count the number of misplaced unit loads, but also considers the priority classes of those unit loads and the availability of storage locations (see Pfrommer et al. (2024)).

Fig. 8 gives an example with two bays that produce a list of virtual lanes. The two bays on top of the figure show an exemplary result of the network flow model for the example from Fig. 3. Thick black lines and colors illustrate the virtual lanes with the respective access directions and access points. At the bottom of the figure, we show the final virtual lane representation that is used throughout the following procedure to determine the pre-marshalling moves.

##### 4.3. Step 2 - alternative 1: Tree search

The new implementation of the A\* algorithm differs in some details from our previous work. We introduce a new tie-breaking rule that considers the total loaded move time for popping nodes out of the priority queue and a faster incremental calculation of the lower bound heuristics (which is not visible in the algorithm).

Algorithm 1 shows the modified algorithm. After initialization, the main search loop runs until a solution with no blocking unit loads is found, until the open list is empty and no solution exists, or until the time limit has been reached. In each iteration of the loop, a node  $n$  that minimizes the cost estimation  $f(n) = g(n) + h(n)$  is popped off the open list, where  $g(n)$  is the number of moves already performed at node  $n$  and  $h(n)$  the lower bound estimating the number of moves until a blockage-free configuration is reached. If there are many nodes with the same cost estimation  $f(n)$ , we use a new tie-breaking rule for node selection

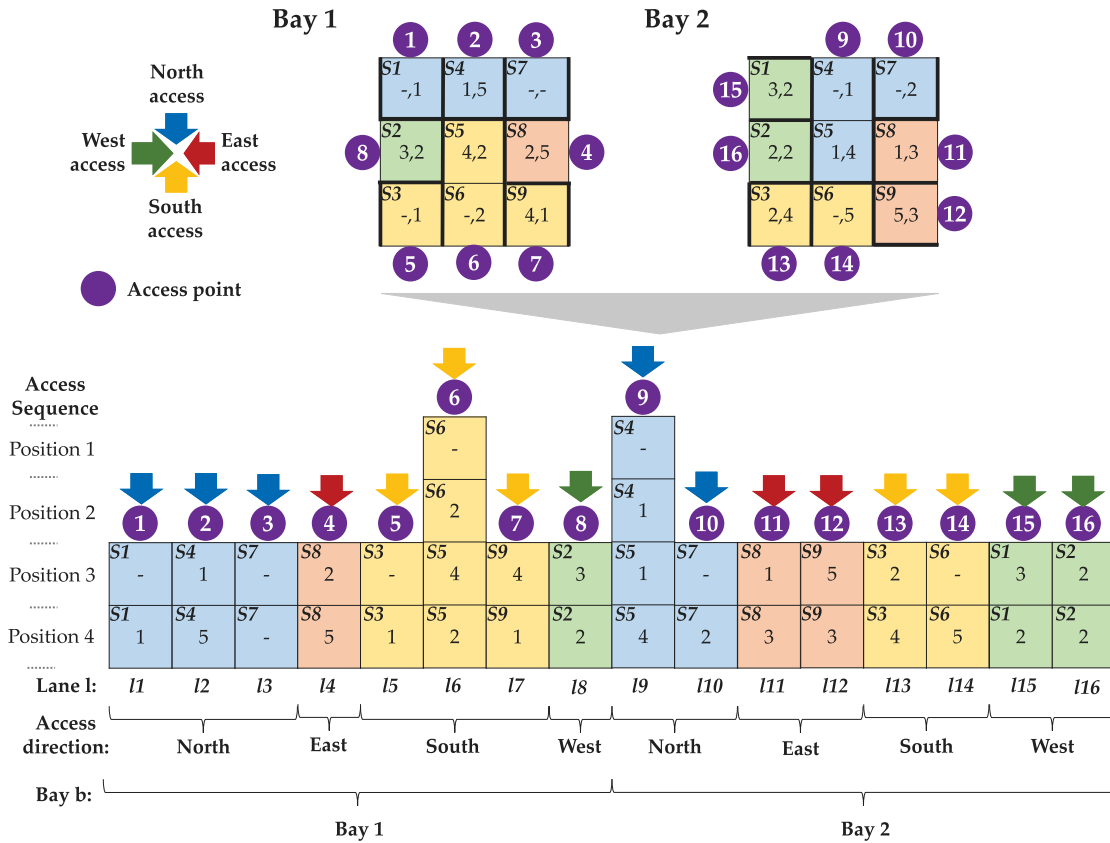


Fig. 8. Resulting virtual lanes for the example from Fig. 3. Thick black lines in bay 1 and bay 2 illustrate the virtual lanes. These lanes are transformed into a representation of one access direction.

that is explained in the subsequent paragraphs. The only difference in calculating successor nodes is that we incrementally calculate and update the total loaded move time. A successor node is pushed to the open list and added to an  $f$ - and travel time-dictionary, if there is not already a node with the same configuration in the  $f$ -dictionary that has a smaller cost estimation or the same cost estimation but a smaller total loaded move time. Our procedure guarantees an exact solution for the minimization of the move number. Since the total loaded move time is considered only for tie-breaking, the resulting total loaded move time is not necessarily optimal for the minimal number of moves. As long as the processing time for handling exceeds the total loaded move time for each move, we expect good results for the total processing time as well.

**Tie-breaking rules with loaded move time** When selecting the next move, our algorithm compares the different rules in a lexicographic order. The applied rules for tie-breaking are the  $f$ -value (total cost estimation),  $h$ -value (lower bound heuristics), and the total loaded move time  $dist$  (aggregated from the root to this node). The loaded move time between two virtual lanes is defined as the length of the Manhattan distance between their respective access points. The travel time within each virtual lane is neglected (it can be added by counting the empty tiles). We build different combinations based on these rules. In our approach, we always select the possible moves with the lowest  $f$ -value first. Because in many cases (especially large warehouses) there are still plenty of options with the same minimum  $f$ -value, we use the  $h$ -value as the first, and the total loaded move time  $dist$  as the second tie-breaker:  $f\_h\_dist$ .

**Incremental lower bound calculation** The  $A^*$  search is further optimized by incremental lower bound calculation requiring less calculation effort, which is not visible in Algorithm 1. If the configuration and lower bound of a given node are known, calculating the lower bound of its successor can be simplified. The estimated number of

**Algorithm 1:** Modified  $A^*$  algorithm from Pfrommer et al. (2024).

**Function** `astar(root)`:

```

open ← PRIORITY_QUEUE();    ▷ new tie-breaking rules
f_lookup ← DICT();
travel_time_lookup ← DICT(); ▷ new distance lookup
closed ← ∅;
PUSH(open, root);
f_lookup[root] ← f(root);
travel_time_lookup[root] ← 0;
while open ≠ ∅ and time < timeout do
    n ← POP(open);
    closed ← closed ∪ {n};
    if blocking(n) = 0 then
        return n;
    end
    successors ← BRANCHING(n);    ▷ new extended
    branching over all bays
    for s ∈ successors do
        if s ∉ closed and (s ∉ f_lookup or f_lookup[s] > f(s) or
            (f_lookup[s] = f(s) and travel_time_lookup[s] >
            total_loaded_time(s))) then
            PUSH(open, s);
            f_lookup[s] ← f(s);
            travel_time_lookup[s] ← total_loaded_time(s);
        end
    end
end
end

```

required moves based on the bad-good and bad-bad (BX) and the good-good and good-bad (GX) moves can be computed faster if information about its predecessor is known. The number of misplaced unit loads can be changed only in the lanes impacted by a move. Therefore, the difference in misplaced unit loads within these lanes is therefore also the total difference in misplaced unit loads in the entire warehouse. The BX moves based on the minimum number of misplaced unit loads per virtual lane, can also be updated simply by comparing it to the number of misplaced unit loads in the virtual lanes affected by the most recent move. The calculation of additional GX moves uses a supply-and-demand model. The change in supply and demand is dependent only on the change in the virtual lanes affected by the most recent move. To calculate the difference, the supply and demand of the two virtual lanes affected by the move must be determined for the parent node and the successor. The difference in supply and demand is calculated by subtracting the parent's supply and demand from the successor's supply and demand. Based on the supply and demand differences, we calculate the cumulative incremental supply and demand, deriving the demand surplus difference. We then add the demand surplus difference to the demand surplus of the parent node to obtain the new demand surplus of the successor. The following steps to derive the GX moves are the same.

#### 4.4. Step 2 - alternative 2: Constraint programming

To demonstrate the performance of the A\* algorithm, we compare its solution to a CP approach. We employ a CP approach proposed by Jiménez-Piqueras et al. (2023). Jiménez-Piqueras et al. (2023) solve the CPMP with the minimum number of moves. The core concept involves constructing a CP model that allows a limited number of moves, starting from a lower bound of moves. If no solution emerges after a complete search, an additional move is incorporated into the model until a solution is identified. The authors introduce multiple model versions. We opt for CP5 as it proved to be the most efficient. In the subsequent sections, we detail only the relevant parts of the model that underwent modifications to solve the MUPMP. The complete model is described in Appendix A.1:

Each stack of containers in the original model equates to a virtual lane, and each tier equates to a position in the access sequence of the virtual lane (see Section 4.2). To ensure comparability, the variable names used are matched to the original model. Let  $\bar{s}$  denote the number of virtual lanes and  $\bar{t}$  represent the number of positions in each virtual lane  $s$ . Accordingly,  $S = \{1, \dots, \bar{s}\}$  is the set of virtual lanes and  $\mathcal{T}_s = \{1, \dots, \bar{t}\}$  is the set of positions for virtual lane  $s \in S$ . A slot  $(s, t)$  is defined by a virtual lane  $s \in S$  and position  $t \in \mathcal{T}_s$ . Let  $\bar{k}$  be the permissible number of moves in the model.  $\mathcal{K}$  is the set of stages, defined as  $\mathcal{K} = \{1, \dots, \bar{k}\}$ . Stage 0 signifies the initial layout.  $\mathcal{K}^0 = \{0, 1, \dots, \bar{k}\}$  is the set of stages, including the initial layout. Further, the variables  $z_{s,t}^k$  and  $y_{s,t}^k$  are introduced.

$$z_{s,t}^k = \begin{cases} 1 & \text{If a unit load is removed from slot } (s, t) \text{ during stage } k \\ 0 & \text{Otherwise} \end{cases} \quad \forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K}$$

$$y_{s,t}^k = \begin{cases} 1 & \text{If a unit load is moved to slot } (s, t) \text{ during stage } k \\ 0 & \text{Otherwise} \end{cases} \quad \forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K}$$

Let  $d_{s,s'}$  be the travel time between virtual lane  $s \in S$  and  $s' \in S$ . The total loaded move time is minimized for the minimum number of moves. The objective function is defined as:

$$\min \sum_{k \in \mathcal{K}} \sum_{s \in S} \sum_{s' \in S} \sum_{t \in \mathcal{T}_s} \sum_{t' \in \mathcal{T}_{s'}} z_{s,t}^k \cdot y_{s',t'}^k \cdot d_{s,s'} \quad (4.1)$$

Let  $c^{UB}$  be the objective value of the solution of the A\* algorithm. To restrict the search space, the objective value of the A\* algorithm is set

**Table 1**

Example move sequence from Step 2.

| Index | Pick-up access point | Drop-off access point | Priority Class |
|-------|----------------------|-----------------------|----------------|
| 0     | 2                    | 3                     | 4              |
| 1     | 2                    | 1                     | 2              |
| 2     | 0                    | 2                     | 5              |
| 3     | 3                    | 2                     | 4              |

as an upper bound for the total loaded move time in constraint Eq. (A.23).

$$\sum_{k \in \mathcal{K}} \sum_{s \in S} \sum_{s' \in S} \sum_{t \in \mathcal{T}_s} \sum_{t' \in \mathcal{T}_{s'}} z_{s,t}^k \cdot y_{s',t'}^k \cdot d_{s,s'} \leq c^{UB} \quad (4.2)$$

Given that the number of virtual lanes can be substantial for large warehouse layouts, the symmetry-breaking constraints (27) of CP5 (Jiménez-Piqueras et al., 2023) are omitted from the model to reduce the model building time. The influence of those constraints is inherently diminished by accounting for the total loaded move time.

#### 4.5. Step 3: Tour planning

In this step we plan tours between the reshuffling moves to solve the MR-MUPMP aiming to minimize the travel time or makespan. While the solution of Step 2 is consistent and respects dependencies between moves, it is necessary to find those dependencies and feed them into the mixed-integer formulation to maintain consistency. A dependency between two moves exists if both moves access the same access point.

We categorize four base types of access point dependencies in Fig. 9: start-end, end-start, start-start, and end-end. A start-end dependency describes the pick-up access point (start) of the earlier move and the drop-off access point (end) of the later move are identical. Further, the priority class of the carried unit loads can either be equal or unequal between the dependent moves. Consequently, a total of eight move dependency types are derived.

The dependency types have different effects on the tour planning stage. For all types, the handling times at the respective identical access points are not allowed to overlap. Also, the execution order is affected by the dependencies. The order of dependent moves has to be followed according to the dependency. For example, for a start-end dependency, the pick-up process of the earlier move has to be completed before the drop-off process of the later move can begin (see Fig. 9 (a) start-end). Two exceptions to that rule are the start-start and end-end dependency types, with equal unit load priority classes in both moves. In these cases, the move order can be swapped arbitrarily, because both moves affect the respective identical lane in the same way.

For each move, sets are created to capture all applicable dependency types. These dependencies are identified by comparing the pick-up and drop-off access points, as well as the priority classes of the unit loads, between each move and all subsequent moves in the sequence. Table 1 presents an example move sequence resulting from Step 2. It lists, for each move, the pick-up and drop-off access points along with the associated priority class of the unit load. For instance, move 1 transports a unit load of priority class 2 from access point 2 (pick-up) to access point 1 (drop-off). As an example of a dependency, move 0 and move 2 exhibit a start-end dependency with unequal priority classes: move 0 drops off at access point 3, while move 2 picks up at the same access point, but their unit loads have priority classes 4 and 5, respectively. All identified dependencies for the example sequence are summarized in Table 2.

We formulate two mixed-integer models to plan tours between the reshuffling moves of Step 2 with multiple robots according to the dependencies. We formulate models similar to an open vehicle routing problem with pick-up and delivery with a capacity of one. The capacity of one allows one to represent each reshuffling move as a single node. The initial starting position of a robot is represented similarly to a depot as a dummy move node. The loaded move times and handling

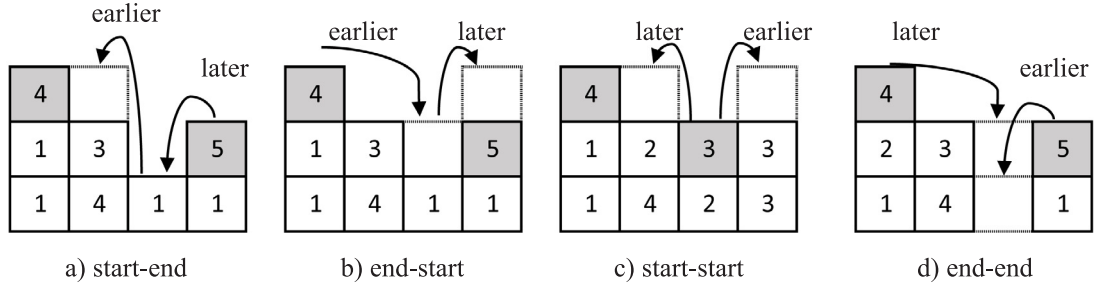


Fig. 9. Dependency base types.

**Table 2**  
Move dependency evaluation example.

| i | Unequal   |           |             |         | Equal     |           |             |         |
|---|-----------|-----------|-------------|---------|-----------|-----------|-------------|---------|
|   | Start-end | End-start | Start-start | End-end | Start-end | End-start | Start-start | End-end |
| 0 | 2         |           | 1           |         | 3         | 3         |             |         |
| 1 | 2,3       |           |             |         |           |           |             |         |
| 2 |           |           |             | 3       |           |           |             |         |

times are the service times in each move node. The unloaded move time between the drop-off access point of the previous move and the pick-up access point of the following move connects two move nodes. The dependencies between moves form precedences with a time component.

Let  $\mathcal{N} = \{1, \dots, |\mathcal{N}|\}$  be the set of reshuffling moves and  $\mathcal{N}^0 = \{0, \dots, |\mathcal{N}^0|\}$  the set of reshuffling moves including the dummy move 0. Let  $\mathcal{K} = \{1, \dots, |\mathcal{K}|\}$  be the set of robots. The variable  $x_{i,j}^k$  is 1, if move  $j \in \mathcal{N}$  is performed after move  $i \in \mathcal{N}$  by robot  $k \in \mathcal{K}$ , otherwise it is 0. Further,  $t_{k,i,j}^u$  is the unloaded move time between move  $i \in \mathcal{N}$  and  $j \in \mathcal{N}$  for robot  $k \in \mathcal{K}$ . The unloaded move time between the moves is asymmetrical, thus  $t_{k,i,j}^u \neq t_{k,j,i}^u$  in most cases. Each robot has its unloaded move time matrix because the initial access point of each robot gets assigned randomly. Let  $t_i^l$  be the loaded move time for move  $i \in \mathcal{N}^0$ . Let  $t_i^h$  be the handling time for the pick-up or drop-off process for move  $i \in \mathcal{N}^0$ . For the dummy move,  $i = 0 \in \mathcal{N}^0$ , the unloaded move time  $t_{k,0,j}^u$  is the travel time from the initial access point of the robot  $k \in \mathcal{K}$  to the pick-up access point of the respective move  $j \in \mathcal{N}^0$ . The dummy unloaded move times  $t_{k,i,0}^u$  are zero for all  $k \in \mathcal{K}$  and  $i \in \mathcal{N}^0$ ; the handling time  $t_0^h$  and the loaded move time  $t_0^l$  are also zero. The variable  $s_i^k$  is the start time of the pick-up for move  $i \in \mathcal{N}^0$  for robot  $k \in \mathcal{K}$ . Variable  $e_i^k$  is the end time of the drop-off for move  $i \in \mathcal{N}^0$  for robot  $k \in \mathcal{K}$ . The variable  $b_i^k$  denotes the waiting time after move  $i \in \mathcal{N}^0$  for robot  $k \in \mathcal{K}$ . Let  $\mathcal{D}_i^{s_i|s_j, p_i \neq p_j}$  be the set of moves with start-start-type dependency, with unequal priority classes between  $s_i$  and  $s_j$  for move  $i \in \mathcal{N}$  and  $j \in \mathcal{N}$ . Let  $\mathcal{D}_i^{s_i|e_j, p_i \neq p_j}$  be the set of moves with start-end-type dependency, with unequal priority classes between  $s_i$  and  $e_j$  for move  $i \in \mathcal{N}$  and  $j \in \mathcal{N}$ . Let  $\mathcal{D}_i^{e_i|s_j, p_i \neq p_j}$  be the set of moves with end-start-type dependency, with unequal priority classes between  $e_i$  and  $s_j$  for move  $i \in \mathcal{N}$  and  $j \in \mathcal{N}$ . Let  $\mathcal{D}_i^{e_i|e_j, p_i \neq p_j}$  be the set of moves with end-end-type dependency, with unequal priority classes between  $e_i$  and  $e_j$  for move  $i \in \mathcal{N}$  and  $j \in \mathcal{N}$ . The dependencies with equal priority classes  $\mathcal{D}_i^{s_i|s_j, p_i = p_j}$ ,  $\mathcal{D}_i^{s_i|e_j, p_i = p_j}$ ,  $\mathcal{D}_i^{e_i|s_j, p_i = p_j}$ , and  $\mathcal{D}_i^{e_i|e_j, p_i = p_j}$  are defined accordingly. The binary indicator variable  $\alpha_{i,j}^{k,k'}$  enforces the dependency between move  $i \in \mathcal{N}$  and  $j \in \mathcal{D}_i^{s_i|s_j, p_i = p_j}$  for  $k \in \mathcal{K}$  and  $k' \in \mathcal{K}$ . The binary indicator variable  $\beta_{i,j}^{k,k'}$  enforces the dependency between move  $i \in \mathcal{N}$  and  $j \in \mathcal{D}_i^{e_i|e_j, p_i = p_j}$  for  $k \in \mathcal{K}$  and  $k' \in \mathcal{K}$ .  $e_{max}$  is the maximum end time of all moves. Let  $\mathcal{T}^{max} = \{\max_{k \in \mathcal{K}} t_{k,i,j}^u \mid (i,j) \in \mathcal{N}^0 \times \mathcal{N}^0\}$  be the set of unloaded move times representing the maximum travel time between each pair of locations  $(i,j)$ , taken over all robots  $k \in \mathcal{K}$ . To ensure the correct functioning of time-dependent conditional constraints involving binary variables, we define

a sufficiently large constant  $M$  that acts as an upper bound on travel and service times. We calculate  $M$  as:

$$M = \sum_{i \in \mathcal{T}^{max}} t + \sum_{i \in \mathcal{N}^0} (t_i^l + t_i^h \cdot 2) \quad (4.3)$$

#### MR – MUPMP – 1

$$\min \sum_{k \in \mathcal{K}} \sum_{i,j \in \mathcal{N}^0} x_{i,j}^k (t_{k,i,j}^u + t_i^l + 2 \cdot t_i^h) + b_i^k \quad (4.4)$$

Subject to :

$$\sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{N}, i \neq j} x_{i,j}^k = 1 \quad \forall j \in \mathcal{N} \quad (4.5)$$

$$\sum_{i \in \mathcal{N}^0} x_{0,i}^k = 1 \quad \forall k \in \mathcal{K} \quad (4.6)$$

$$\sum_{j \in \mathcal{N}} x_{i,j}^k = \sum_{j \in \mathcal{N}} x_{ji}^k \quad \forall i \in \mathcal{N}, \forall k \in \mathcal{K} \quad (4.7)$$

$$s_0^k = 0 \quad \forall k \in \mathcal{K} \quad (4.8)$$

$$e_i^k + t_{k,i,j}^u + b_i^k - M(1 - x_{i,j}^k) \leq s_j^k \quad \forall i \in \mathcal{N}^0, j \in \mathcal{N}, i \neq j, \forall k \in \mathcal{K} \quad (4.9)$$

$$e_i^k + t_{k,i,j}^u + b_i^k + M(1 - x_{i,j}^k) \geq s_j^k \quad \forall i \in \mathcal{N}^0, j \in \mathcal{N}, i \neq j, \forall k \in \mathcal{K} \quad (4.10)$$

$$e_i^k = s_i^k + t_i^l + (2 \cdot t_i^h) \quad \forall i \in \mathcal{N}^0, j \in \mathcal{N}, i \neq j, \forall k \in \mathcal{K} \quad (4.11)$$

$$e_i^k \leq s_j^{k'} \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{D}_i^{e_i|s_j, p_i \neq p_j}, \forall k, k' \in \mathcal{K} \quad (4.12)$$

$$s_i^k + t_i^h + t_j^{k'} \leq e_j^{k'} \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{D}_i^{s_i|e_j, p_i \neq p_j}, \forall k, k' \in \mathcal{K} \quad (4.13)$$

$$s_i^k + t_i^h \leq s_j^{k'} \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{D}_i^{s_i|s_j, p_i \neq p_j}, \forall k, k' \in \mathcal{K} \quad (4.14)$$

$$e_i^k + t_j^h \leq e_j^{k'} \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{D}_i^{e_i|e_j, p_i \neq p_j}, \forall k, k' \in \mathcal{K} \quad (4.15)$$

$$e_i^k \leq s_j^{k'} \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{D}_i^{e_i|s_j, p_i=p_j}, \forall k, k' \in \mathcal{K} \quad (4.16)$$

$$s_i^k + t_i^h + t_j^h \leq e_j^{k'} \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{D}_i^{s_i|e_j, p_i=p_j}, \forall k, k' \in \mathcal{K} \quad (4.17)$$

$$s_i^k + t_i^h \leq s_j^{k'} + M(1 - \alpha_{i,j}^{k,k'}) \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{D}_i^{s_i|s_j, p_i=p_j}, \forall k, k' \in \mathcal{K} \quad (4.18)$$

$$s_j^k + t_j^h \leq s_i^{k'} + M \cdot \alpha_{i,j}^{k,k'} \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{D}_i^{s_i|s_j, p_i=p_j}, \forall k, k' \in \mathcal{K} \quad (4.19)$$

$$e_i^k + t_j^h \leq e_j^{k'} + M(1 - \beta_{i,j}^{k,k'}) \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{D}_i^{e_i|e_j, p_i=p_j}, \forall k, k' \in \mathcal{K} \quad (4.20)$$

$$e_j^k + t_i^h \leq e_i^{k'} + M \cdot \beta_{i,j}^{k,k'} \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{D}_i^{e_i|e_j, p_i=p_j}, \forall k, k' \in \mathcal{K} \quad (4.21)$$

$$x_{i,j}^k \in \{0, 1\} \quad \forall i, j \in \mathcal{N}^0, \forall k \in \mathcal{K} \quad (4.22)$$

$$s_i^k \in \mathbb{N}_0^+ \quad \forall i \in \mathcal{N}, \forall k \in \mathcal{K} \quad (4.23)$$

$$e_i^k \in \mathbb{N}_0^+ \quad \forall i \in \mathcal{N}, \forall k \in \mathcal{K} \quad (4.24)$$

$$\alpha_{i,j}^{k,k'} \in \{0, 1\} \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{D}_i^{s_i|s_j, p_i=p_j}, \forall k, k' \in \mathcal{K} \quad (4.25)$$

$$\beta_{i,j}^{k,k'} \in \{0, 1\} \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{D}_i^{e_i|e_j, p_i=p_j}, \forall k, k' \in \mathcal{K} \quad (4.26)$$

$$b_i^k \in \mathbb{N}_0^+ \quad \forall i \in \mathcal{N}, \forall k \in \mathcal{K} \quad (4.27)$$

MR-MUPMP-1: The objective function (4.4) minimizes the total travel time. Constraints (4.5) assign each move to exactly one robot. The Constraints (4.6) define that each robot has to start in the dummy move 0. Constraints (4.7) enforce flow conservation. Constraints (4.8) set the start times in dummy move 0 to zero. Constraints (4.9) and (4.10) connect the start time of the following move with the end time of the previous move. Constraints (4.11) connect the end time with the start time of the same move. Constraints (4.13), (4.12), (4.14), and (4.15) enforce dependencies between move start and end times for move dependencies between moves of unit loads with unequal priority classes. Constraints (4.16) to (4.21) enforce dependencies between moves of unit loads with equal priority classes. Constraints (4.22), (4.23), (4.24), (4.25), (4.26), and (4.27) determine the variable domains.

## MR – MUPMP – 2

$$\min e_{\max} \quad (4.28)$$

Subject to:

$$e_i^k \leq e_{\max} \quad \forall i \in \mathcal{N}, \forall k \in \mathcal{K} \quad (4.29)$$

$$e_{\max} \in \mathbb{N}_0^+ \quad (4.30)$$

MR-MUPMP-2: The objective function (4.28) minimizes the makespan of all reshuffling moves. The model includes the constraints (4.5) to (4.27). Constraints (4.29) set  $e_{\max}$  to the maximum value of all  $e_i^k$ . Constraint (4.30) defines the domain of  $e_{\max}$ .

## 5. Experiments

In this section, we first describe the problem instances, then we present the experimental results for the MUPMP and MR-MUPMP.

We present our findings through illustrative examples, with a comprehensive summary of all results available in the appendix. The detailed results of Step 1 (Section 4.2) are shown in Appendix A.2, Step 2 (Section 4.2) in Appendices A.3 and A.4; Step 3 (Section 4.5) in Appendix A.5.

### 5.1. Instance dataset and parameters

We conduct experiments on 3520 one-tier and 1120 two-tier instances and publish an even more extensive dataset for future research. The instances are available here: <https://zenodo.org/records/11093870>. Table 3 shows an overview of the varied configuration parameters for this study. In all instances, we consider four access directions (north, east, south, west). The varied parameters include the number of tiers, priority classes, fill percentage, bay layout, warehouse layout, and robots. For each configuration, we create 10 randomly generated instances (seeds 1-10).

The test instances consider five or 10 different priority classes. Fill percentages of 40%, 60%, 80%, and 90% are taken into account. For this study, we only consider quadratic layouts. A one-tier  $6 \times 6$  bay layout describes a bay in which six lanes are arranged next to each other with a depth of six slots. This results in 36 slots per bay. A warehouse layout of  $5 \times 5$  describes a warehouse that consists of 25 bays that are arranged in a quadratic pattern. Hence, a one-tier  $6 \times 6$  bay layout and a  $5 \times 5$  warehouse layout combined results in 900 slots. This study includes bay layouts from  $3 \times 3$  up to  $6 \times 6$  and warehouse layouts from  $2 \times 2$  up to  $12 \times 12$ . Table 4 shows the resulting number of slots for each considered bay and warehouse layout configuration. The largest layout configurations include 1296 slots. For the two-tier case the number of slots doubles respectively.

We conduct computational experiments on the Linux High-Performance-Computing Cluster LiDo3 at the Technical University of Dortmund. We run all experiments on a node with 4 × Intel Xeon E5 4640v4 2.1 GHz and 512 GB RAM. The algorithms are implemented in Python using Google OR-Tools 9.5 with default parameters for the network flow model, CP model, and routing models. The solution time of the A\* algorithm is limited to 10 min. The solution time of the CP model is limited to 60 min. The solution time of the routing models is limited to five minutes.

### 5.2. MUPMP experimental analysis

The objective of this analysis is to evaluate the performance of the A\* algorithm approach (see Section 4.3) and compare it with the CP approach (see Section 4.4). We focus on solvability, runtime, and solution quality.

**Solved instances** Table 5 shows the number of solved instances by A\* for each one-tier instance configuration. The A\* poses the bottleneck in the proposed step-based solution approach. Hence all instances solved by the A\* in Step 2 are solved in Step 1. The results show that instances with 10 priority classes are harder to solve than instances with five priority classes. An example is given for a  $5 \times 5$  bay layout,  $6 \times 6$  warehouse layout, and 90% fill percentage. For five priority classes, all instances have been solved, for 10 priority classes only four have been solved. Further, the bay layout has a stronger impact on the solvability of an instance than the warehouse layout. For example, the instances with a  $5 \times 5$  bay layout and  $6 \times 6$  warehouse layout are solvable for the A\*, while instances with a  $6 \times 6$  bay layout and  $5 \times 5$  warehouse layout are barely solvable for fill percentages over 40%. Both configurations contain the same number of slots.

Also, a larger fill percentage seems to make instances harder to solve up to a certain point. The number of solved instances decreases with a rising fill percentage from 40% to 80%. The comparison of 80% fill percentage and 90% shows that the instances with 80% fill percentage are harder to solve than the ones with 90%. The reason for that is

**Table 3**  
Dataset configurations.

| Parameter        | Value                                                                               |
|------------------|-------------------------------------------------------------------------------------|
| Tiers            | {1, 2}                                                                              |
| Priority classes | {5, 10}                                                                             |
| Fill percentage  | {40%, 60%, 80%, 90%}                                                                |
| Bay layout       | {3 × 3, 4 × 4, 5 × 5, 6 × 6}                                                        |
| Warehouse layout | {2 × 2, 3 × 3, 4 × 4, 5 × 5, 6 × 6, 7 × 7, 8 × 8, 9 × 9, 10 × 10, 11 × 11, 12 × 12} |
| Robots           | {2, 3, 4, 5}                                                                        |

**Table 4**

Number of slots for each one-tier layout configuration.

| Bay layout | Warehouse layout |       |       |       |       |       |       |       |         |         |         |
|------------|------------------|-------|-------|-------|-------|-------|-------|-------|---------|---------|---------|
|            | 2 × 2            | 3 × 3 | 4 × 4 | 5 × 5 | 6 × 6 | 7 × 7 | 8 × 8 | 9 × 9 | 10 × 10 | 11 × 11 | 12 × 12 |
| 3 × 3      | 36               | 81    | 144   | 225   | 324   | 441   | 576   | 729   | 900     | 1089    | 1296    |
| 4 × 4      | 64               | 144   | 256   | 400   | 576   | 784   | 1024  |       |         |         |         |
| 5 × 5      | 100              | 225   | 400   | 625   | 900   |       |       |       |         |         |         |
| 6 × 6      | 144              | 324   | 576   | 900   | 1296  |       |       |       |         |         |         |

**Table 5**

Solved one-tier instances for A\*.

| Bay layout | Priority classes | 5   |     |     |     | 10  |     |     |     |
|------------|------------------|-----|-----|-----|-----|-----|-----|-----|-----|
|            | Fill percentage  | 40% | 60% | 80% | 90% | 40% | 60% | 80% | 90% |
|            | Warehouse layout |     |     |     |     |     |     |     |     |
| 3 × 3      | 2 × 2            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 3 × 3            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 4 × 4            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 5 × 5            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 6 × 6            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 7 × 7            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 8 × 8            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 9 × 9            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 10 × 10          | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 11 × 11          | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 12 × 12          | 10  | 10  | 9   | 10  | 10  | 10  | 8   | 10  |
| 4 × 4      | 2 × 2            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 3 × 3            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 4 × 4            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 5 × 5            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 6 × 6            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 7 × 7            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 8 × 8            | 10  | 10  | 10  | 10  | 10  | 9   | 3   | 9   |
|            |                  |     |     |     |     |     |     |     |     |
| 5 × 5      | 2 × 2            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 3 × 3            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 4 × 4            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 9   |
|            | 5 × 5            | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
|            | 6 × 6            | 10  | 10  | 5   | 10  | 10  | 10  | 0   | 4   |
| 6 × 6      | 2 × 2            | 10  | 10  | 10  | 9   | 10  | 10  | 10  | 10  |
|            | 3 × 3            | 10  | 10  | 10  | 7   | 10  | 10  | 10  | 7   |
|            | 4 × 4            | 10  | 10  | 10  | 6   | 10  | 10  | 10  | 1   |
|            | 5 × 5            | 10  | 5   | 0   | 0   | 10  | 2   | 0   | 0   |
|            | 6 × 6            | 3   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |

that a high 90% fill percentage heavily restricts the potential slots for relocations. Hence, the A\* has to evaluate fewer nodes to find a solution.

Fig. 10 shows the mean number of evaluated nodes for one-tier instances with a 4 × 4 bay layout. The mean number of evaluated nodes is an indicator of the solution effort of each instance. The mean number of evaluated nodes for 80% fill percentage instances exceeds the number for 90% fill percentage. Consequently, the solution effort for 80% is higher than for 90% which results in an A\* time-out for smaller layout configurations than for 90% fill percentage.

Table 6 presents the solved two-tier instances. As with the one-tier instances, solvability declines as the bay layout size, warehouse layout size, number of priority classes, and fill percentage increase.

The experiments reveal that two-tier instances significantly heighten solution complexity. This increase is attributable to three factors: the doubling of the number of slots, the increased depths of virtual lanes,

and the reduced potential to avoid blocking unit loads by selecting a favorable access direction.

The introduction of a second tier doubles the number of slots and unit loads in each instance, making the differences between the two instance size configurations considerably more pronounced. In two-tier cases, an increase in warehouse layout size adds twice the additional slots compared to one-tier scenarios.

Moreover, the additional tier doubles the depths of virtual lanes, leading to a greater number of misplaced unit loads and, consequently, more reshuffling moves. For instance, a 3 × 3 bay layout results in a mean virtual lane depth of 1.125 slots in the one-tier case, but 2.25 slots in the two-tier scenario. Interestingly, a 3 × 3 bay layout with two tiers has deeper lanes than a 6 × 6 bay layout with one-tier (1.8 slots). Even though the number of slots is the same. This is because the 6 × 6 bay layout offers more access points.

Lastly, introducing a second tier under a shared storage policy generates numerous blockages that cannot be resolved by choosing a

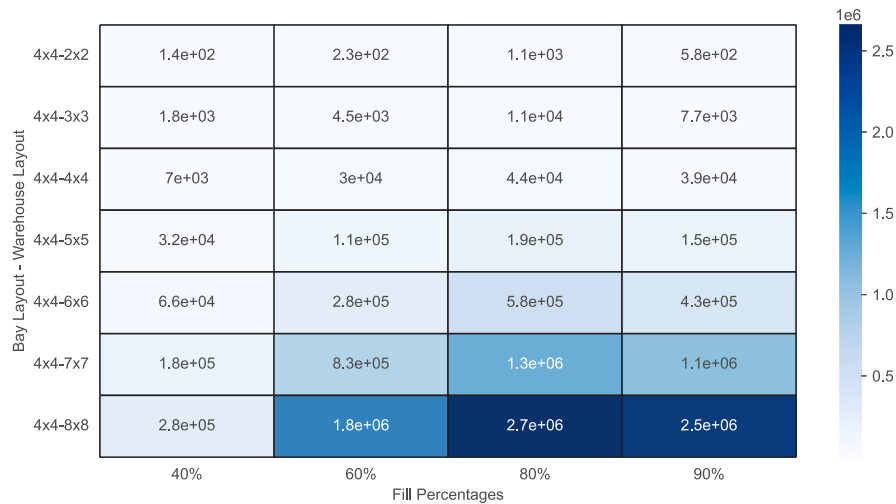


Fig. 10. Mean number of evaluated nodes in A\* for 10 priority classes and one-tier.

Table 6

Solved two-tier instances for A\*.

| Bay layout | Priority classes | 5   |     |     |     | 10  |     |     |     |
|------------|------------------|-----|-----|-----|-----|-----|-----|-----|-----|
|            |                  | 40% | 60% | 80% | 90% | 40% | 60% | 80% | 90% |
| 3 × 3      | Warehouse layout |     |     |     |     |     |     |     |     |
|            | 2 × 2            | 10  | 10  | 10  | 9   | 10  | 10  | 10  | 7   |
|            | 3 × 3            | 10  | 10  | 8   | 3   | 10  | 10  | 7   | 1   |
|            | 4 × 4            | 10  | 10  | 5   | 0   | 10  | 10  | 3   | 0   |
|            | 5 × 5            | 10  | 8   | 0   | 0   | 10  | 2   | 0   | 0   |
| 4 × 4      | 6 × 6            | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
|            | 2 × 2            | 10  | 10  | 5   | 1   | 10  | 10  | 4   | 0   |
|            | 3 × 3            | 10  | 10  | 0   | 0   | 10  | 10  | 0   | 0   |
|            | 4 × 4            | 10  | 0   | 0   | 0   | 9   | 0   | 0   | 0   |
| 5 × 5      | 5 × 5            | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
|            | 2 × 2            | 10  | 10  | 0   | 0   | 10  | 10  | 0   | 0   |
|            | 3 × 3            | 10  | 5   | 0   | 0   | 10  | 0   | 0   | 0   |
| 6 × 6      | 4 × 4            | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
|            | 2 × 2            | 10  | 8   | 0   | 0   | 10  | 7   | 0   | 0   |
|            | 3 × 3            | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |

favorable access direction. For example, when a lower-priority unit load is placed above a higher-priority unit, it becomes a persistent blockage regardless of the selected access direction. In contrast, for one-tier bay layouts, increasing the layout size allows strategic selection of access directions to mitigate blockages.

In conclusion, two-tier instances exhibit similar characteristics to one-tier instances but require greater solution effort. Consequently, the following analysis focuses on one-tier instances, where a greater number of instances have been solved, and the effects of varying parameters can be presented more clearly. For completeness, all results for the two-tier instances are provided in the appendix.

**Runtimes** The runtime of the MUPMP is composed of two elements: the access direction fixing (Step 1) and the reshuffling move search (Step 2). In the following, we will discuss each of these components in detail.

The runtime for the access direction fixing pre-processing step (see Section 4.2) is shown in Fig. 11. Fig. 11 shows that the pre-processing runtime is not dependent on the fill percentages, but only on the size of the layout configuration. The pre-processing runtime increases in proportion to the number of bays because the pre-processing step has to be performed for each bay individually. Larger bay layouts cause longer pre-processing times. This becomes evident when comparing two one-tier layout configurations with the same number of slots: The mean pre-processing runtime for a 4 × 4 bay layout and a 5 × 5 warehouse layout is 3.31 s for a 5 × 5 bay layout and a 4 × 4 warehouse layout the mean is 4.39 s. The number of priority classes does not show

a significant impact on the pre-processing time. The maximum pre-processing time of all solved one-tier instances is 39.25 s for a 6 × 6 bay layout, 6 × 6 warehouse layout, 40% fill percentage, and five priority classes.

Fig. 12 shows the solution time of the A\* algorithm to find the reshuffling moves (see Section 4.3). The runtime increases with the number of evaluated nodes. Consequently, the A\* runtime increases with the size of the bay and warehouse layout. Further, the A\* runtime increases with the fill percentage until 80%. However, the solving times for the 90% fill percentage instances are lower than for the 80%. The reason for this is that more nodes have to be evaluated for 80% fill percentage than for 90% fill percentage (see Fig. 10).

**Loaded move time optimality** To analyze the A\* approach, we compare its objective value (total loaded move time for the minimal number of moves) with the exact CP approach. Table 8 shows the number of proven optimally solved one-tier instances for each solution approach. Please note that we only run the CP model if a solution was found by the A\*, because the A\* solution serves as an upper bound for the CP model. The number 20 indicates that all instances for that configuration were solved proven optimally. If the number of instances for the A\* is lower than the number of optimally solved instances by the CP model, a difference between the A\* objective value and the proven optimal objective value of the CP model is found. Overall, the CP model found the optimal solution in 1364 one-tier instances. The A\* found the same solution in 97.43% (1329) of these one-tier instances. In 35 one-tier

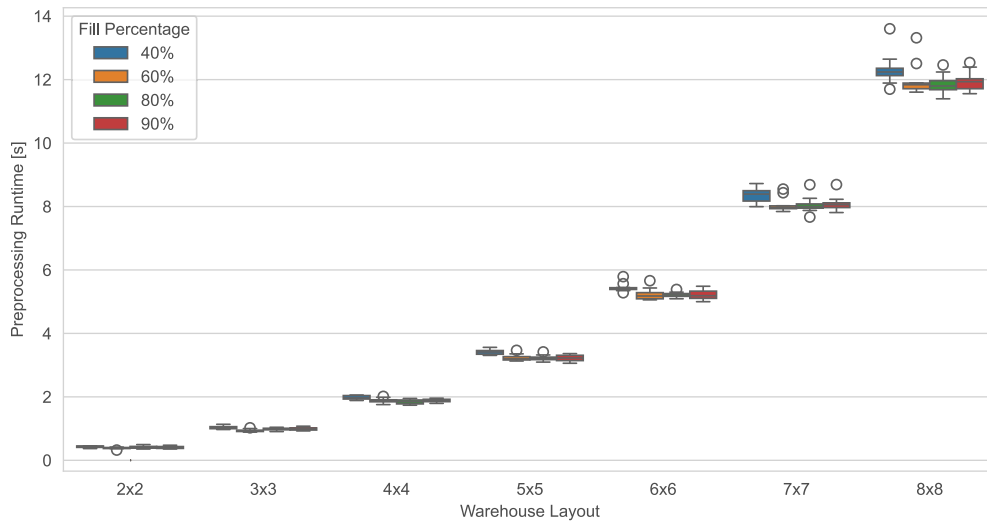


Fig. 11. Access direction fixing (pre-processing) runtime for one-tier,  $4 \times 4$  bay layout, and 10 priority classes.

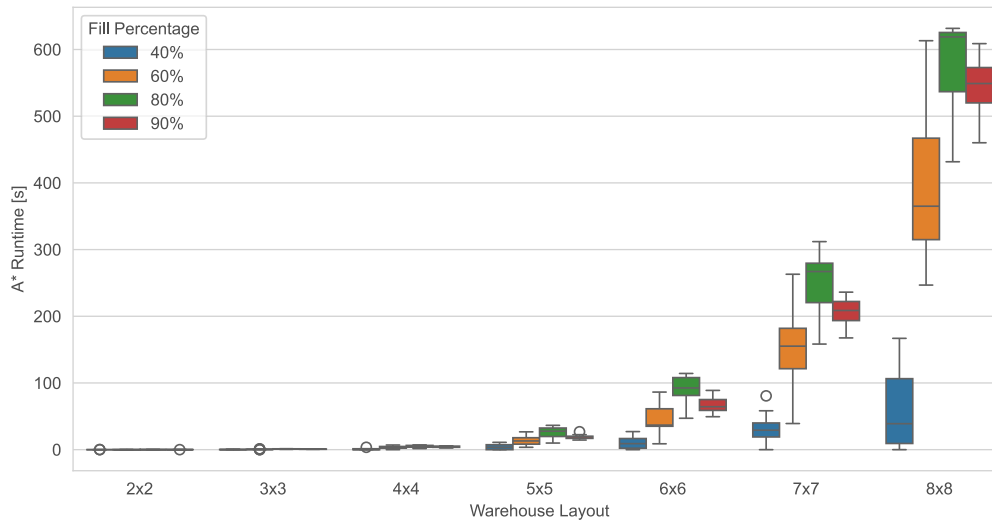


Fig. 12. A\* (tree search) runtime for a one-tier,  $4 \times 4$  bay layout, and 10 priority classes.

**Table 7**  
Number of proven optimal solved two-tier instances.

| Bay layout | Fill percentage | 40%              |    | 60% |    | 80% |    | 90% |    |
|------------|-----------------|------------------|----|-----|----|-----|----|-----|----|
|            |                 | A*               | CP | A*  | CP | A*  | CP | A*  | CP |
|            |                 | Warehouse layout |    |     |    |     |    |     |    |
| 3 × 3      | 2 × 2           | 17               | 20 | 9   | 14 | –   | –  | –   | –  |
| 4 × 4      | 2 × 2           | 9                | 11 | 0   | 0  | –   | –  | –   | –  |

instances the CP model found an optimal solution that differs from the A\* solution.

The A\* can find the proven optimal solution for almost every one-tier  $3 \times 3$  and  $4 \times 4$  bay layout configuration that the CP model was able to solve to optimality. Only for fill percentages of 90% few suboptimal solutions exist. For one-tier  $5 \times 5$  and  $6 \times 6$  bay layouts, more instances cannot be optimally solved for 80% and 90% fill percentages by A\*. Bay layout and fill percentage have the biggest impact on the optimality of the A\* solution. The warehouse layout has little to no impact.

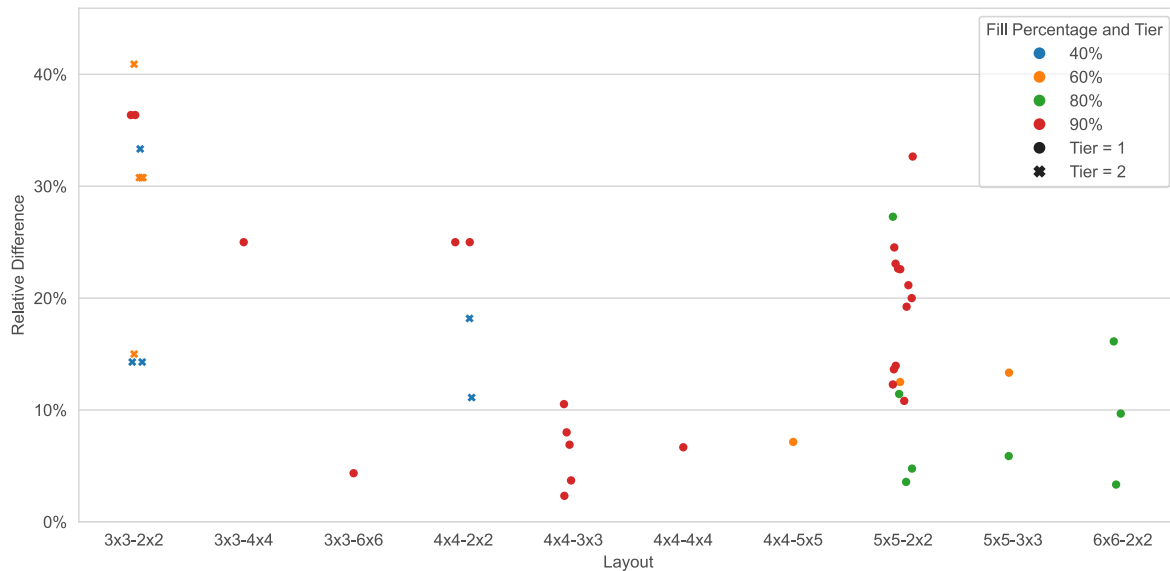
Table 7 presents a comparison of optimal solutions for the two-tier instances. Overall, the CP approach was able to solve only a few small two-tier instances to optimality. Unlike in the one-tier case, A\* produces suboptimal solutions for instances with a 40% fill percentage.

Fig. 13 shows an overview of the relative difference between the total loaded move time in the A\* solution and the CP solution if the objective value differs. A value of 20% indicates that the loaded move time of the A\* solution is 20% longer than the optimal loaded move time found by the CP model. For most layout configurations no or only a few data points exist. For a  $5 \times 5$  bay layout and a  $2 \times 2$  warehouse layout, the A\* was not able to find the loaded move time optimal solution in overall 19 instances. For this one-tier layout configuration, the mean relative difference of the differing instances is 17.4% across all fill percentage groups. The largest difference in loaded move time was found for a two-tier instance solution with more than 40% more loaded move time in the A\* solution than in the CP solution.

A closer look into the move sequence of both approaches in comparison explains why the A\* total loaded move time is not optimal for some

**Table 8**  
Number of proven optimal solved one-tier instances.

| Bay layout       | Fill percentage | 40% |    | 60% |    | 80% |    | 90% |    |
|------------------|-----------------|-----|----|-----|----|-----|----|-----|----|
|                  |                 | A*  | CP | A*  | CP | A*  | CP | A*  | CP |
| Warehouse layout |                 |     |    |     |    |     |    |     |    |
| 3 × 3            | 2 × 2           | 20  | 20 | 20  | 20 | 20  | 20 | 18  | 20 |
|                  | 3 × 3           | 20  | 20 | 20  | 20 | 20  | 20 | 20  | 20 |
|                  | 4 × 4           | 20  | 20 | 20  | 20 | 20  | 20 | 19  | 20 |
|                  | 5 × 5           | 20  | 20 | 20  | 20 | 20  | 20 | 20  | 20 |
|                  | 6 × 6           | 20  | 20 | 20  | 20 | 20  | 20 | 18  | 19 |
|                  | 7 × 7           | 20  | 20 | 20  | 20 | 20  | 20 | 17  | 17 |
|                  | 8 × 8           | 20  | 20 | 20  | 20 | 19  | 19 | 9   | 9  |
|                  | 9 × 9           | 20  | 20 | 20  | 20 | 15  | 15 | 9   | 9  |
|                  | 10 × 10         | 20  | 20 | 20  | 20 | 8   | 8  | 1   | 1  |
|                  | 11 × 11         | 20  | 20 | 20  | 20 | 4   | 4  | 1   | 1  |
|                  | 12 × 12         | 10  | 10 | 10  | 10 | 3   | 3  | 1   | 1  |
| 4 × 4            | 2 × 2           | 20  | 20 | 20  | 20 | 20  | 20 | 18  | 20 |
|                  | 3 × 3           | 20  | 20 | 20  | 20 | 20  | 20 | 14  | 19 |
|                  | 4 × 4           | 20  | 20 | 20  | 20 | 15  | 15 | 6   | 7  |
|                  | 5 × 5           | 20  | 20 | 18  | 19 | 4   | 4  | 0   | 0  |
|                  | 6 × 6           | 20  | 20 | 17  | 17 | 1   | 1  | 0   | 0  |
|                  | 7 × 7           | 20  | 20 | 12  | 12 | 0   | 0  | 0   | 0  |
|                  | 8 × 8           | 20  | 20 | 9   | 9  | 0   | 0  | 0   | 0  |
| 5 × 5            | 2 × 2           | 20  | 20 | 19  | 20 | 15  | 19 | 6   | 18 |
|                  | 3 × 3           | 20  | 20 | 19  | 20 | 2   | 3  | 0   | 0  |
|                  | 4 × 4           | 20  | 20 | 8   | 8  | 0   | 0  | 0   | 0  |
|                  | 5 × 5           | 20  | 20 | 1   | 1  | 0   | 0  | 0   | 0  |
|                  | 6 × 6           | 18  | 18 | 0   | 0  | 0   | 0  | 0   | 0  |
| 6 × 6            | 2 × 2           | 20  | 20 | 20  | 20 | 3   | 6  | 0   | 0  |
|                  | 3 × 3           | 20  | 20 | 2   | 2  | 0   | 0  | 0   | 0  |
|                  | 4 × 4           | 15  | 15 | 0   | 0  | 0   | 0  | 0   | 0  |
|                  | 5 × 5           | 5   | 5  | 0   | 0  |     |    |     |    |
|                  | 6 × 6           | 0   | 0  |     |    |     |    |     |    |



**Fig. 13.** Relative difference between total loaded move time of the A\* and CP approach for one-tier and two-tier instances optimally solved by CP.

instances. Fig. 14 shows the move sequence of the A\* (purple) and CP (pink, dotted) approach in comparison for a one-tier 5 × 5 bay layout, 2 × 2 warehouse layout, 90% fill percentage, and 10 priority classes. Move 1 of the A\* is identical to move 2 of the CP approach. The same is true for the moves 2/1, 4/5, and 5/4. The longer loaded move time of the A\* results from the fact that dependencies between moves are not taken into account during the search. The A\* selects the shortest moves greedily. However, a shorter move earlier in the sequence can cause longer loaded move time later in the sequence. For example, the A\* performs a short move 3 that results in a longer loaded move time for move 6 later. A\* move 6 causes a greater loaded move time for

move 7. The CP model respects these dependencies, which results in a lower total move time for the same number of moves.

**Move number and loaded move time** Fig. 15 shows the distribution for the number of moves for five and 10 priority classes in a one-tier, 5 × 5 bay layout, and 4 × 4 warehouse layout. For each fill percentage, the number of moves for 10 priority classes is larger than for five priority classes. This is because the chance that a unit load is blocking another unit load increases with the number of priority classes.

For a better understanding, we calculate the mean likelihood that a unit load is blocking another. We assume that the priority classes are

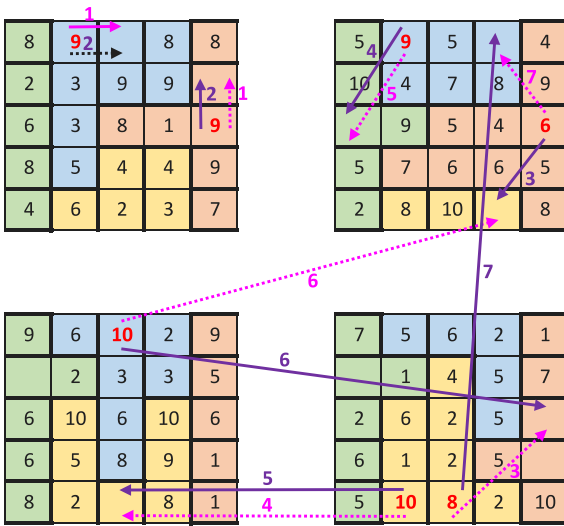


Fig. 14. Move sequence of A\* (purple) and CP (pink, dotted) approach in comparison for a one-tier, 5 × 5 bay layout, 2 × 2 warehouse layout, 90% fill percentage and 10 priority classes.

equally distributed. We sum up the likelihood for each priority class that it is blocking if it is standing in front of a random unit load in a virtual lane with a depth of two. Let  $\mathcal{P}$  be the set of priority classes and  $\bar{p}$  the maximum priority class  $p \in \mathcal{P}$ . The mean blockage likelihood  $\mathcal{L}_{\bar{p}}$  is calculated as:

$$\mathcal{L}_{\bar{p}} = \frac{1}{\bar{p}} \sum_{p \in \mathcal{P}} \left(1 - \frac{p}{\bar{p}}\right) \quad (5.1)$$

For five priority classes, the mean likelihood of blocking is  $\mathcal{L}_5 = 40\%$ . For 10 priority classes, it is  $\mathcal{L}_{10} = 45\%$ . The effect of extra blockages decreases as the number of priority classes increases:  $\lim_{\bar{p} \rightarrow \infty} \mathcal{L}_{\bar{p}} = 0.5$ .

Fig. 16 shows the number of moves and the total loaded move time for various fill percentages and layout configurations. Both configurations have 400 slots in total. The combination of a 4 × 4 bay layout with a 5 × 5 warehouse layout requires fewer reshuffling moves than a 5 × 5 bay layout with a 4 × 4 warehouse layout. Shallower lanes result in fewer blockages. The total loaded move time shows a similar pattern, as the reshuffling move number and loaded move time are strongly correlated. Further, the figure displays that a higher fill percentage results in more reshuffling moves and higher total loaded move times. Especially, the step from 80% to 90% shows a substantial increase in the total loaded move time.

Fig. 17 presents the mean loaded move time for instances with one-tier, a 4 × 4 bay layout, and 10 priority classes. It shows that the mean loaded move time per move increases with the fill percentage. The reason for this is that fewer repositioning slots are available in close range. Larger warehouse layouts cause smaller mean loaded move times because the blocking unit loads are less likely at the edge of a warehouse. Hence, more potential repositioning slots are nearby. For a 40% fill percentage, this effect does not show because enough open slots are available in the surrounding area of a blocking unit load.

### 5.3 MR-MUPMP experimental analysis

This subsection analyzes the performance of the proposed routing approach to extend the MUPMP to the MR-MUPMP (see Section 4.5), focusing on runtime behavior and solution quality for two objective functions: total travel time and makespan.

**Routing runtime** Fig. 18 illustrates the routing runtime (see Section 4.5) required to find an initial routing solution for each considered objective function. The results indicate that finding a solution for the travel time objective (Fig. 18(a)) is computationally less demanding compared to finding a first solution for the makespan objective (Fig. 18(b)). Additionally, the solution time increases with the number of robots. Both effects can be attributed to the higher degree of symmetry in the solution space for the makespan objective. The time required to find the first solution also grows with the fill percentage, warehouse layout, and bay layout dimensions, as these factors directly contribute to an increased number of reshuffling moves. Hence, the routing becomes computationally more challenging.

Fig. 19 shows the routing runtime of the best found solution within the 300-second routing runtime limit. The figure shows for the travel time objective (Fig. 19(a)) no improvement is found after a short time. The whole runtime is used for the makespan objective (Fig. 19(b)) to improve the solution for bigger layout configurations. However, Fig. 20 shows how the major improvement in solution quality is achieved swiftly after a first solution is found. Hence, the routing for the makespan objective can be stopped 20 s after the first solution is found while still achieving a good solution quality.

**Travel time and makespan** Fig. 21 presents the makespan and travel time objective values when optimizing for travel time (Fig. 21(a)) and makespan (Fig. 21(b)). When optimizing for the makespan, a linear relationship between the makespan and travel time for each number of robots becomes apparent. This indicates that optimizing for makespan inherently involves an indirect optimization for travel time. Conversely, minimizing travel time in the objective function does not result in any implicit optimization for the makespan.

Fig. 22 shows the loaded and unloaded move time over the warehouse layout size. Even though the data covers the 90% fill percentage cases with generally longer loaded move times it becomes evident that the unloaded move time is more dominant as the warehouse layout size increases. The structure of the approach leads to a reduction of the loaded travel time, which is advantageous because loaded routes are more energy-intensive.

## 6. Conclusion

In this work, we extended the UPMP from a single bay to multiple bays - MUPMP. As the objective, we considered the total loaded move time for the minimal number of moves. To solve the problem, we adapted the two-step approach from Pfrommer et al. (2024) that is based on a network flow model and an A\* tree search procedure. However, given the potential for suboptimal solutions of the tree search in terms of loaded move time due to move dependencies, we devised an alternative strategy proposing an exact CP approach. In this study, we meticulously evaluated and contrasted the performance of both approaches.

The experiments show that the A\* approach can achieve optimal solutions for the total loaded move time in almost all instances that the CP approach was able to solve optimally while providing a tremendously faster runtime. Suboptimal solutions were particularly noticeable in one-tier instances characterized by larger bay layouts and high fill levels. At these high fill levels of 80% or 90%, the reduced availability of repositioning options in close distance heightens the significance of optimizing loaded move time. For two-tier instances, this effect was also observable for smaller layout configurations and lower fill percentages. Further, we found that an increase in fill percentage does not necessarily increase the A\* solution time, even though more moves are necessary because of a reduced branching factor by a smaller number of possible moves. Overall, the number of reshuffling moves increases with the number of priority classes and the size of the layout configuration. The bay size has a significantly larger impact on the number of reshuffling moves than the warehouse size. Hence, it can be beneficial to split the same number of slots into multiple bays.

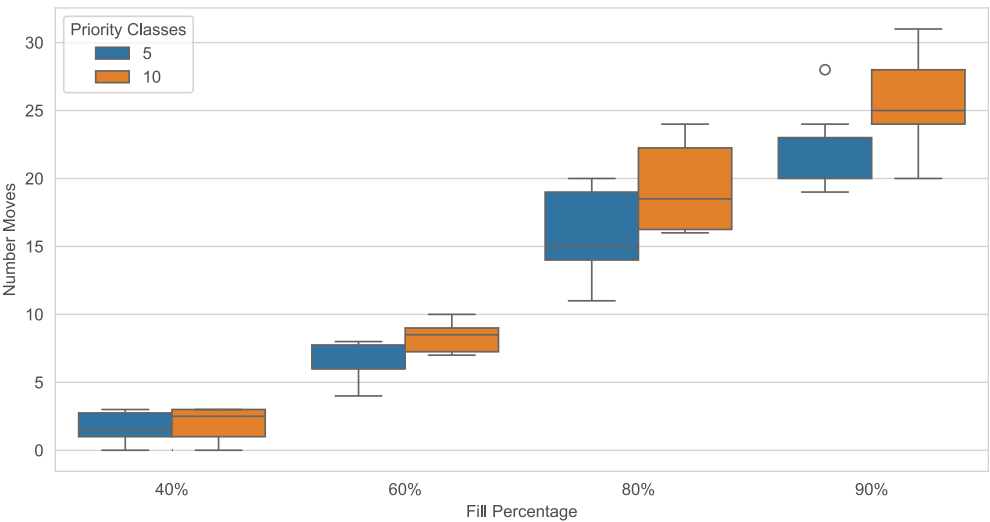


Fig. 15. Number of moves per fill percentage for each priority class configuration in a one-tier, 5 × 5 bay layout, and 4 × 4 warehouse layout.

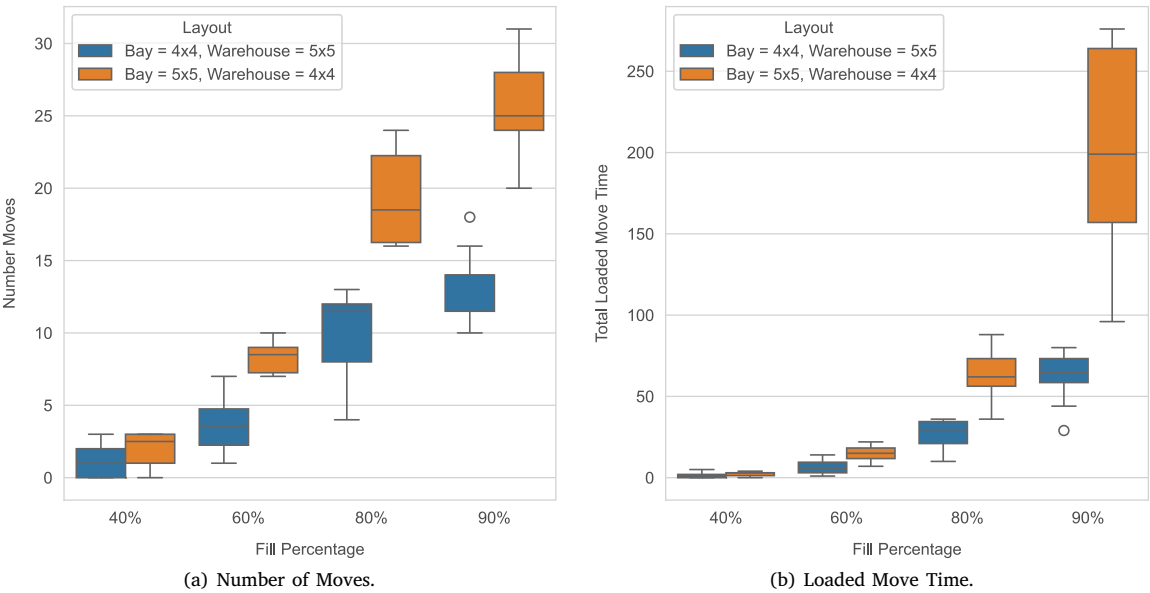


Fig. 16. Number of moves and total loaded move time for two one-tier layout configurations with the same number of slots, one-tier, and 10 priority classes.

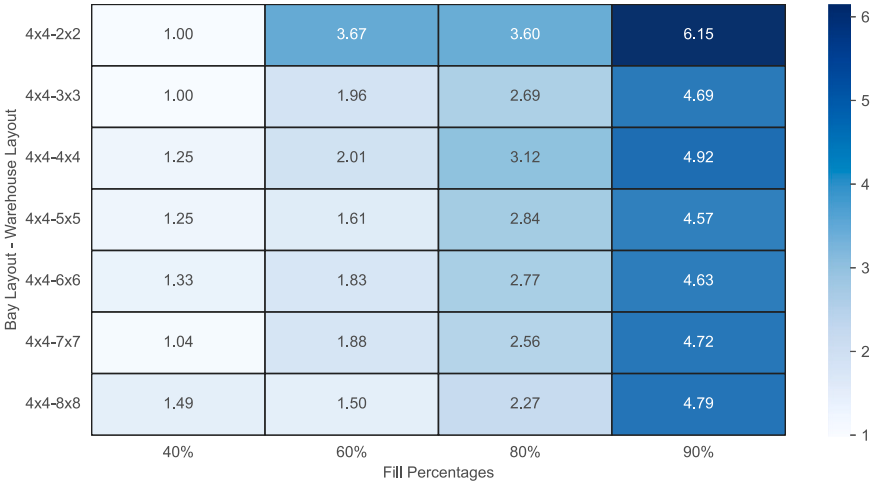
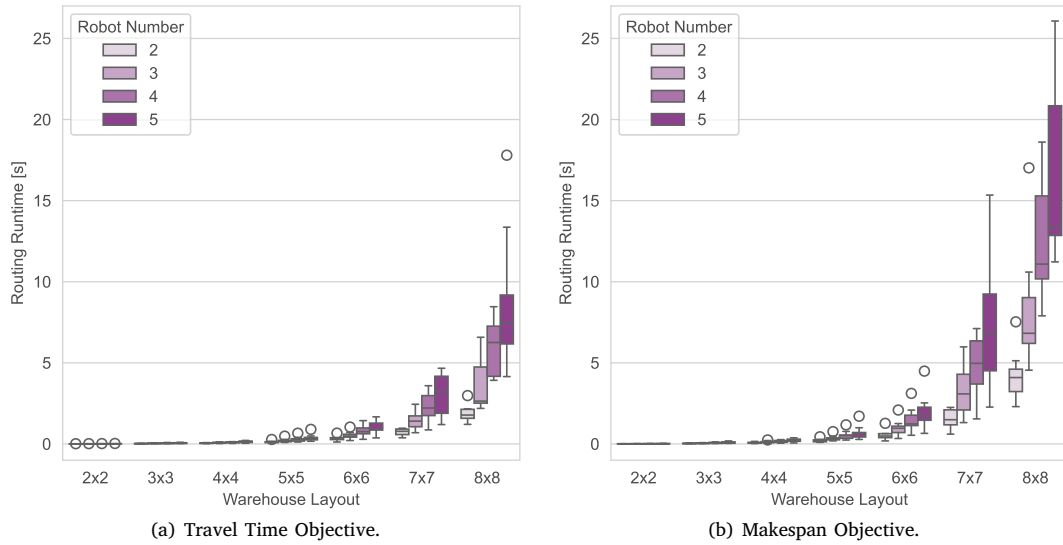
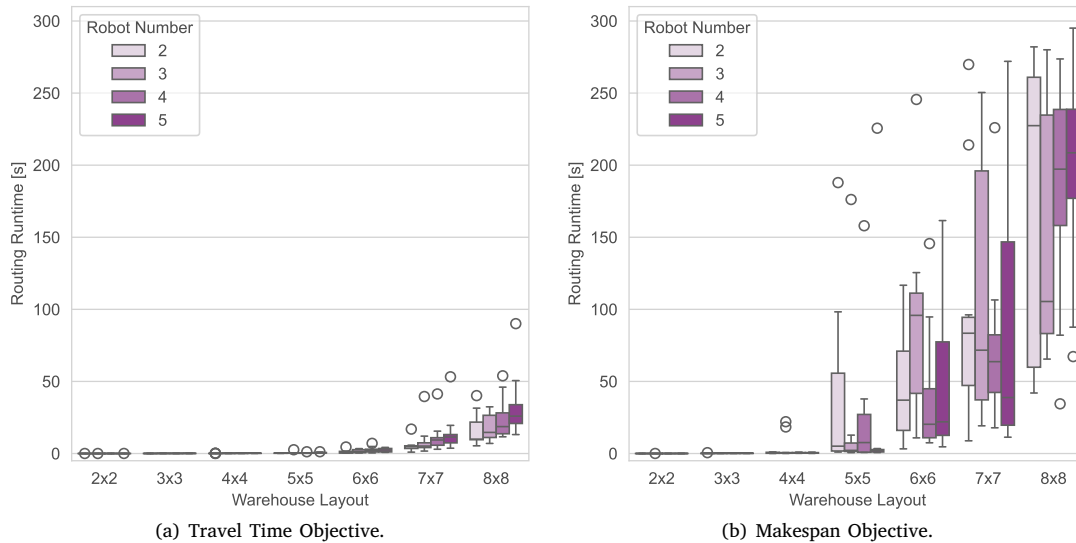


Fig. 17. Mean loaded move time for one-tier instances with 10 priority classes.



**Fig. 18.** Comparison of routing runtimes for the first solutions with travel time objective and makespan objective in a one-tier,  $4 \times 4$  bay layout, 10 priority classes, and 90% fill percentage.



**Fig. 19.** Comparison of routing runtimes for the best solutions with travel time objective and makespan objective in a one-tier,  $4 \times 4$  bay layout, 10 priority classes, and 90% fill percentage.

Further, we extended the approach by introducing an additional routing step that assigns reshuffling moves to multiple AMRs, addressing the multi-robot version of the problem (MR-MUPMP). This extension increases the practical relevance of the method, reflecting real-world warehouse scenarios where several AMRs operate in parallel to complete tasks cooperatively. The proposed MIP formulations efficiently route robots between fixed pre-marshalling moves while preserving move dependencies, aiming to minimize overall travel time or makespan. Experimental results show that the sequential approach tends to shift movement toward unloaded travel time, which is beneficial, as loaded travel time is generally more energy-intensive in warehouse operations.

Some simplifications were introduced in the problem setup that have little algorithmic impact but may affect realism. Firstly, Manhattan distance is used for routing, which may slightly overestimate travel times in environments where shortcut paths are possible. Second, travel time is assumed to be proportional to distance, without accounting

for acceleration, deceleration, or other motion dynamics. Third, travel within bays is neglected, which may lead to an underestimation of actual travel time. Finally, potential delays due to AMRs crossing paths or waiting are not modeled. These simplifications suggest opportunities for future work to incorporate more realistic motion and timing.

The proposed sequential step-based approach introduces limitations that affect overall optimality. Each step optimizes a specific subproblem without revisiting earlier decisions, which can lead to suboptimal global solutions. In Step 1, the focus lies solely on minimizing the number of misplaced unit loads, without considering that alternative configurations could result in lower travel times. Additionally, access directions for each stack are fixed at the beginning of the process. As shown in our prior work (Pfrommer et al., 2024), this restriction can lead to additional moves in specific cases, as certain blocking situations could be resolved more efficiently if stacks were allowed to be accessed from multiple directions. Step 2 then prioritizes minimizing the number of moves and only uses loaded move time as a secondary

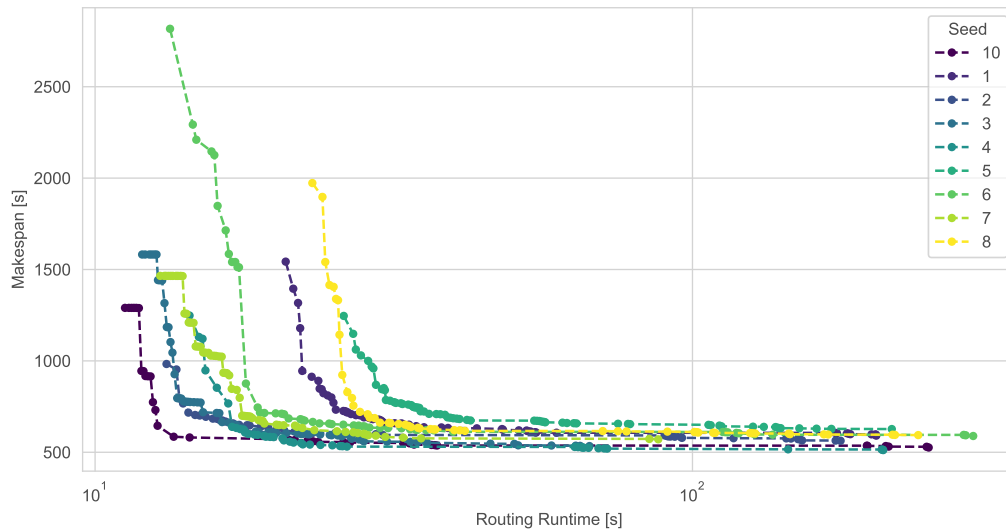


Fig. 20. Solution quality over routing runtime for makespan objective in a one-tier,  $4 \times 4$  bay layout, 10 priority classes, 90% fill percentage, and five robots.

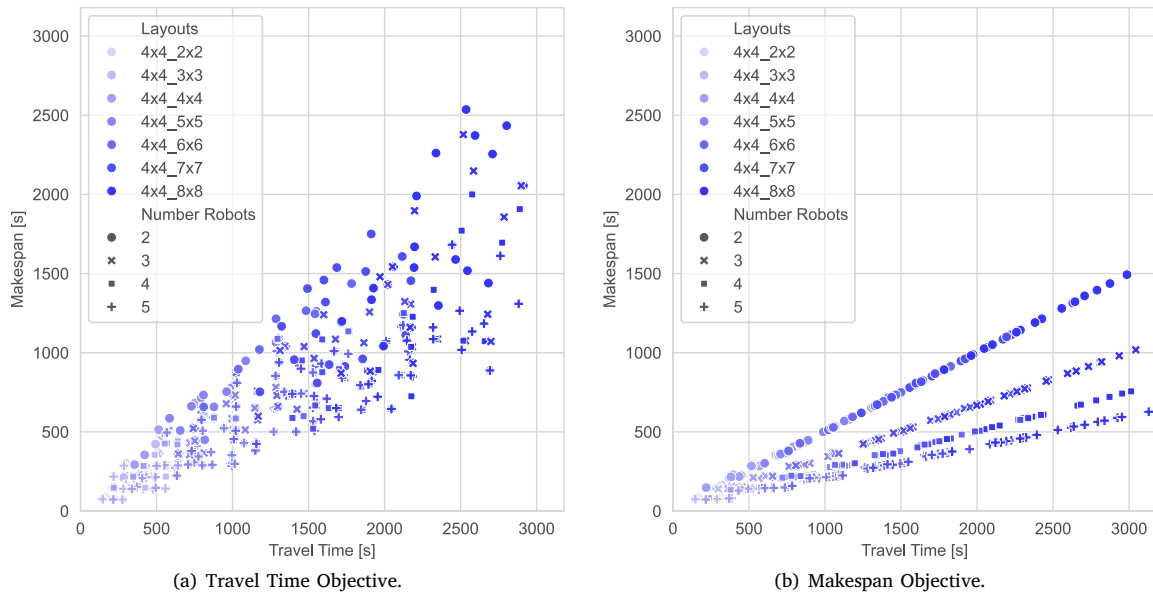


Fig. 21. Makespan and travel time value while optimizing for travel time and makespan.

criterion. However, this prioritization may overlook solutions with additional moves but significantly lower loaded travel time. Finally, Step 3 attempts to optimize makespan and total travel time for a fixed sequence of moves. Yet, better overall outcomes might be achieved with a different move sequence altogether. These limitations highlight the trade-off between problem decomposition for solvability and the loss of global optimality. Future work could explore integrated or iterative approaches that allow feedback between steps to improve overall solution quality. Because the tree search in Step 2 shows limited scalability, especially in multi-tier configurations where A\* may fail to return a solution, future work should explore heuristic or metaheuristic approaches to improve robustness and efficiency under practical time constraints. Moreover, exploring the integration of the MUPMP into a simulation model akin to Pfrommer et al. (2022), which comprehensively addresses pertinent operational decision problems (Pfrommer and Meyer, 2020), would provide valuable insights into the collective effect on warehouse performance.

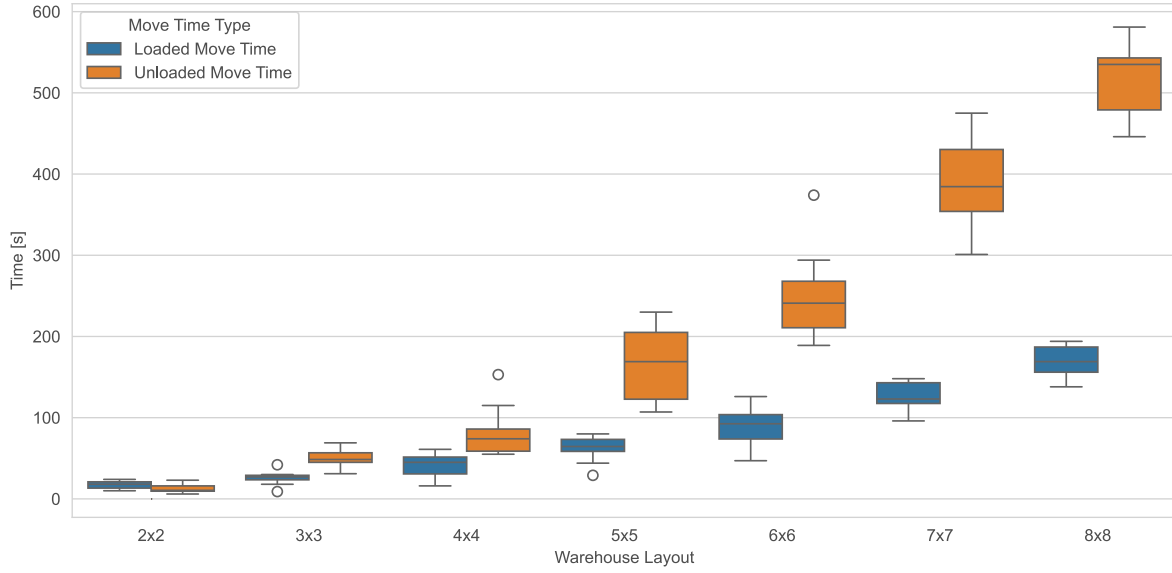
#### CRediT authorship contribution statement

**Thomas Bömer:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology. **Jakob Pfrommer:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Conceptualization. **Daniyar Akizhanov:** Writing – original draft, Software, Methodology. **Anne Meyer:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

#### Appendix

##### A.1. Complete constraint programming model

In this section, the complete CP model is presented. Let  $\bar{s}$  denote the number of virtual lanes and  $\bar{t}$  represent the number of positions in each virtual lane  $s$ . Accordingly,  $S = \{1, \dots, \bar{s}\}$  is the set of virtual lanes and



**Fig. 22.** Loaded and unloaded move time over warehouse layouts for makespan objective, five robots, one-tier, 4 × 4 bay layout, 10 priority classes, and 90% fill percentage.

$\mathcal{T}_s = \{1, \dots, \bar{t}\}$  is the set of positions for virtual lane  $s \in S$ . A slot  $(s, t)$  is defined by virtual lane  $s \in S$  and position  $t \in \mathcal{T}_s$ . Let  $d_{s,s'}$  be the distance between virtual lane  $s \in S$  and  $s' \in S$ . Let  $\bar{k}$  be the permissible number of moves in the model.  $\mathcal{K}$  is the set of stages, defined as  $\mathcal{K} = \{1, \dots, \bar{k}\}$ . Stage 0 signifies the initial layout.  $\mathcal{K}^0 = \{0, 1, \dots, \bar{k}\}$  is the set of stages, including the initial layout. Let  $\bar{p}$  denote the maximum priority class and let  $\mathcal{P}$  be the set of priority classes  $\mathcal{P} \in \{1, \dots, \bar{p}\}$ . An empty slot has the priority class 0. Further, the variables  $x_{s,t}^k$ ,  $y_{s,t}^k$ ,  $\delta_{s,t}^k$ ,  $z_{s,t}^k$ , and  $w_{s,t}^k$  are introduced.

$$x_{s,t}^k = \begin{cases} 0 & \text{If the slot } (s, t) \text{ is empty during stage } k \\ p & \text{If a unit load with priority } p \text{ is placed in slot } (s, t) \text{ during stage } k \end{cases}$$

$$\forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K}^0$$

$$y_{s,t}^k = \begin{cases} 1 & \text{If a unit load is moved to slot } (s, t) \text{ during stage } k \\ 0 & \text{Otherwise} \end{cases}$$

$$\forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K}$$

$$\delta_{s,t}^k = \begin{cases} 1 & \text{If there is a unit load in slot } (s, t) \text{ is empty during stage } k \\ 0 & \text{If a slot } (s, t) \text{ is empty during stage } k \end{cases}$$

$$\forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K}^0$$

$$z_{s,t}^k = \begin{cases} 1 & \text{If a unit load is removed from slot } (s, t) \text{ during stage } k \\ 0 & \text{Otherwise} \end{cases}$$

$$\forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K}$$

$$w_{s,t}^k = \begin{cases} 1 & \text{If there is a blocking unit load in slot } (s, t) \text{ during stage } k \\ 0 & \text{Otherwise} \end{cases}$$

$$\forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K}$$

$$\min \sum_{k \in \mathcal{K}} \sum_{s \in S} \sum_{s' \in S} \sum_{t \in \mathcal{T}_s} \sum_{t' \in \mathcal{T}_{s'}} z_{s,t}^k \cdot y_{s',t'}^k \cdot d_{s,s'} \quad (\text{A.1})$$

Subject to :

$$x_{s,t}^0 = f_{s,t} \quad \forall s \in S, \forall t \in \mathcal{T}_s \quad (\text{A.2})$$

$$|\{x_{s,t}^k : s \in S, t \in \mathcal{T}_s, x_{s,t}^k = p\}| = m_p \quad p \in \mathcal{P}^0, k \in \mathcal{K} \quad (\text{A.3})$$

$$\sum_{s \in S} \sum_{t \in \mathcal{T}_s} y_{s,t}^k = 1 \quad \forall k \in \mathcal{K} \quad (\text{A.4})$$

$$x_{s,t}^k \leq \bar{p} \cdot \delta_{s,t}^k \quad \forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K}^0 \quad (\text{A.5})$$

$$\delta_{s,t}^k \leq x_{s,t}^k \quad \forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K}^0 \quad (\text{A.6})$$

$$x_{s,t}^{k-1} \leq x_{s,t}^k + \bar{p}(1 - \delta_{s,t}^k) \quad \forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K} \quad (\text{A.7})$$

$$x_{s,t}^k \leq x_{s,t}^{k-1} + \bar{p}(1 - \delta_{s,t}^{k-1}) \quad \forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K} \quad (\text{A.8})$$

$$y_{s,1}^k + \delta_{s,1}^{k-1} \leq 1 \quad \forall s \in S, \forall k \in \mathcal{K} \quad (\text{A.9})$$

$$y_{s,t}^k \leq \delta_{s,t}^{k+1} \quad \forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K} \setminus \{\bar{k}\} \quad (\text{A.10})$$

$$\sum_{s \in S} \sum_{t \in \mathcal{T}_s} z_{s,t}^k = 1 \quad \forall k \in \mathcal{K} \quad (\text{A.11})$$

$$\delta_{s,t}^k + z_{s,t}^k = y_{s,t}^k + \delta_{s,t}^{k-1} \quad \forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K} \quad (\text{A.12})$$

$$y_{s,t+1}^k + \delta_{s,t+1}^{k-1} + z_{s,t}^k \leq \delta_{s,t}^{k-1} \quad \forall s \in S, \forall t \in \mathcal{T}_s \setminus \{\bar{t}\}, \forall k \in \mathcal{K} \quad (\text{A.13})$$

$$z_{s,\bar{t}}^{k+1} + y_{s,\bar{t}}^k \leq \delta_{s,\bar{t}}^k \quad \forall s \in S, \forall k \in \mathcal{K} \setminus \{\bar{k}\} \quad (\text{A.14})$$

$$z_{s,\bar{t}}^1 \leq \delta_{s,\bar{t}}^0 \quad \forall s \in S \quad (\text{A.15})$$

$$\sum_{t \in \mathcal{T}_s} y_{s,t}^k + \sum_{t \in \mathcal{T}_s} z_{s,t}^{k+1} \leq 1 \quad \forall s \in S, \forall k \in \mathcal{K} \setminus \{\bar{k}\} \quad (\text{A.16})$$

$$x_{s,t+1}^k \leq x_{s,t}^k + \bar{p} \cdot w_{s,t+1}^k \quad \forall s \in S, \forall t \in \mathcal{T}_s \setminus \{\bar{t}\}, \forall k \in \mathcal{K} \quad (\text{A.17})$$

**Table 9**

Step 1: Detailed Results for access direction fixing one-tier.

| Layout (Bay-Warehouse) | Fill % | Priority classes | Mean runtime |
|------------------------|--------|------------------|--------------|
| 3 × 3-2 × 2            | 40%    | 5                | 0.19         |
| 3 × 3-2 × 2            | 40%    | 10               | 0.19         |
| 3 × 3-2 × 2            | 60%    | 5                | 0.17         |
| 3 × 3-2 × 2            | 60%    | 10               | 0.17         |
| 3 × 3-2 × 2            | 80%    | 5                | 0.18         |
| 3 × 3-2 × 2            | 80%    | 10               | 0.17         |
| 3 × 3-2 × 2            | 90%    | 5                | 0.18         |
| 3 × 3-2 × 2            | 90%    | 10               | 0.17         |
| 3 × 3-3 × 3            | 40%    | 5                | 0.44         |
| 3 × 3-3 × 3            | 40%    | 10               | 0.44         |
| 3 × 3-3 × 3            | 60%    | 5                | 0.42         |
| 3 × 3-3 × 3            | 60%    | 10               | 0.41         |
| 3 × 3-3 × 3            | 80%    | 5                | 0.42         |
| 3 × 3-3 × 3            | 80%    | 10               | 0.42         |
| 3 × 3-3 × 3            | 90%    | 5                | 0.44         |
| 3 × 3-3 × 3            | 90%    | 10               | 0.43         |
| 3 × 3-4 × 4            | 40%    | 5                | 0.88         |
| 3 × 3-4 × 4            | 40%    | 10               | 0.87         |
| 3 × 3-4 × 4            | 60%    | 5                | 0.85         |
| 3 × 3-4 × 4            | 60%    | 10               | 0.83         |
| 3 × 3-4 × 4            | 80%    | 5                | 0.86         |
| 3 × 3-4 × 4            | 80%    | 10               | 0.84         |
| 3 × 3-4 × 4            | 90%    | 5                | 0.86         |
| 3 × 3-4 × 4            | 90%    | 10               | 0.84         |
| 3 × 3-5 × 5            | 40%    | 5                | 1.57         |
| 3 × 3-5 × 5            | 40%    | 10               | 1.56         |
| 3 × 3-5 × 5            | 60%    | 5                | 1.50         |
| 3 × 3-5 × 5            | 60%    | 10               | 1.49         |
| 3 × 3-5 × 5            | 80%    | 5                | 1.52         |
| 3 × 3-5 × 5            | 80%    | 10               | 1.49         |
| 3 × 3-5 × 5            | 90%    | 5                | 1.52         |
| 3 × 3-5 × 5            | 90%    | 10               | 1.49         |
| 3 × 3-6 × 6            | 40%    | 5                | 2.61         |
| 3 × 3-6 × 6            | 40%    | 10               | 2.58         |
| 3 × 3-6 × 6            | 60%    | 5                | 2.51         |
| 3 × 3-6 × 6            | 60%    | 10               | 2.47         |
| 3 × 3-6 × 6            | 80%    | 5                | 2.51         |
| 3 × 3-6 × 6            | 80%    | 10               | 2.47         |
| 3 × 3-6 × 6            | 90%    | 5                | 2.50         |
| 3 × 3-6 × 6            | 90%    | 10               | 2.47         |
| 3 × 3-7 × 7            | 40%    | 5                | 4.07         |
| 3 × 3-7 × 7            | 40%    | 10               | 4.03         |
| 3 × 3-7 × 7            | 60%    | 5                | 3.98         |
| 3 × 3-7 × 7            | 60%    | 10               | 3.91         |
| 3 × 3-7 × 7            | 80%    | 5                | 3.98         |
| 3 × 3-7 × 7            | 80%    | 10               | 3.92         |
| 3 × 3-7 × 7            | 90%    | 5                | 3.96         |
| 3 × 3-7 × 7            | 90%    | 10               | 3.92         |
| 3 × 3-8 × 8            | 40%    | 5                | 6.17         |
| 3 × 3-8 × 8            | 40%    | 10               | 6.10         |
| 3 × 3-8 × 8            | 60%    | 5                | 5.96         |
| 3 × 3-8 × 8            | 60%    | 10               | 5.90         |
| 3 × 3-8 × 8            | 80%    | 5                | 5.99         |
| 3 × 3-8 × 8            | 80%    | 10               | 5.88         |
| 3 × 3-8 × 8            | 90%    | 5                | 5.96         |
| 3 × 3-8 × 8            | 90%    | 10               | 5.90         |
| 3 × 3-9 × 9            | 40%    | 5                | 8.98         |
| 3 × 3-9 × 9            | 40%    | 10               | 8.89         |
| 3 × 3-9 × 9            | 60%    | 5                | 8.78         |
| 3 × 3-9 × 9            | 60%    | 10               | 8.66         |
| 3 × 3-9 × 9            | 80%    | 5                | 8.74         |
| 3 × 3-9 × 9            | 80%    | 10               | 8.61         |
| 3 × 3-9 × 9            | 90%    | 5                | 8.70         |
| 3 × 3-9 × 9            | 90%    | 10               | 8.58         |
| 3 × 3-10 × 10          | 40%    | 5                | 12.74        |
| 3 × 3-10 × 10          | 40%    | 10               | 12.60        |
| 3 × 3-10 × 10          | 60%    | 5                | 12.51        |
| 3 × 3-10 × 10          | 60%    | 10               | 12.33        |
| 3 × 3-10 × 10          | 80%    | 5                | 12.45        |
| 3 × 3-10 × 10          | 80%    | 10               | 12.25        |
| 3 × 3-10 × 10          | 90%    | 5                | 12.44        |
| 3 × 3-10 × 10          | 90%    | 10               | 12.28        |
| 3 × 3-11 × 11          | 40%    | 5                | 17.68        |

(continued on next page)

Table 9 (continued).

| Layout (Bay-Warehouse) | Fill % | Priority classes | Mean runtime |
|------------------------|--------|------------------|--------------|
| 3 × 3-11 × 11          | 40%    | 10               | 17.42        |
| 3 × 3-11 × 11          | 60%    | 5                | 17.29        |
| 3 × 3-11 × 11          | 60%    | 10               | 17.21        |
| 3 × 3-11 × 11          | 80%    | 5                | 17.25        |
| 3 × 3-11 × 11          | 80%    | 10               | 16.92        |
| 3 × 3-11 × 11          | 90%    | 5                | 17.10        |
| 3 × 3-11 × 11          | 90%    | 10               | 16.89        |
| 3 × 3-12 × 12          | 40%    | 5                | 23.82        |
| 3 × 3-12 × 12          | 40%    | 10               | 23.61        |
| 3 × 3-12 × 12          | 60%    | 5                | 23.38        |
| 3 × 3-12 × 12          | 60%    | 10               | 23.06        |
| 3 × 3-12 × 12          | 80%    | 5                | 23.27        |
| 3 × 3-12 × 12          | 80%    | 10               | 22.87        |
| 3 × 3-12 × 12          | 90%    | 5                | 23.10        |
| 3 × 3-12 × 12          | 90%    | 10               | 22.81        |
| 4 × 4-2 × 2            | 40%    | 5                | 0.44         |
| 4 × 4-2 × 2            | 40%    | 10               | 0.43         |
| 4 × 4-2 × 2            | 60%    | 5                | 0.40         |
| 4 × 4-2 × 2            | 60%    | 10               | 0.38         |
| 4 × 4-2 × 2            | 80%    | 5                | 0.42         |
| 4 × 4-2 × 2            | 80%    | 10               | 0.42         |
| 4 × 4-2 × 2            | 90%    | 5                | 0.42         |
| 4 × 4-2 × 2            | 90%    | 10               | 0.41         |
| 4 × 4-3 × 3            | 40%    | 5                | 1.05         |
| 4 × 4-3 × 3            | 40%    | 10               | 1.03         |
| 4 × 4-3 × 3            | 60%    | 5                | 0.97         |
| 4 × 4-3 × 3            | 60%    | 10               | 0.94         |
| 4 × 4-3 × 3            | 80%    | 5                | 1.00         |
| 4 × 4-3 × 3            | 80%    | 10               | 0.98         |
| 4 × 4-3 × 3            | 90%    | 5                | 1.01         |
| 4 × 4-3 × 3            | 90%    | 10               | 0.99         |
| 4 × 4-4 × 4            | 40%    | 5                | 2.00         |
| 4 × 4-4 × 4            | 40%    | 10               | 1.98         |
| 4 × 4-4 × 4            | 60%    | 5                | 1.93         |
| 4 × 4-4 × 4            | 60%    | 10               | 1.89         |
| 4 × 4-4 × 4            | 80%    | 5                | 1.89         |
| 4 × 4-4 × 4            | 80%    | 10               | 1.84         |
| 4 × 4-4 × 4            | 90%    | 5                | 1.93         |
| 4 × 4-4 × 4            | 90%    | 10               | 1.88         |
| 4 × 4-5 × 5            | 40%    | 5                | 3.46         |
| 4 × 4-5 × 5            | 40%    | 10               | 3.42         |
| 4 × 4-5 × 5            | 60%    | 5                | 3.31         |
| 4 × 4-5 × 5            | 60%    | 10               | 3.23         |
| 4 × 4-5 × 5            | 80%    | 5                | 3.29         |
| 4 × 4-5 × 5            | 80%    | 10               | 3.23         |
| 4 × 4-5 × 5            | 90%    | 5                | 3.32         |
| 4 × 4-5 × 5            | 90%    | 10               | 3.22         |
| 4 × 4-6 × 6            | 40%    | 5                | 5.50         |
| 4 × 4-6 × 6            | 40%    | 10               | 5.45         |
| 4 × 4-6 × 6            | 60%    | 5                | 5.34         |
| 4 × 4-6 × 6            | 60%    | 10               | 5.23         |
| 4 × 4-6 × 6            | 80%    | 5                | 5.30         |
| 4 × 4-6 × 6            | 80%    | 10               | 5.22         |
| 4 × 4-6 × 6            | 90%    | 5                | 5.37         |
| 4 × 4-6 × 6            | 90%    | 10               | 5.22         |
| 4 × 4-7 × 7            | 40%    | 5                | 8.44         |
| 4 × 4-7 × 7            | 40%    | 10               | 8.37         |
| 4 × 4-7 × 7            | 60%    | 5                | 8.17         |
| 4 × 4-7 × 7            | 60%    | 10               | 8.05         |
| 4 × 4-7 × 7            | 80%    | 5                | 8.14         |
| 4 × 4-7 × 7            | 80%    | 10               | 8.06         |
| 4 × 4-7 × 7            | 90%    | 5                | 8.23         |
| 4 × 4-7 × 7            | 90%    | 10               | 8.09         |
| 4 × 4-8 × 8            | 40%    | 5                | 12.43        |
| 4 × 4-8 × 8            | 40%    | 10               | 12.33        |
| 4 × 4-8 × 8            | 60%    | 5                | 12.12        |
| 4 × 4-8 × 8            | 60%    | 10               | 11.99        |
| 4 × 4-8 × 8            | 80%    | 5                | 12.03        |
| 4 × 4-8 × 8            | 80%    | 10               | 11.86        |
| 4 × 4-8 × 8            | 90%    | 5                | 12.14        |
| 4 × 4-8 × 8            | 90%    | 10               | 11.95        |
| 5 × 5-2 × 2            | 40%    | 5                | 1.17         |
| 5 × 5-2 × 2            | 40%    | 10               | 1.05         |
| 5 × 5-2 × 2            | 60%    | 5                | 0.95         |

(continued on next page)

Table 9 (continued).

| Layout (Bay-Warehouse) | Fill % | Priority classes | Mean runtime |
|------------------------|--------|------------------|--------------|
| 5 × 5-2 × 2            | 60%    | 10               | 0.89         |
| 5 × 5-2 × 2            | 80%    | 5                | 1.01         |
| 5 × 5-2 × 2            | 80%    | 10               | 0.97         |
| 5 × 5-2 × 2            | 90%    | 5                | 1.10         |
| 5 × 5-2 × 2            | 90%    | 10               | 1.01         |
| 5 × 5-3 × 3            | 40%    | 5                | 2.63         |
| 5 × 5-3 × 3            | 40%    | 10               | 2.45         |
| 5 × 5-3 × 3            | 60%    | 5                | 2.18         |
| 5 × 5-3 × 3            | 60%    | 10               | 2.10         |
| 5 × 5-3 × 3            | 80%    | 5                | 2.41         |
| 5 × 5-3 × 3            | 80%    | 10               | 2.27         |
| 5 × 5-3 × 3            | 90%    | 5                | 2.47         |
| 5 × 5-3 × 3            | 90%    | 10               | 2.39         |
| 5 × 5-4 × 4            | 40%    | 5                | 4.81         |
| 5 × 5-4 × 4            | 40%    | 10               | 4.60         |
| 5 × 5-4 × 4            | 60%    | 5                | 4.15         |
| 5 × 5-4 × 4            | 60%    | 10               | 3.97         |
| 5 × 5-4 × 4            | 80%    | 5                | 4.45         |
| 5 × 5-4 × 4            | 80%    | 10               | 4.17         |
| 5 × 5-4 × 4            | 90%    | 5                | 4.55         |
| 5 × 5-4 × 4            | 90%    | 10               | 4.39         |
| 5 × 5-5 × 5            | 40%    | 5                | 7.87         |
| 5 × 5-5 × 5            | 40%    | 10               | 7.59         |
| 5 × 5-5 × 5            | 60%    | 5                | 6.95         |
| 5 × 5-5 × 5            | 60%    | 10               | 6.54         |
| 5 × 5-5 × 5            | 80%    | 5                | 7.39         |
| 5 × 5-5 × 5            | 80%    | 10               | 7.00         |
| 5 × 5-5 × 5            | 90%    | 5                | 7.40         |
| 5 × 5-5 × 5            | 90%    | 10               | 7.09         |
| 5 × 5-6 × 6            | 40%    | 5                | 12.05        |
| 5 × 5-6 × 6            | 40%    | 10               | 11.52        |
| 5 × 5-6 × 6            | 60%    | 5                | 10.80        |
| 5 × 5-6 × 6            | 60%    | 10               | 10.19        |
| 5 × 5-6 × 6            | 80%    | 5                | 11.26        |
| 5 × 5-6 × 6            | 80%    | 10               | 10.83        |
| 5 × 5-6 × 6            | 90%    | 5                | 11.47        |
| 5 × 5-6 × 6            | 90%    | 10               | 11.06        |
| 6 × 6-2 × 2            | 40%    | 5                | 3.40         |
| 6 × 6-2 × 2            | 40%    | 10               | 3.12         |
| 6 × 6-2 × 2            | 60%    | 5                | 2.95         |
| 6 × 6-2 × 2            | 60%    | 10               | 2.65         |
| 6 × 6-2 × 2            | 80%    | 5                | 3.55         |
| 6 × 6-2 × 2            | 80%    | 10               | 2.77         |
| 6 × 6-2 × 2            | 90%    | 5                | 4.20         |
| 6 × 6-2 × 2            | 90%    | 10               | 3.72         |
| 6 × 6-3 × 3            | 40%    | 5                | 7.48         |
| 6 × 6-3 × 3            | 40%    | 10               | 6.71         |
| 6 × 6-3 × 3            | 60%    | 5                | 7.04         |
| 6 × 6-3 × 3            | 60%    | 10               | 6.22         |
| 6 × 6-3 × 3            | 80%    | 5                | 7.54         |
| 6 × 6-3 × 3            | 80%    | 10               | 6.77         |
| 6 × 6-3 × 3            | 90%    | 5                | 9.30         |
| 6 × 6-3 × 3            | 90%    | 10               | 8.76         |
| 6 × 6-4 × 4            | 40%    | 5                | 14.38        |
| 6 × 6-4 × 4            | 40%    | 10               | 13.19        |
| 6 × 6-4 × 4            | 60%    | 5                | 12.72        |
| 6 × 6-4 × 4            | 60%    | 10               | 11.79        |
| 6 × 6-4 × 4            | 80%    | 5                | 13.88        |
| 6 × 6-4 × 4            | 80%    | 10               | 12.42        |
| 6 × 6-4 × 4            | 90%    | 5                | 17.29        |
| 6 × 6-4 × 4            | 90%    | 10               | 16.85        |
| 6 × 6-5 × 5            | 40%    | 5                | 24.11        |
| 6 × 6-5 × 5            | 40%    | 10               | 21.64        |
| 6 × 6-5 × 5            | 60%    | 5                | 21.13        |
| 6 × 6-5 × 5            | 60%    | 10               | 19.30        |
| 6 × 6-5 × 5            | 80%    | 5                | 22.71        |
| 6 × 6-5 × 5            | 80%    | 10               | 20.72        |
| 6 × 6-5 × 5            | 90%    | 5                | 29.54        |
| 6 × 6-5 × 5            | 90%    | 10               | 28.99        |
| 6 × 6-6 × 6            | 40%    | 5                | 35.78        |
| 6 × 6-6 × 6            | 40%    | 10               | 32.18        |
| 6 × 6-6 × 6            | 60%    | 5                | 32.14        |
| 6 × 6-6 × 6            | 60%    | 10               | 29.40        |
| 6 × 6-6 × 6            | 80%    | 5                | 33.44        |
| 6 × 6-6 × 6            | 80%    | 10               | 31.20        |
| 6 × 6-6 × 6            | 90%    | 5                | 43.59        |
| 6 × 6-6 × 6            | 90%    | 10               | 43.52        |

**Table 10**

Step 1: Detailed Results for access direction fixing two-tier.

| Layout (Bay-Warehouse) | Fill % | Priority classes | Mean runtime |
|------------------------|--------|------------------|--------------|
| 3 × 3-2 × 2            | 40%    | 5                | 0.10         |
| 3 × 3-2 × 2            | 40%    | 10               | 0.10         |
| 3 × 3-2 × 2            | 60%    | 5                | 0.10         |
| 3 × 3-2 × 2            | 60%    | 10               | 0.11         |
| 3 × 3-2 × 2            | 80%    | 5                | 0.13         |
| 3 × 3-2 × 2            | 80%    | 10               | 0.13         |
| 3 × 3-2 × 2            | 90%    | 5                | 0.15         |
| 3 × 3-2 × 2            | 90%    | 10               | 0.15         |
| 3 × 3-3 × 3            | 40%    | 5                | 0.25         |
| 3 × 3-3 × 3            | 40%    | 10               | 0.26         |
| 3 × 3-3 × 3            | 60%    | 5                | 0.25         |
| 3 × 3-3 × 3            | 60%    | 10               | 0.26         |
| 3 × 3-3 × 3            | 80%    | 5                | 0.34         |
| 3 × 3-3 × 3            | 80%    | 10               | 0.42         |
| 3 × 3-3 × 3            | 90%    | 5                | 0.49         |
| 3 × 3-3 × 3            | 90%    | 10               | 0.47         |
| 3 × 3-4 × 4            | 40%    | 5                | 0.52         |
| 3 × 3-4 × 4            | 40%    | 10               | 0.51         |
| 3 × 3-4 × 4            | 60%    | 5                | 0.52         |
| 3 × 3-4 × 4            | 60%    | 10               | 0.54         |
| 3 × 3-4 × 4            | 80%    | 5                | 0.97         |
| 3 × 3-4 × 4            | 80%    | 10               | 0.85         |
| 3 × 3-4 × 4            | 90%    | 5                | 1.16         |
| 3 × 3-4 × 4            | 90%    | 10               | 1.12         |
| 3 × 3-5 × 5            | 40%    | 5                | 0.96         |
| 3 × 3-5 × 5            | 40%    | 10               | 0.95         |
| 3 × 3-5 × 5            | 60%    | 5                | 0.98         |
| 3 × 3-5 × 5            | 60%    | 10               | 1.00         |
| 3 × 3-5 × 5            | 80%    | 5                | 1.86         |
| 3 × 3-5 × 5            | 80%    | 10               | 2.02         |
| 3 × 3-5 × 5            | 90%    | 5                | 2.10         |
| 3 × 3-5 × 5            | 90%    | 10               | 2.16         |
| 3 × 3-6 × 6            | 40%    | 5                | 1.61         |
| 3 × 3-6 × 6            | 40%    | 10               | 1.61         |
| 3 × 3-6 × 6            | 60%    | 5                | 1.66         |
| 3 × 3-6 × 6            | 60%    | 10               | 1.67         |
| 3 × 3-6 × 6            | 80%    | 5                | 3.70         |
| 3 × 3-6 × 6            | 80%    | 10               | 3.95         |
| 3 × 3-6 × 6            | 90%    | 5                | 3.88         |
| 3 × 3-6 × 6            | 90%    | 10               | 4.45         |
| 4 × 4-2 × 2            | 40%    | 5                | 0.22         |
| 4 × 4-2 × 2            | 40%    | 10               | 0.22         |
| 4 × 4-2 × 2            | 60%    | 5                | 0.25         |
| 4 × 4-2 × 2            | 60%    | 10               | 0.25         |
| 4 × 4-2 × 2            | 80%    | 5                | 0.36         |
| 4 × 4-2 × 2            | 80%    | 10               | 0.36         |
| 4 × 4-2 × 2            | 90%    | 5                | 0.37         |
| 4 × 4-2 × 2            | 90%    | 10               | 0.42         |
| 4 × 4-3 × 3            | 40%    | 5                | 0.54         |
| 4 × 4-3 × 3            | 40%    | 10               | 0.54         |
| 4 × 4-3 × 3            | 60%    | 5                | 0.58         |
| 4 × 4-3 × 3            | 60%    | 10               | 0.58         |
| 4 × 4-3 × 3            | 80%    | 5                | 1.00         |
| 4 × 4-3 × 3            | 80%    | 10               | 1.06         |
| 4 × 4-3 × 3            | 90%    | 5                | 0.96         |
| 4 × 4-3 × 3            | 90%    | 10               | 1.05         |
| 4 × 4-4 × 4            | 40%    | 5                | 1.07         |
| 4 × 4-4 × 4            | 40%    | 10               | 1.08         |
| 4 × 4-4 × 4            | 60%    | 5                | 1.15         |
| 4 × 4-4 × 4            | 60%    | 10               | 1.16         |
| 4 × 4-4 × 4            | 80%    | 5                | 2.32         |
| 4 × 4-4 × 4            | 80%    | 10               | 2.25         |
| 4 × 4-4 × 4            | 90%    | 5                | 1.90         |
| 4 × 4-4 × 4            | 90%    | 10               | 2.32         |
| 4 × 4-5 × 5            | 40%    | 5                | 1.94         |
| 4 × 4-5 × 5            | 40%    | 10               | 1.94         |
| 4 × 4-5 × 5            | 60%    | 5                | 2.06         |
| 4 × 4-5 × 5            | 60%    | 10               | 2.10         |
| 4 × 4-5 × 5            | 80%    | 5                | 4.64         |
| 4 × 4-5 × 5            | 80%    | 10               | 4.74         |
| 4 × 4-5 × 5            | 90%    | 5                | 4.02         |
| 4 × 4-5 × 5            | 90%    | 10               | 5.19         |

(continued on next page)

Table 10 (continued).

| Layout (Bay-Warehouse) | Fill % | Priority classes | Mean runtime |
|------------------------|--------|------------------|--------------|
| 5 × 5-2 × 2            | 40%    | 5                | 0.48         |
| 5 × 5-2 × 2            | 40%    | 10               | 0.48         |
| 5 × 5-2 × 2            | 60%    | 5                | 0.54         |
| 5 × 5-2 × 2            | 60%    | 10               | 0.56         |
| 5 × 5-2 × 2            | 80%    | 5                | 0.73         |
| 5 × 5-2 × 2            | 80%    | 10               | 0.73         |
| 5 × 5-2 × 2            | 90%    | 5                | 0.80         |
| 5 × 5-2 × 2            | 90%    | 10               | 0.89         |
| 5 × 5-3 × 3            | 40%    | 5                | 1.11         |
| 5 × 5-3 × 3            | 40%    | 10               | 1.13         |
| 5 × 5-3 × 3            | 60%    | 5                | 1.22         |
| 5 × 5-3 × 3            | 60%    | 10               | 1.30         |
| 5 × 5-3 × 3            | 80%    | 5                | 1.87         |
| 5 × 5-3 × 3            | 80%    | 10               | 1.94         |
| 5 × 5-3 × 3            | 90%    | 5                | 2.08         |
| 5 × 5-3 × 3            | 90%    | 10               | 2.35         |
| 5 × 5-4 × 4            | 40%    | 5                | 2.08         |
| 5 × 5-4 × 4            | 40%    | 10               | 2.08         |
| 5 × 5-4 × 4            | 60%    | 5                | 2.35         |
| 5 × 5-4 × 4            | 60%    | 10               | 2.43         |
| 5 × 5-4 × 4            | 80%    | 5                | 4.03         |
| 5 × 5-4 × 4            | 80%    | 10               | 4.43         |
| 5 × 5-4 × 4            | 90%    | 5                | 4.49         |
| 5 × 5-4 × 4            | 90%    | 10               | 5.00         |
| 6 × 6-2 × 2            | 40%    | 5                | 1.19         |
| 6 × 6-2 × 2            | 40%    | 10               | 1.30         |
| 6 × 6-2 × 2            | 60%    | 5                | 1.58         |
| 6 × 6-2 × 2            | 60%    | 10               | 1.65         |
| 6 × 6-2 × 2            | 80%    | 5                | 2.44         |
| 6 × 6-2 × 2            | 80%    | 10               | 2.84         |
| 6 × 6-2 × 2            | 90%    | 5                | 3.70         |
| 6 × 6-2 × 2            | 90%    | 10               | 4.10         |
| 6 × 6-3 × 3            | 40%    | 5                | 2.96         |
| 6 × 6-3 × 3            | 40%    | 10               | 3.13         |
| 6 × 6-3 × 3            | 60%    | 5                | 3.72         |
| 6 × 6-3 × 3            | 60%    | 10               | 3.97         |
| 6 × 6-3 × 3            | 80%    | 5                | 6.31         |
| 6 × 6-3 × 3            | 80%    | 10               | 7.05         |
| 6 × 6-3 × 3            | 90%    | 5                | 8.52         |
| 6 × 6-3 × 3            | 90%    | 10               | 10.10        |

$$w_{s,t}^k + \delta_{s,t+1}^k \leq w_{s,t+1}^k + 1 \quad \forall s \in S, \forall t \in \mathcal{T}_s \setminus \{\bar{t}\}, \forall k \in \mathcal{K} \quad (\text{A.18})$$

$$w_{s,t}^k \leq \delta_{s,t}^k \quad \forall s \in S, \forall t \in \mathcal{T}_s, \forall k \in \mathcal{K} \quad (\text{A.19})$$

$$w_{s,1}^k = 0 \quad \forall s \in S, \forall k \in \mathcal{K} \quad (\text{A.20})$$

$$x_{s,t}^k + 1 \leq x_{s,t+1}^k + (\bar{p} + 1) \cdot (1 - w_{s,t+1}^k + w_{s,t}^k) \quad \forall s \in S, \forall t \in \mathcal{T}_s \setminus \{\bar{t}\}, \forall k \in \mathcal{K} \quad (\text{A.21})$$

$$\sum_{s \in S} \sum_{t \in \mathcal{T}_s} w_{s,t}^k + k \leq \bar{k} \quad \forall k \in \mathcal{K} \quad (\text{A.22})$$

$$\sum_{k \in \mathcal{K}} \sum_{s \in S} \sum_{s' \in S} \sum_{t \in \mathcal{T}_s} \sum_{t' \in \mathcal{T}_{s'}} z_{s,t}^k \cdot y_{s',t'}^k \cdot d_{s,s'} \leq c^{UB} \quad (\text{A.23})$$

The objective function (A.1) minimizes the total loaded move distance. Constraints (A.2) assign the initial layout to the virtual lanes of the warehouse. Constraints (A.3) ensure that the number of unit loads per priority group and the number of empty slots stays consistent for each stage. The number of moves per stage is restricted to one by constraints (A.4). Constraints (A.5) and (A.6) link the variables  $x_{s,t}^k$  and  $\delta_{s,t}^k$ .  $\delta_{s,t}^k$  is 0 if  $x_{s,t}^k$  is 0, else  $\delta_{s,t}^k$  is 1. Unit loads that are not moved are fixed to their position by constraints (A.7) and (A.8). Constraints (A.9) impose that a unit load can only be moved to a slot that was empty in the previous stage. Constraints (A.10) prevent the unit loads from being moved in two consecutive stages because the two moves could have been performed in one move. This rule is also called “transitive move avoidance” (Tierney et al., 2017). Constraints (A.11) set the number of

unit loads removed from the virtual lanes to 1 for each stage. Constraints (A.12) make sure that if a unit load is in a slot. It has been there in the previous stage or was moved there in the current stage. (A.13) impose that a unit load can be removed from a certain slot in a stage  $k$  only if the respective slot was occupied and the slot in front ( $s, t+1$ ) was empty during the previous stage. Constraints (A.14) impose that a unit load can only be moved to a slot ( $s, t$ ) that was empty during the previous stage. It also requires that the slot ( $s, t-1$ ) was occupied. Constraints (A.15) do the same for the first stage. Constraints (A.16) impose that when a unit load is moved to a certain virtual lane, no unit load can be removed from that virtual lane in the next stage. Constraints (A.17) express that a unit load that is in front of another unit load with a higher priority class is a blocking unit load. Constraints (A.18) require that if there is a blocking unit load on slot ( $s, t$ ) and slot ( $s, t+1$ ) is occupied, there is also a blocking unit load on slot ( $s, t+1$ ). Constraints (A.19) impose that empty slots cannot be blocking. Constraints (A.20) define that the first position of a virtual lane is never blocking because access is always granted. Constraints (A.21) determine that if there is no blocking unit load in slot ( $s, t$ ) and there is no higher priority unit load in the slot in front of it, then there is no blocking unit load in slot ( $s, t+1$ ). Constraints (A.22) impose that the number of blocking unit loads at each stage cannot be greater than the number of blocking unit loads in the following stages. Constraint (A.23) limits the total loaded move distance to the objective value of the A\* algorithm.

#### A.2. Step 1: Detailed results for access direction fixing

See Tables 9 and 10.

**Table 11**

Step 2: Detailed Results for A\* one-tier.

| Layout<br>(Bay-Warehouse) | Fill % | Priority<br>Classes | Number<br>Solved | Number<br>Optimal | Mean<br>Moves | Mean<br>Loaded time | Mean (solved)<br>A* runtime [s] | Mean (all)<br>A* runtime<br>[s] | Mean (all)<br>Evaluated nodes |
|---------------------------|--------|---------------------|------------------|-------------------|---------------|---------------------|---------------------------------|---------------------------------|-------------------------------|
| 3 × 3-2 × 2               | 40%    | 5                   | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-2 × 2               | 40%    | 10                  | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-2 × 2               | 60%    | 5                   | 10               | 10                | 0.10          | 0.30                | 0                               | 0                               | 26.50                         |
| 3 × 3-2 × 2               | 60%    | 10                  | 10               | 10                | 0.10          | 0.30                | 0                               | 0                               | 26.50                         |
| 3 × 3-2 × 2               | 80%    | 5                   | 10               | 10                | 0.10          | 0.40                | 0                               | 0                               | 18.70                         |
| 3 × 3-2 × 2               | 80%    | 10                  | 10               | 10                | 0.20          | 0.70                | 0                               | 0                               | 36.80                         |
| 3 × 3-2 × 2               | 90%    | 5                   | 10               | 9                 | 0.60          | 3.30                | 0                               | 0                               | 68.90                         |
| 3 × 3-2 × 2               | 90%    | 10                  | 10               | 9                 | 0.50          | 2.90                | 0                               | 0                               | 57.10                         |
| 3 × 3-3 × 3               | 40%    | 5                   | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-3 × 3               | 40%    | 10                  | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-3 × 3               | 60%    | 5                   | 10               | 10                | 0.30          | 1.00                | 0.03                            | 0.03                            | 412.60                        |
| 3 × 3-3 × 3               | 60%    | 10                  | 10               | 10                | 0.30          | 1.00                | 0.03                            | 0.03                            | 412.60                        |
| 3 × 3-3 × 3               | 80%    | 5                   | 10               | 10                | 0.30          | 1.20                | 0.02                            | 0.02                            | 274.60                        |
| 3 × 3-3 × 3               | 80%    | 10                  | 10               | 10                | 0.40          | 1.50                | 0.03                            | 0.03                            | 370.20                        |
| 3 × 3-3 × 3               | 90%    | 5                   | 10               | 10                | 1.30          | 6.30                | 0.05                            | 0.05                            | 670.30                        |
| 3 × 3-3 × 3               | 90%    | 10                  | 10               | 10                | 1.40          | 6.90                | 0.06                            | 0.06                            | 724.30                        |
| 3 × 3-4 × 4               | 40%    | 5                   | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-4 × 4               | 40%    | 10                  | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-4 × 4               | 60%    | 5                   | 10               | 10                | 0.20          | 0.60                | 0.07                            | 0.07                            | 890                           |
| 3 × 3-4 × 4               | 60%    | 10                  | 10               | 10                | 0.30          | 0.90                | 0.11                            | 0.11                            | 1324.40                       |
| 3 × 3-4 × 4               | 80%    | 5                   | 10               | 10                | 0.70          | 2.40                | 0.17                            | 0.17                            | 2077.40                       |
| 3 × 3-4 × 4               | 80%    | 10                  | 10               | 10                | 1.10          | 3.40                | 0.29                            | 0.29                            | 3318.20                       |
| 3 × 3-4 × 4               | 90%    | 5                   | 10               | 9                 | 1.50          | 9.10                | 0.21                            | 0.21                            | 2446.70                       |
| 3 × 3-4 × 4               | 90%    | 10                  | 10               | 10                | 1.80          | 10.10               | 0.26                            | 0.26                            | 2939.80                       |
| 3 × 3-5 × 5               | 40%    | 5                   | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-5 × 5               | 40%    | 10                  | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-5 × 5               | 60%    | 5                   | 10               | 10                | 0.20          | 0.60                | 0.19                            | 0.19                            | 2172.60                       |
| 3 × 3-5 × 5               | 60%    | 10                  | 10               | 10                | 0.20          | 0.60                | 0.20                            | 0.20                            | 2181.20                       |
| 3 × 3-5 × 5               | 80%    | 5                   | 10               | 10                | 1.00          | 3.90                | 0.65                            | 0.65                            | 7156.80                       |
| 3 × 3-5 × 5               | 80%    | 10                  | 10               | 10                | 1.40          | 5.00                | 0.98                            | 0.98                            | 10 127.90                     |
| 3 × 3-5 × 5               | 90%    | 5                   | 10               | 10                | 2.30          | 11.30               | 0.86                            | 0.86                            | 9170.30                       |
| 3 × 3-5 × 5               | 90%    | 10                  | 10               | 10                | 2.90          | 14.30               | 1.11                            | 1.11                            | 11 519.60                     |
| 3 × 3-6 × 6               | 40%    | 5                   | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-6 × 6               | 40%    | 10                  | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-6 × 6               | 60%    | 5                   | 10               | 10                | 0.20          | 0.20                | 0.46                            | 0.46                            | 4526.10                       |
| 3 × 3-6 × 6               | 60%    | 10                  | 10               | 10                | 0.30          | 0.30                | 0.73                            | 0.73                            | 6770.30                       |
| 3 × 3-6 × 6               | 80%    | 5                   | 10               | 10                | 1.60          | 5.10                | 2.46                            | 2.46                            | 24 022.30                     |
| 3 × 3-6 × 6               | 80%    | 10                  | 10               | 10                | 2.20          | 6.90                | 3.66                            | 3.66                            | 33 202.50                     |
| 3 × 3-6 × 6               | 90%    | 5                   | 10               | 10                | 2.40          | 11.90               | 2.08                            | 2.08                            | 19 762.90                     |
| 3 × 3-6 × 6               | 90%    | 10                  | 10               | 8                 | 3.40          | 17.80               | 3.12                            | 3.12                            | 28 070.70                     |
| 3 × 3-7 × 7               | 40%    | 5                   | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-7 × 7               | 40%    | 10                  | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-7 × 7               | 60%    | 5                   | 10               | 10                | 0.60          | 1.60                | 2.97                            | 2.97                            | 24 955.50                     |
| 3 × 3-7 × 7               | 60%    | 10                  | 10               | 10                | 0.50          | 1.50                | 2.59                            | 2.59                            | 20 901.70                     |
| 3 × 3-7 × 7               | 80%    | 5                   | 10               | 10                | 2.00          | 6.80                | 6.53                            | 6.53                            | 55 077.20                     |
| 3 × 3-7 × 7               | 80%    | 10                  | 10               | 10                | 2.40          | 7.60                | 8.41                            | 8.41                            | 66 775.80                     |
| 3 × 3-7 × 7               | 90%    | 5                   | 10               | 10                | 3.10          | 16.20               | 5.81                            | 5.81                            | 47 855.10                     |
| 3 × 3-7 × 7               | 90%    | 10                  | 10               | 7                 | 4.80          | 26.00               | 9.25                            | 9.25                            | 74 456.70                     |
| 3 × 3-8 × 8               | 40%    | 5                   | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-8 × 8               | 40%    | 10                  | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-8 × 8               | 60%    | 5                   | 10               | 10                | 0.40          | 0.80                | 3.86                            | 3.86                            | 28 259.30                     |
| 3 × 3-8 × 8               | 60%    | 10                  | 10               | 10                | 0.60          | 1.50                | 6.29                            | 6.29                            | 42 748.20                     |
| 3 × 3-8 × 8               | 80%    | 5                   | 10               | 10                | 2.60          | 8.60                | 16.58                           | 16.58                           | 122 547.40                    |
| 3 × 3-8 × 8               | 80%    | 10                  | 10               | 9                 | 3.40          | 10.90               | 22.93                           | 22.93                           | 161 588.10                    |
| 3 × 3-8 × 8               | 90%    | 5                   | 10               | 5                 | 4.40          | 21.90               | 16.17                           | 16.17                           | 117 164.20                    |
| 3 × 3-8 × 8               | 90%    | 10                  | 10               | 4                 | 6.30          | 30.60               | 24.46                           | 24.46                           | 168 428.00                    |
| 3 × 3-9 × 9               | 40%    | 5                   | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-9 × 9               | 40%    | 10                  | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-9 × 9               | 60%    | 5                   | 10               | 10                | 0.70          | 2.00                | 12.45                           | 12.45                           | 79 208.10                     |
| 3 × 3-9 × 9               | 60%    | 10                  | 10               | 10                | 1.30          | 3.80                | 24.14                           | 24.14                           | 148 341.30                    |
| 3 × 3-9 × 9               | 80%    | 5                   | 10               | 9                 | 4.00          | 13.20               | 48.29                           | 48.29                           | 302 799.20                    |
| 3 × 3-9 × 9               | 80%    | 10                  | 10               | 6                 | 5.10          | 16.40               | 64.41                           | 64.41                           | 389 257.90                    |
| 3 × 3-9 × 9               | 90%    | 5                   | 10               | 5                 | 5.20          | 22.00               | 34.93                           | 34.93                           | 221 346.80                    |
| 3 × 3-9 × 9               | 90%    | 10                  | 10               | 4                 | 7.80          | 33.40               | 53.98                           | 53.98                           | 333 319.70                    |
| 3 × 3-10 × 10             | 40%    | 5                   | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-10 × 10             | 40%    | 10                  | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-10 × 10             | 60%    | 5                   | 10               | 10                | 1.10          | 3.30                | 34.05                           | 34.05                           | 189 601.20                    |
| 3 × 3-10 × 10             | 60%    | 10                  | 10               | 10                | 1.50          | 4.20                | 49.45                           | 49.45                           | 261 124.70                    |
| 3 × 3-10 × 10             | 80%    | 5                   | 10               | 5                 | 5.20          | 17.30               | 107.78                          | 107.78                          | 599 225.80                    |
| 3 × 3-10 × 10             | 80%    | 10                  | 10               | 3                 | 6.30          | 21.30               | 139.42                          | 139.42                          | 731 393.00                    |

(continued on next page)

Table 11 (continued).

| Layout<br>(Bay-Warehouse) | Fill % | Priority<br>Classes | Number<br>Solved | Number<br>Optimal | Mean<br>Moves | Mean<br>Loaded time | Mean (solved)<br>A* runtime [s] | Mean (all)<br>A* runtime<br>[s] | Mean (all)<br>Evaluated nodes |
|---------------------------|--------|---------------------|------------------|-------------------|---------------|---------------------|---------------------------------|---------------------------------|-------------------------------|
| 3 × 3-10 × 10             | 90%    | 5                   | 10               | 1                 | 7.40          | 33.50               | 85.65                           | 85.65                           | 482 019.00                    |
| 3 × 3-10 × 10             | 90%    | 10                  | 10               | 0                 | 10.30         | 49.00               | 127.19                          | 127.19                          | 673 714.80                    |
| 3 × 3-11 × 11             | 40%    | 5                   | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-11 × 11             | 40%    | 10                  | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-11 × 11             | 60%    | 5                   | 10               | 10                | 0.90          | 1.50                | 47.15                           | 47.15                           | 227 332.80                    |
| 3 × 3-11 × 11             | 60%    | 10                  | 10               | 10                | 1.50          | 3.20                | 78.87                           | 78.87                           | 381 905.20                    |
| 3 × 3-11 × 11             | 80%    | 5                   | 10               | 3                 | 5.80          | 19.60               | 208.41                          | 208.41                          | 981 061.40                    |
| 3 × 3-11 × 11             | 80%    | 10                  | 10               | 1                 | 7.30          | 25.40               | 260.28                          | 260.28                          | 1 244 995.00                  |
| 3 × 3-11 × 11             | 90%    | 5                   | 10               | 1                 | 8.30          | 37.20               | 166.26                          | 166.26                          | 791 859.00                    |
| 3 × 3-11 × 11             | 90%    | 10                  | 10               | 0                 | 11.70         | 53.30               | 233.99                          | 233.99                          | 1 121 264.80                  |
| 3 × 3-12 × 12             | 40%    | 5                   | 10               | 10                | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-12 × 12             | 40%    | 10                  | 10               | 0                 | 0             | 0                   | 0                               | 0                               | 0                             |
| 3 × 3-12 × 12             | 60%    | 5                   | 10               | 10                | 1.20          | 3.30                | 100.43                          | 100.43                          | 427 072.60                    |
| 3 × 3-12 × 12             | 60%    | 10                  | 10               | 0                 | 1.90          | 5.40                | 159.62                          | 159.62                          | 683 436.70                    |
| 3 × 3-12 × 12             | 80%    | 5                   | 9                | 3                 | 6.11          | 21.33               | 352.40                          | 380.74                          | 1 576 710.10                  |
| 3 × 3-12 × 12             | 80%    | 10                  | 8                | 0                 | 7.38          | 26.12               | 418.76                          | 461.84                          | 1 950 353.70                  |
| 3 × 3-12 × 12             | 90%    | 5                   | 10               | 1                 | 9.20          | 43.00               | 296.32                          | 296.32                          | 1 242 832.90                  |
| 3 × 3-12 × 12             | 90%    | 10                  | 10               | 0                 | 13.30         | 62.80               | 424.78                          | 424.78                          | 1 803 927.20                  |
| 4 × 4-2 × 2               | 40%    | 5                   | 10               | 10                | 0.20          | 0.20                | 0.01                            | 0.01                            | 140.50                        |
| 4 × 4-2 × 2               | 40%    | 10                  | 10               | 10                | 0.20          | 0.20                | 0.01                            | 0.01                            | 143.60                        |
| 4 × 4-2 × 2               | 60%    | 5                   | 10               | 10                | 0.10          | 0.10                | 0.01                            | 0.01                            | 74.30                         |
| 4 × 4-2 × 2               | 60%    | 10                  | 10               | 10                | 0.30          | 1.10                | 0.02                            | 0.02                            | 225.40                        |
| 4 × 4-2 × 2               | 80%    | 5                   | 10               | 10                | 1.60          | 4.70                | 0.06                            | 0.06                            | 765.80                        |
| 4 × 4-2 × 2               | 80%    | 10                  | 10               | 10                | 2.30          | 9.00                | 0.10                            | 0.10                            | 1113.00                       |
| 4 × 4-2 × 2               | 90%    | 5                   | 10               | 9                 | 1.70          | 10.60               | 0.04                            | 0.04                            | 431.90                        |
| 4 × 4-2 × 2               | 90%    | 10                  | 10               | 9                 | 2.20          | 14.10               | 0.05                            | 0.05                            | 577.10                        |
| 4 × 4-3 × 3               | 40%    | 5                   | 10               | 10                | 0.50          | 0.50                | 0.16                            | 0.16                            | 1824.80                       |
| 4 × 4-3 × 3               | 40%    | 10                  | 10               | 10                | 0.50          | 0.50                | 0.17                            | 0.17                            | 1845.50                       |
| 4 × 4-3 × 3               | 60%    | 5                   | 10               | 10                | 0.90          | 1.60                | 0.30                            | 0.30                            | 3362.40                       |
| 4 × 4-3 × 3               | 60%    | 10                  | 10               | 10                | 1.20          | 2.50                | 0.42                            | 0.42                            | 4488.90                       |
| 4 × 4-3 × 3               | 80%    | 5                   | 10               | 10                | 3.00          | 9.00                | 0.65                            | 0.65                            | 7370.80                       |
| 4 × 4-3 × 3               | 80%    | 10                  | 10               | 10                | 4.30          | 11.80               | 1.00                            | 1.00                            | 10 582.70                     |
| 4 × 4-3 × 3               | 90%    | 5                   | 10               | 7                 | 4.20          | 21.70               | 0.53                            | 0.53                            | 5790.30                       |
| 4 × 4-3 × 3               | 90%    | 10                  | 10               | 7                 | 5.60          | 25.90               | 0.75                            | 0.75                            | 7738.40                       |
| 4 × 4-4 × 4               | 40%    | 5                   | 10               | 10                | 0.50          | 0.50                | 0.60                            | 0.60                            | 5733.80                       |
| 4 × 4-4 × 4               | 40%    | 10                  | 10               | 10                | 0.60          | 0.70                | 0.75                            | 0.75                            | 7010                          |
| 4 × 4-4 × 4               | 60%    | 5                   | 10               | 10                | 2.10          | 3.30                | 2.64                            | 2.64                            | 24 637.80                     |
| 4 × 4-4 × 4               | 60%    | 10                  | 10               | 10                | 2.50          | 4.50                | 3.24                            | 3.24                            | 29 887.30                     |
| 4 × 4-4 × 4               | 80%    | 5                   | 10               | 8                 | 4.30          | 13.20               | 3.57                            | 3.57                            | 33 630.40                     |
| 4 × 4-4 × 4               | 80%    | 10                  | 10               | 7                 | 5.60          | 17.80               | 4.85                            | 4.85                            | 44 190.50                     |
| 4 × 4-4 × 4               | 90%    | 5                   | 10               | 4                 | 6.80          | 32.40               | 3.37                            | 3.37                            | 31 007.10                     |
| 4 × 4-4 × 4               | 90%    | 10                  | 10               | 2                 | 8.50          | 42.30               | 4.30                            | 4.30                            | 38 524.00                     |
| 4 × 4-5 × 5               | 40%    | 5                   | 10               | 10                | 0.90          | 0.90                | 3.13                            | 3.13                            | 25 710.90                     |
| 4 × 4-5 × 5               | 40%    | 10                  | 10               | 10                | 1.10          | 1.40                | 4.07                            | 4.07                            | 31 678.50                     |
| 4 × 4-5 × 5               | 60%    | 5                   | 10               | 10                | 3.20          | 5.30                | 11.30                           | 11.30                           | 92 090.40                     |
| 4 × 4-5 × 5               | 60%    | 10                  | 10               | 8                 | 3.70          | 6.30                | 13.88                           | 13.88                           | 107 858.60                    |
| 4 × 4-5 × 5               | 80%    | 5                   | 10               | 2                 | 7.70          | 21.80               | 18.23                           | 18.23                           | 148 077.00                    |
| 4 × 4-5 × 5               | 80%    | 10                  | 10               | 2                 | 9.80          | 27.20               | 25.60                           | 25.60                           | 190 096.30                    |
| 4 × 4-5 × 5               | 90%    | 5                   | 10               | 0                 | 11.40         | 52.50               | 15.41                           | 15.41                           | 124 148.00                    |
| 4 × 4-5 × 5               | 90%    | 10                  | 10               | 0                 | 13.50         | 62.10               | 19.34                           | 19.34                           | 146 985.60                    |
| 4 × 4-6 × 6               | 40%    | 5                   | 10               | 10                | 0.90          | 1.40                | 7.55                            | 7.55                            | 53 388.10                     |
| 4 × 4-6 × 6               | 40%    | 10                  | 10               | 10                | 1.10          | 1.70                | 10.15                           | 10.15                           | 65 781.70                     |
| 4 × 4-6 × 6               | 60%    | 5                   | 10               | 9                 | 3.90          | 5.90                | 33.64                           | 33.64                           | 231 822.10                    |
| 4 × 4-6 × 6               | 60%    | 10                  | 10               | 8                 | 4.70          | 8.30                | 43.49                           | 43.49                           | 282 370.50                    |
| 4 × 4-6 × 6               | 80%    | 5                   | 10               | 1                 | 10.80         | 32.50               | 62.57                           | 62.57                           | 429 111.60                    |
| 4 × 4-6 × 6               | 80%    | 10                  | 10               | 0                 | 14.50         | 40.70               | 89.78                           | 89.78                           | 581 696.30                    |
| 4 × 4-6 × 6               | 90%    | 5                   | 10               | 0                 | 15.70         | 71.00               | 52.82                           | 52.82                           | 358 401.80                    |
| 4 × 4-6 × 6               | 90%    | 10                  | 10               | 0                 | 18.90         | 88.60               | 66.34                           | 66.34                           | 430 959.40                    |
| 4 × 4-7 × 7               | 40%    | 5                   | 10               | 10                | 1.20          | 1.30                | 22.55                           | 22.55                           | 131 013.60                    |
| 4 × 4-7 × 7               | 40%    | 10                  | 10               | 10                | 1.60          | 1.70                | 31.46                           | 31.46                           | 176 378.10                    |
| 4 × 4-7 × 7               | 60%    | 5                   | 10               | 7                 | 5.90          | 10.90               | 112.84                          | 112.84                          | 644 435.70                    |
| 4 × 4-7 × 7               | 60%    | 10                  | 10               | 5                 | 7.50          | 14.20               | 154.60                          | 154.60                          | 830 804.90                    |
| 4 × 4-7 × 7               | 80%    | 5                   | 10               | 0                 | 13.40         | 35.70               | 175.45                          | 175.45                          | 985 488.20                    |
| 4 × 4-7 × 7               | 80%    | 10                  | 10               | 0                 | 18.00         | 46.40               | 249.72                          | 249.72                          | 1 335 510                     |
| 4 × 4-7 × 7               | 90%    | 5                   | 10               | 0                 | 20.80         | 91.20               | 154.76                          | 154.76                          | 869 454.60                    |
| 4 × 4-7 × 7               | 90%    | 10                  | 10               | 0                 | 26.60         | 125.50              | 205.80                          | 205.80                          | 1 114 507.90                  |
| 4 × 4-8 × 8               | 40%    | 5                   | 10               | 10                | 1.30          | 2.10                | 47.86                           | 47.86                           | 242 777.50                    |
| 4 × 4-8 × 8               | 40%    | 10                  | 10               | 10                | 1.50          | 2.40                | 60.47                           | 60.47                           | 283 148.40                    |
| 4 × 4-8 × 8               | 60%    | 5                   | 10               | 6                 | 7.90          | 12.20               | 303.83                          | 303.83                          | 1 471 892.00                  |
| 4 × 4-8 × 8               | 60%    | 10                  | 9                | 3                 | 9.22          | 14.22               | 373.44                          | 397.42                          | 1 830 648.00                  |
| 4 × 4-8 × 8               | 80%    | 5                   | 10               | 0                 | 17.00         | 47.70               | 443.61                          | 443.61                          | 2 136 719.20                  |

(continued on next page)

Table 11 (continued).

| Layout<br>(Bay-Warehouse) | Fill % | Priority<br>Classes | Number<br>Solved | Number<br>Optimal | Mean<br>Moves | Mean<br>Loaded time | Mean (solved)<br>A* runtime [s] | Mean (all)<br>A* runtime<br>[s] | Mean (all)<br>Evaluated nodes |
|---------------------------|--------|---------------------|------------------|-------------------|---------------|---------------------|---------------------------------|---------------------------------|-------------------------------|
| 4 × 4-8 × 8               | 80%    | 10                  | 3                | 0                 | 17.00         | 39.00               | 468.89                          | 576.38                          | 2 658 906.30                  |
| 4 × 4-8 × 8               | 90%    | 5                   | 10               | 0                 | 28.40         | 134.00              | 417.38                          | 417.38                          | 2 013 887.50                  |
| 4 × 4-8 × 8               | 90%    | 10                  | 9                | 0                 | 35.44         | 170.11              | 539.11                          | 546.08                          | 2 541 578.90                  |
| 5 × 5-2 × 2               | 40%    | 5                   | 10               | 10                | 0.20          | 0.20                | 0.02                            | 0.02                            | 279.00                        |
| 5 × 5-2 × 2               | 40%    | 10                  | 10               | 10                | 0.10          | 0.10                | 0.01                            | 0.01                            | 143.90                        |
| 5 × 5-2 × 2               | 60%    | 5                   | 10               | 10                | 1.40          | 2.00                | 0.18                            | 0.18                            | 2062.30                       |
| 5 × 5-2 × 2               | 60%    | 10                  | 10               | 9                 | 1.90          | 3.00                | 0.28                            | 0.28                            | 2894.70                       |
| 5 × 5-2 × 2               | 80%    | 5                   | 10               | 8                 | 4.80          | 16.90               | 0.45                            | 0.45                            | 4931.40                       |
| 5 × 5-2 × 2               | 80%    | 10                  | 10               | 7                 | 5.60          | 20.20               | 0.56                            | 0.56                            | 5791.50                       |
| 5 × 5-2 × 2               | 90%    | 5                   | 10               | 3                 | 6.30          | 40.40               | 0.78                            | 0.78                            | 3633.20                       |
| 5 × 5-2 × 2               | 90%    | 10                  | 10               | 3                 | 6.50          | 42.70               | 0.70                            | 0.70                            | 3811.30                       |
| 5 × 5-3 × 3               | 40%    | 5                   | 10               | 10                | 0.80          | 1.40                | 0.62                            | 0.62                            | 5887.10                       |
| 5 × 5-3 × 3               | 40%    | 10                  | 10               | 10                | 0.90          | 1.50                | 0.73                            | 0.73                            | 6911.80                       |
| 5 × 5-3 × 3               | 60%    | 5                   | 10               | 9                 | 4.00          | 5.60                | 3.25                            | 3.25                            | 30 512.20                     |
| 5 × 5-3 × 3               | 60%    | 10                  | 10               | 10                | 5.10          | 8.00                | 4.28                            | 4.28                            | 39 562.40                     |
| 5 × 5-3 × 3               | 80%    | 5                   | 10               | 2                 | 9.30          | 28.30               | 5.23                            | 5.23                            | 48 149.60                     |
| 5 × 5-3 × 3               | 80%    | 10                  | 10               | 0                 | 11.00         | 35.50               | 6.45                            | 6.45                            | 57 883.80                     |
| 5 × 5-3 × 3               | 90%    | 5                   | 10               | 0                 | 12.90         | 78.60               | 4.69                            | 4.69                            | 36 873.70                     |
| 5 × 5-3 × 3               | 90%    | 10                  | 10               | 0                 | 15.00         | 103.60              | 8.69                            | 8.69                            | 43 014.20                     |
| 5 × 5-4 × 4               | 40%    | 5                   | 10               | 10                | 1.60          | 2.00                | 4.75                            | 4.75                            | 38 372.20                     |
| 5 × 5-4 × 4               | 40%    | 10                  | 10               | 10                | 2.00          | 2.40                | 6.51                            | 6.51                            | 49 292.20                     |
| 5 × 5-4 × 4               | 60%    | 5                   | 10               | 7                 | 6.40          | 10.40               | 19.66                           | 19.66                           | 154 610                       |
| 5 × 5-4 × 4               | 60%    | 10                  | 10               | 1                 | 8.30          | 14.90               | 27.46                           | 27.46                           | 204 025.80                    |
| 5 × 5-4 × 4               | 80%    | 5                   | 9                | 0                 | 16.00         | 50.56               | 34.19                           | 34.19                           | 262 830.33                    |
| 5 × 5-4 × 4               | 80%    | 10                  | 10               | 0                 | 19.30         | 63.10               | 44.24                           | 44.24                           | 318 932.60                    |
| 5 × 5-4 × 4               | 90%    | 5                   | 10               | 0                 | 22.30         | 129.30              | 27.74                           | 27.74                           | 203 788.00                    |
| 5 × 5-4 × 4               | 90%    | 10                  | 9                | 0                 | 25.67         | 202.11              | 42.49                           | 101.27                          | 223 789.70                    |
| 5 × 5-5 × 5               | 40%    | 5                   | 10               | 10                | 2.60          | 2.90                | 23.71                           | 23.71                           | 152 807.90                    |
| 5 × 5-5 × 5               | 40%    | 10                  | 10               | 10                | 3.20          | 3.70                | 31.68                           | 31.68                           | 193 354.70                    |
| 5 × 5-5 × 5               | 60%    | 5                   | 10               | 1                 | 10            | 14.80               | 94.71                           | 94.71                           | 587 673.70                    |
| 5 × 5-5 × 5               | 60%    | 10                  | 10               | 0                 | 12.10         | 20.60               | 120.27                          | 120.27                          | 723 945.20                    |
| 5 × 5-5 × 5               | 80%    | 5                   | 10               | 0                 | 25.90         | 74.90               | 172.19                          | 172.19                          | 1 034 880.90                  |
| 5 × 5-5 × 5               | 80%    | 10                  | 10               | 0                 | 30.40         | 92.20               | 209.08                          | 209.08                          | 1 229 095.20                  |
| 5 × 5-5 × 5               | 90%    | 5                   | 10               | 0                 | 34.00         | 222.20              | 133.05                          | 133.05                          | 756 237.40                    |
| 5 × 5-5 × 5               | 90%    | 10                  | 10               | 0                 | 40            | 320.20              | 207.42                          | 207.42                          | 892 873.00                    |
| 5 × 5-6 × 6               | 40%    | 5                   | 10               | 9                 | 4.50          | 5.90                | 107.20                          | 107.20                          | 554 191.00                    |
| 5 × 5-6 × 6               | 40%    | 10                  | 10               | 9                 | 5.00          | 6.10                | 127.52                          | 127.52                          | 629 140.20                    |
| 5 × 5-6 × 6               | 60%    | 5                   | 10               | 0                 | 14.40         | 21.80               | 347.42                          | 347.42                          | 1 764 740.10                  |
| 5 × 5-6 × 6               | 60%    | 10                  | 10               | 0                 | 17.50         | 28.40               | 445.59                          | 445.59                          | 2 165 744.20                  |
| 5 × 5-6 × 6               | 80%    | 5                   | 5                | 0                 | 33.40         | 95.80               | 543.73                          | 580.59                          | 2 936 941.50                  |
| 5 × 5-6 × 6               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 619.01                          | 2 978 653.50                  |
| 5 × 5-6 × 6               | 90%    | 5                   | 10               | 0                 | 49.90         | 294.60              | 463.28                          | 463.28                          | 2 321 518.40                  |
| 5 × 5-6 × 6               | 90%    | 10                  | 4                | 0                 | 55.00         | 398.75              | 547.08                          | 588.91                          | 2 474 100.70                  |
| 6 × 6-2 × 2               | 40%    | 5                   | 10               | 10                | 1.30          | 1.60                | 0.34                            | 0.34                            | 3524.90                       |
| 6 × 6-2 × 2               | 40%    | 10                  | 10               | 10                | 1.80          | 1.90                | 0.50                            | 0.50                            | 4814.50                       |
| 6 × 6-2 × 2               | 60%    | 5                   | 10               | 10                | 3.80          | 6.10                | 1.03                            | 1.03                            | 10 097.90                     |
| 6 × 6-2 × 2               | 60%    | 10                  | 10               | 10                | 4.10          | 7.20                | 1.12                            | 1.12                            | 11 035.50                     |
| 6 × 6-2 × 2               | 80%    | 5                   | 10               | 3                 | 9.00          | 30.80               | 1.66                            | 1.66                            | 16 101.90                     |
| 6 × 6-2 × 2               | 80%    | 10                  | 10               | 0                 | 10            | 38.40               | 1.95                            | 1.95                            | 18 053.00                     |
| 6 × 6-2 × 2               | 90%    | 5                   | 9                | 0                 | 15.22         | 109.22              | 28.15                           | 85.50                           | 53 779.20                     |
| 6 × 6-2 × 2               | 90%    | 10                  | 10               | 0                 | 17.80         | 134.90              | 24.79                           | 24.79                           | 17 581.10                     |
| 6 × 6-3 × 3               | 40%    | 5                   | 10               | 10                | 2.50          | 3.00                | 4.10                            | 4.10                            | 34 221.90                     |
| 6 × 6-3 × 3               | 40%    | 10                  | 10               | 10                | 3.40          | 3.60                | 5.86                            | 5.86                            | 46 321.70                     |
| 6 × 6-3 × 3               | 60%    | 5                   | 10               | 1                 | 9.20          | 14.90               | 15.44                           | 15.44                           | 125 896.90                    |
| 6 × 6-3 × 3               | 60%    | 10                  | 10               | 1                 | 10.70         | 17.90               | 18.92                           | 18.92                           | 147 818.40                    |
| 6 × 6-3 × 3               | 80%    | 5                   | 10               | 0                 | 21.40         | 76.70               | 24.68                           | 24.68                           | 196 502.70                    |
| 6 × 6-3 × 3               | 80%    | 10                  | 10               | 0                 | 23.60         | 90.60               | 29.36                           | 29.36                           | 217 582.90                    |
| 6 × 6-3 × 3               | 90%    | 5                   | 7                | 0                 | 29.86         | 243.14              | 119.54                          | 265.82                          | 143 359.60                    |
| 6 × 6-3 × 3               | 90%    | 10                  | 7                | 0                 | 34.71         | 309.57              | 232.29                          | 345.43                          | 161 045.90                    |
| 6 × 6-4 × 4               | 40%    | 5                   | 10               | 8                 | 5.20          | 6.30                | 34.91                           | 34.91                           | 225 499.70                    |
| 6 × 6-4 × 4               | 40%    | 10                  | 10               | 7                 | 6.60          | 8.30                | 47.12                           | 47.12                           | 289 254.70                    |
| 6 × 6-4 × 4               | 60%    | 5                   | 10               | 0                 | 16.90         | 28.60               | 116.39                          | 116.39                          | 723 113.90                    |
| 6 × 6-4 × 4               | 60%    | 10                  | 10               | 0                 | 20.10         | 34.70               | 146.04                          | 146.04                          | 872 274.70                    |
| 6 × 6-4 × 4               | 80%    | 5                   | 10               | 0                 | 37.30         | 127.60              | 176.75                          | 176.75                          | 1 068 095.50                  |
| 6 × 6-4 × 4               | 80%    | 10                  | 10               | 0                 | 42.30         | 160.30              | 208.81                          | 208.81                          | 1 225 004.20                  |
| 6 × 6-4 × 4               | 90%    | 5                   | 6                | 0                 | 51.33         | 420                 | 414.45                          | 523.04                          | 521 842.80                    |
| 6 × 6-4 × 4               | 90%    | 10                  | 1                | 0                 | 57.00         | 561.00              | 589.96                          | 645.70                          | 237 768.50                    |
| 6 × 6-5 × 5               | 40%    | 5                   | 10               | 4                 | 7.70          | 9.10                | 159.38                          | 159.38                          | 805 432.80                    |
| 6 × 6-5 × 5               | 40%    | 10                  | 10               | 1                 | 9.90          | 12.00               | 221.38                          | 221.38                          | 1 055 137.80                  |
| 6 × 6-5 × 5               | 60%    | 5                   | 5                | 0                 | 24.40         | 37.40               | 518.08                          | 568.19                          | 2 816 754.70                  |
| 6 × 6-5 × 5               | 60%    | 10                  | 2                | 0                 | 27.00         | 48.00               | 601.73                          | 617.49                          | 2 915 731.00                  |

(continued on next page)

Table 11 (continued).

| Layout<br>(Bay-Warehouse) | Fill % | Priority<br>Classes | Number<br>Solved | Number<br>Optimal | Mean<br>Moves | Mean<br>Loaded time | Mean (solved)<br>A* runtime [s] | Mean (all)<br>A* runtime<br>[s] | Mean (all)<br>Evaluated nodes |
|---------------------------|--------|---------------------|------------------|-------------------|---------------|---------------------|---------------------------------|---------------------------------|-------------------------------|
| 6 × 6-5 × 5               | 80%    | 5                   | 0                | 0                 | –             | –                   | –                               | 615.98                          | 3 055 372.20                  |
| 6 × 6-5 × 5               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 615.86                          | 2 896 008.00                  |
| 6 × 6-5 × 5               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 746.66                          | 372 995.60                    |
| 6 × 6-5 × 5               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 887.26                          | 109 171.70                    |
| 6 × 6-6 × 6               | 40%    | 5                   | 3                | 0                 | 7.67          | 8.67                | 417.46                          | 566.43                          | 2 219 468.90                  |
| 6 × 6-6 × 6               | 40%    | 10                  | 0                | 0                 | –             | –                   | –                               | 642.65                          | 2 406 356.67                  |
| 6 × 6-6 × 6               | 60%    | 5                   | 0                | 0                 | –             | –                   | –                               | 640.71                          | 2 457 076.10                  |
| 6 × 6-6 × 6               | 60%    | 10                  | 0                | 0                 | –             | –                   | –                               | 626.10                          | 2 423 895.50                  |
| 6 × 6-6 × 6               | 80%    | 5                   | 0                | 0                 | –             | –                   | –                               | 635.19                          | 2 457 173.50                  |
| 6 × 6-6 × 6               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 624.92                          | 2 323 745.33                  |
| 6 × 6-6 × 6               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 1005.20                         | 690 075.70                    |
| 6 × 6-6 × 6               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 1230.21                         | 422 809.60                    |

Table 12

Step 2: Detailed Results for A\* two-tier.

| Layout<br>(Bay-Warehouse) | Fill % | Priority<br>Classes | Number<br>Solved | Number<br>Optimal | Mean<br>Moves | Mean<br>Loaded time | Mean (solved)<br>A* runtime [s] | Mean (all)<br>A* runtime [s] | Mean (all)<br>Evaluated nodes |
|---------------------------|--------|---------------------|------------------|-------------------|---------------|---------------------|---------------------------------|------------------------------|-------------------------------|
| 3 × 3-2 × 2               | 40%    | 5                   | 10               | 9                 | 2.90          | 4.70                | 0.55                            | 0.55                         | 1832.40                       |
| 3 × 3-2 × 2               | 40%    | 10                  | 10               | 8                 | 3.10          | 5.40                | 0.64                            | 0.64                         | 1974.70                       |
| 3 × 3-2 × 2               | 60%    | 5                   | 10               | 5                 | 5.60          | 15.00               | 1.05                            | 1.05                         | 3375.50                       |
| 3 × 3-2 × 2               | 60%    | 10                  | 10               | 4                 | 6.60          | 19.70               | 1.33                            | 1.33                         | 4067.10                       |
| 3 × 3-2 × 2               | 80%    | 5                   | 10               | 0                 | 11.90         | 52.40               | 3.94                            | 3.94                         | 4144.60                       |
| 3 × 3-2 × 2               | 80%    | 10                  | 10               | 0                 | 13.80         | 70.90               | 9.36                            | 9.36                         | 9017.60                       |
| 3 × 3-2 × 2               | 90%    | 5                   | 9                | 0                 | 15.56         | 88.56               | 41.89                           | 97.89                        | 32 569.40                     |
| 3 × 3-2 × 2               | 90%    | 10                  | 7                | 0                 | 16.57         | 91.29               | 81.62                           | 237.74                       | 77 318.30                     |
| 3 × 3-3 × 3               | 40%    | 5                   | 10               | 0                 | 7.00          | 10.90               | 8.11                            | 8.11                         | 21 336.70                     |
| 3 × 3-3 × 3               | 40%    | 10                  | 10               | 0                 | 7.60          | 13.20               | 9.31                            | 9.31                         | 23 490.80                     |
| 3 × 3-3 × 3               | 60%    | 5                   | 10               | 0                 | 13.50         | 34.50               | 16.77                           | 16.77                        | 42 396.50                     |
| 3 × 3-3 × 3               | 60%    | 10                  | 10               | 0                 | 16.10         | 48.80               | 21.31                           | 21.31                        | 51 779.00                     |
| 3 × 3-3 × 3               | 80%    | 5                   | 8                | 0                 | 25.62         | 143.38              | 65.25                           | 173.17                       | 67 236.40                     |
| 3 × 3-3 × 3               | 80%    | 10                  | 7                | 0                 | 29.14         | 180.71              | 143.64                          | 281.69                       | 85 616.70                     |
| 3 × 3-3 × 3               | 90%    | 5                   | 3                | 0                 | 33.67         | 183.33              | 225.54                          | 489.74                       | 111 728.40                    |
| 3 × 3-3 × 3               | 90%    | 10                  | 1                | 0                 | 36.00         | 244.00              | 202.44                          | 563.39                       | 103 695.40                    |
| 3 × 3-4 × 4               | 40%    | 5                   | 10               | 0                 | 11.60         | 19.40               | 55.92                           | 55.92                        | 116 027.90                    |
| 3 × 3-4 × 4               | 40%    | 10                  | 10               | 0                 | 12.70         | 22.40               | 63.02                           | 63.02                        | 129 063.60                    |
| 3 × 3-4 × 4               | 60%    | 5                   | 10               | 0                 | 24.60         | 59.40               | 119.52                          | 119.52                       | 247 046.30                    |
| 3 × 3-4 × 4               | 60%    | 10                  | 10               | 0                 | 29.10         | 80.50               | 149.61                          | 149.61                       | 297 217.50                    |
| 3 × 3-4 × 4               | 80%    | 5                   | 5                | 0                 | 44.00         | 235.20              | 308.92                          | 465.81                       | 174 439.30                    |
| 3 × 3-4 × 4               | 80%    | 10                  | 3                | 0                 | 49.67         | 305.67              | 363.46                          | 548.05                       | 141 177.70                    |
| 3 × 3-4 × 4               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 613.37                       | 67 624.80                     |
| 3 × 3-4 × 4               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 619.24                       | 64 045.00                     |
| 3 × 3-5 × 5               | 40%    | 5                   | 10               | 0                 | 17.50         | 30.70               | 260.88                          | 260.88                       | 435 785.40                    |
| 3 × 3-5 × 5               | 40%    | 10                  | 10               | 0                 | 19.90         | 35.80               | 307.26                          | 307.26                       | 499 850.30                    |
| 3 × 3-5 × 5               | 60%    | 5                   | 8                | 0                 | 34.75         | 92.50               | 521.91                          | 540.63                       | 886 651.30                    |
| 3 × 3-5 × 5               | 60%    | 10                  | 2                | 0                 | 36.50         | 97.00               | 593.44                          | 616.33                       | 983 474.30                    |
| 3 × 3-5 × 5               | 80%    | 5                   | 0                | 0                 | –             | –                   | –                               | 669.55                       | 169 383.50                    |
| 3 × 3-5 × 5               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 655.83                       | 128 231.60                    |
| 3 × 3-5 × 5               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 652.30                       | 44 878.40                     |
| 3 × 3-5 × 5               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 645.60                       | 43 305.40                     |
| 3 × 3-6 × 6               | 40%    | 5                   | 0                | 0                 | –             | –                   | –                               | 630.50                       | 848 955.00                    |
| 3 × 3-6 × 6               | 40%    | 10                  | 0                | 0                 | –             | –                   | –                               | 624.08                       | 823 485.00                    |
| 3 × 3-6 × 6               | 60%    | 5                   | 0                | 0                 | –             | –                   | –                               | 626.96                       | 835 031.90                    |
| 3 × 3-6 × 6               | 60%    | 10                  | 0                | 0                 | –             | –                   | –                               | 629.98                       | 824 539.30                    |
| 3 × 3-6 × 6               | 80%    | 5                   | 0                | 0                 | –             | –                   | –                               | 839.17                       | 188 654.50                    |
| 3 × 3-6 × 6               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 878.10                       | 144 075.00                    |
| 3 × 3-6 × 6               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 685.98                       | 34 199.00                     |
| 3 × 3-6 × 6               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 685.28                       | 34 107.50                     |
| 4 × 4-2 × 2               | 40%    | 5                   | 10               | 7                 | 6.70          | 9.60                | 3.62                            | 3.62                         | 9832.10                       |
| 4 × 4-2 × 2               | 40%    | 10                  | 10               | 2                 | 7.50          | 13.50               | 4.28                            | 4.28                         | 11 184.40                     |
| 4 × 4-2 × 2               | 60%    | 5                   | 10               | 0                 | 15.60         | 61.80               | 8.86                            | 8.86                         | 22 560.20                     |
| 4 × 4-2 × 2               | 60%    | 10                  | 10               | 0                 | 17.10         | 69.40               | 10.33                           | 10.33                        | 24 750.40                     |
| 4 × 4-2 × 2               | 80%    | 5                   | 5                | 0                 | 21.80         | 107.20              | 55.39                           | 328.81                       | 90 717.10                     |
| 4 × 4-2 × 2               | 80%    | 10                  | 4                | 0                 | 28.00         | 173.00              | 136.69                          | 415.86                       | 116 866.60                    |
| 4 × 4-2 × 2               | 90%    | 5                   | 1                | 0                 | 32.00         | 203.00              | 393.87                          | 581.52                       | 135 455.20                    |
| 4 × 4-2 × 2               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 602.22                       | 140 393.60                    |
| 4 × 4-3 × 3               | 40%    | 5                   | 10               | 0                 | 15.30         | 24.90               | 56.96                           | 56.96                        | 116 949.00                    |
| 4 × 4-3 × 3               | 40%    | 10                  | 10               | 0                 | 17.10         | 29.90               | 67.85                           | 67.85                        | 134 823.60                    |
| 4 × 4-3 × 3               | 60%    | 5                   | 10               | 0                 | 32.90         | 107.70              | 119.76                          | 119.76                       | 237 159.00                    |
| 4 × 4-3 × 3               | 60%    | 10                  | 10               | 0                 | 35.90         | 124.50              | 137.44                          | 137.44                       | 264 089.20                    |
| 4 × 4-3 × 3               | 80%    | 5                   | 0                | 0                 | –             | –                   | –                               | 613.02                       | 75 705.60                     |

(continued on next page)

Table 12 (continued).

| Layout<br>(Bay-Warehouse) | Fill % | Priority<br>Classes | Number<br>Solved | Number<br>Optimal | Mean<br>Moves | Mean<br>Loaded time | Mean (solved)<br>A* runtime [s] | Mean (all)<br>A* runtime [s] | Mean (all)<br>Evaluated nodes |
|---------------------------|--------|---------------------|------------------|-------------------|---------------|---------------------|---------------------------------|------------------------------|-------------------------------|
| 4 × 4-3 × 3               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 613.22                       | 76 251.40                     |
| 4 × 4-3 × 3               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 610.20                       | 70 129.20                     |
| 4 × 4-3 × 3               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 609.99                       | 70 885.70                     |
| 4 × 4-4 × 4               | 40%    | 5                   | 10               | 0                 | 23.90         | 35.60               | 381.34                          | 381.34                       | 575 239.50                    |
| 4 × 4-4 × 4               | 40%    | 10                  | 9                | 0                 | 26.89         | 42.56               | 450.06                          | 467.31                       | 688 892.00                    |
| 4 × 4-4 × 4               | 60%    | 5                   | 0                | 0                 | –             | –                   | –                               | 620.20                       | 915 573.60                    |
| 4 × 4-4 × 4               | 60%    | 10                  | 0                | 0                 | –             | –                   | –                               | 616.67                       | 890 990.20                    |
| 4 × 4-4 × 4               | 80%    | 5                   | 0                | 0                 | –             | –                   | –                               | 660.37                       | 46 932.20                     |
| 4 × 4-4 × 4               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 642.94                       | 46 766.60                     |
| 4 × 4-4 × 4               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 629.51                       | 43 335.70                     |
| 4 × 4-4 × 4               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 637.01                       | 43 310                        |
| 4 × 4-5 × 5               | 40%    | 5                   | 0                | 0                 | –             | –                   | –                               | 638.23                       | 742 506.60                    |
| 4 × 4-5 × 5               | 40%    | 10                  | 0                | 0                 | –             | –                   | –                               | 631.20                       | 722 001.00                    |
| 4 × 4-5 × 5               | 60%    | 5                   | 0                | 0                 | –             | –                   | –                               | 629.22                       | 719 761.60                    |
| 4 × 4-5 × 5               | 60%    | 10                  | 0                | 0                 | –             | –                   | –                               | 637.24                       | 714 141.50                    |
| 4 × 4-5 × 5               | 80%    | 5                   | 0                | 0                 | –             | –                   | –                               | 822.21                       | 38 372.70                     |
| 4 × 4-5 × 5               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 822.94                       | 38 424.00                     |
| 4 × 4-5 × 5               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 968.77                       | 42 563.20                     |
| 4 × 4-5 × 5               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 963.55                       | 42 660.90                     |
| 5 × 5-2 × 2               | 40%    | 5                   | 10               | 0                 | 12.90         | 26.60               | 16.75                           | 16.75                        | 37 898.00                     |
| 5 × 5-2 × 2               | 40%    | 10                  | 10               | 0                 | 14.50         | 31.10               | 19.92                           | 19.92                        | 43 462.60                     |
| 5 × 5-2 × 2               | 60%    | 5                   | 10               | 0                 | 27.00         | 95.10               | 39.80                           | 39.80                        | 74 788.30                     |
| 5 × 5-2 × 2               | 60%    | 10                  | 10               | 0                 | 31.70         | 147.60              | 50.29                           | 50.29                        | 86 468.80                     |
| 5 × 5-2 × 2               | 80%    | 5                   | 0                | 0                 | –             | –                   | –                               | 604.85                       | 116 874.20                    |
| 5 × 5-2 × 2               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 604.02                       | 116 520.60                    |
| 5 × 5-2 × 2               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 603.36                       | 106 636.90                    |
| 5 × 5-2 × 2               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 602.40                       | 107 784.90                    |
| 5 × 5-3 × 3               | 40%    | 5                   | 10               | 0                 | 27.40         | 45.80               | 255.36                          | 255.36                       | 406 739.60                    |
| 5 × 5-3 × 3               | 40%    | 10                  | 10               | 0                 | 31.20         | 57.40               | 304.60                          | 304.60                       | 472 724.00                    |
| 5 × 5-3 × 3               | 60%    | 5                   | 5                | 0                 | 56.00         | 199.60              | 527.41                          | 570.55                       | 787 161.60                    |
| 5 × 5-3 × 3               | 60%    | 10                  | 0                | 0                 | –             | –                   | –                               | 610.70                       | 710 608.60                    |
| 5 × 5-3 × 3               | 80%    | 5                   | 0                | 0                 | –             | –                   | –                               | 643.43                       | 58 241.30                     |
| 5 × 5-3 × 3               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 648.26                       | 58 533.20                     |
| 5 × 5-3 × 3               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 618.23                       | 52 939.50                     |
| 5 × 5-3 × 3               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 622.92                       | 53 780.60                     |
| 5 × 5-4 × 4               | 40%    | 5                   | 0                | 0                 | –             | –                   | –                               | 630.08                       | 710 927.60                    |
| 5 × 5-4 × 4               | 40%    | 10                  | 0                | 0                 | –             | –                   | –                               | 625.89                       | 695 152.20                    |
| 5 × 5-4 × 4               | 60%    | 5                   | 0                | 0                 | –             | –                   | –                               | 629.81                       | 695 911.40                    |
| 5 × 5-4 × 4               | 60%    | 10                  | 0                | 0                 | –             | –                   | –                               | 629.79                       | 683 153.90                    |
| 5 × 5-4 × 4               | 80%    | 5                   | 0                | 0                 | –             | –                   | –                               | 986.92                       | 51 547.60                     |
| 5 × 5-4 × 4               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 1103.01                      | 58 042.10                     |
| 5 × 5-4 × 4               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 742.00                       | 35 807.80                     |
| 5 × 5-4 × 4               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 744.06                       | 35 871.20                     |
| 6 × 6-2 × 2               | 40%    | 5                   | 10               | 0                 | 22.10         | 50.50               | 57.50                           | 57.50                        | 108 281.50                    |
| 6 × 6-2 × 2               | 40%    | 10                  | 10               | 0                 | 24.40         | 63.90               | 66.11                           | 66.11                        | 120 940.70                    |
| 6 × 6-2 × 2               | 60%    | 5                   | 8                | 0                 | 45.12         | 209.62              | 151.80                          | 244.24                       | 182 588.90                    |
| 6 × 6-2 × 2               | 60%    | 10                  | 7                | 0                 | 51.14         | 268.57              | 179.62                          | 308.61                       | 188 250.50                    |
| 6 × 6-2 × 2               | 80%    | 5                   | 0                | 0                 | –             | –                   | –                               | 609.58                       | 89 553.70                     |
| 6 × 6-2 × 2               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 609.90                       | 89 092.50                     |
| 6 × 6-2 × 2               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 606.60                       | 84 369.80                     |
| 6 × 6-2 × 2               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 607.92                       | 84 261.20                     |
| 6 × 6-3 × 3               | 40%    | 5                   | 0                | 0                 | –             | –                   | –                               | 617.01                       | 769 308.80                    |
| 6 × 6-3 × 3               | 40%    | 10                  | 0                | 0                 | –             | –                   | –                               | 618.39                       | 757 708.00                    |
| 6 × 6-3 × 3               | 60%    | 5                   | 0                | 0                 | –             | –                   | –                               | 616.63                       | 676 000.80                    |
| 6 × 6-3 × 3               | 60%    | 10                  | 0                | 0                 | –             | –                   | –                               | 640.79                       | 554 955.70                    |
| 6 × 6-3 × 3               | 80%    | 5                   | 0                | 0                 | –             | –                   | –                               | 703.61                       | 48 512.90                     |
| 6 × 6-3 × 3               | 80%    | 10                  | 0                | 0                 | –             | –                   | –                               | 718.41                       | 50 195.50                     |
| 6 × 6-3 × 3               | 90%    | 5                   | 0                | 0                 | –             | –                   | –                               | 658.22                       | 41 507.50                     |
| 6 × 6-3 × 3               | 90%    | 10                  | 0                | 0                 | –             | –                   | –                               | 685.14                       | 43 726.10                     |

Table 13

Step 2: Detailed Results for CP one-tier.

| Layout<br>(Bay-Warehouse) | Fill % | Priority<br>Classes | Number<br>Solved | Number<br>Optimal | Mean<br>Moves | Mean<br>Distance | Model build time [s] |      | Model runtime [s] |      |
|---------------------------|--------|---------------------|------------------|-------------------|---------------|------------------|----------------------|------|-------------------|------|
|                           |        |                     |                  |                   |               |                  | Solved               | All  | Solved            | All  |
| 3 × 3-2 × 2               | 40%    | 5                   | 10               | 10                | 0             | 0                | –                    | –    | –                 | –    |
| 3 × 3-2 × 2               | 40%    | 10                  | 10               | 10                | 0             | 0                | –                    | –    | –                 | –    |
| 3 × 3-2 × 2               | 60%    | 5                   | 10               | 10                | 0.1           | 0.3              | 0.39                 | 0.39 | 0.05              | 0.05 |
| 3 × 3-2 × 2               | 60%    | 10                  | 10               | 10                | 0.1           | 0.3              | 0.45                 | 0.45 | 0.05              | 0.05 |
| 3 × 3-2 × 2               | 80%    | 5                   | 10               | 10                | 0.1           | 0.4              | 0.4                  | 0.4  | 0.05              | 0.05 |
| 3 × 3-2 × 2               | 80%    | 10                  | 10               | 10                | 0.2           | 0.7              | 0.46                 | 0.46 | 0.05              | 0.05 |

(continued on next page)

Table 13 (continued).

| Layout<br>(Bay-Warehouse) | Fill % | Priority<br>Classes | Number<br>Solved | Number<br>Optimal | Mean<br>Moves | Mean<br>Distance | Model build time [s] |         | Model runtime [s] |         |
|---------------------------|--------|---------------------|------------------|-------------------|---------------|------------------|----------------------|---------|-------------------|---------|
|                           |        |                     |                  |                   |               |                  | Solved               | All     | Solved            | All     |
| 3 × 3-2 × 2               | 90%    | 5                   | 10               | 10                | 0.6           | 2.9              | 0.48                 | 0.48    | 0.07              | 0.07    |
| 3 × 3-2 × 2               | 90%    | 10                  | 10               | 10                | 0.5           | 2.5              | 0.6                  | 0.6     | 0.09              | 0.09    |
| 3 × 3-3 × 3               | 40%    | 5                   | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-3 × 3               | 40%    | 10                  | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-3 × 3               | 60%    | 5                   | 10               | 10                | 0.3           | 1                | 1.75                 | 1.75    | 0.2               | 0.2     |
| 3 × 3-3 × 3               | 60%    | 10                  | 10               | 10                | 0.3           | 1                | 1.93                 | 1.93    | 0.21              | 0.21    |
| 3 × 3-3 × 3               | 80%    | 5                   | 10               | 10                | 0.3           | 1.2              | 2.62                 | 2.62    | 0.38              | 0.38    |
| 3 × 3-3 × 3               | 80%    | 10                  | 10               | 10                | 0.4           | 1.5              | 2.42                 | 2.42    | 0.34              | 0.34    |
| 3 × 3-3 × 3               | 90%    | 5                   | 10               | 10                | 1.3           | 6.3              | 3.28                 | 3.28    | 1.32              | 1.32    |
| 3 × 3-3 × 3               | 90%    | 10                  | 10               | 10                | 1.4           | 6.9              | 3.37                 | 3.37    | 1.33              | 1.33    |
| 3 × 3-4 × 4               | 40%    | 5                   | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-4 × 4               | 40%    | 10                  | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-4 × 4               | 60%    | 5                   | 10               | 10                | 0.2           | 0.6              | 5.31                 | 5.31    | 0.59              | 0.59    |
| 3 × 3-4 × 4               | 60%    | 10                  | 10               | 10                | 0.3           | 0.9              | 5.76                 | 5.76    | 0.65              | 0.65    |
| 3 × 3-4 × 4               | 80%    | 5                   | 10               | 10                | 0.7           | 2.4              | 10.65                | 10.65   | 1.07              | 1.07    |
| 3 × 3-4 × 4               | 80%    | 10                  | 10               | 10                | 1.1           | 3.4              | 10.06                | 10.06   | 2.36              | 2.36    |
| 3 × 3-4 × 4               | 90%    | 5                   | 10               | 10                | 1.5           | 8.7              | 11.48                | 11.48   | 7.81              | 7.81    |
| 3 × 3-4 × 4               | 90%    | 10                  | 10               | 10                | 1.8           | 10.1             | 10.51                | 10.51   | 6                 | 6       |
| 3 × 3-5 × 5               | 40%    | 5                   | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-5 × 5               | 40%    | 10                  | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-5 × 5               | 60%    | 5                   | 10               | 10                | 0.2           | 0.6              | 13.29                | 13.29   | 1.63              | 1.63    |
| 3 × 3-5 × 5               | 60%    | 10                  | 10               | 10                | 0.2           | 0.6              | 14.77                | 14.77   | 1.67              | 1.67    |
| 3 × 3-5 × 5               | 80%    | 5                   | 10               | 10                | 1             | 3.9              | 18.21                | 18.21   | 2.42              | 2.42    |
| 3 × 3-5 × 5               | 80%    | 10                  | 10               | 10                | 1.4           | 5                | 23.16                | 23.16   | 6.83              | 6.83    |
| 3 × 3-5 × 5               | 90%    | 5                   | 10               | 10                | 2.3           | 11.3             | 38.44                | 38.44   | 45.09             | 45.09   |
| 3 × 3-5 × 5               | 90%    | 10                  | 10               | 10                | 2.9           | 14.3             | 46.28                | 46.28   | 62.92             | 62.92   |
| 3 × 3-6 × 6               | 40%    | 5                   | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-6 × 6               | 40%    | 10                  | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-6 × 6               | 60%    | 5                   | 10               | 10                | 0.2           | 0.2              | 26.41                | 26.41   | 3.75              | 3.75    |
| 3 × 3-6 × 6               | 60%    | 10                  | 10               | 10                | 0.3           | 0.3              | 29.01                | 29.01   | 3.5               | 3.5     |
| 3 × 3-6 × 6               | 80%    | 5                   | 10               | 10                | 1.6           | 5.1              | 57.51                | 57.51   | 11.56             | 11.56   |
| 3 × 3-6 × 6               | 80%    | 10                  | 10               | 10                | 2.2           | 6.9              | 78.06                | 78.06   | 201.29            | 201.29  |
| 3 × 3-6 × 6               | 90%    | 5                   | 10               | 10                | 2.4           | 11.9             | 92.23                | 92.23   | 116.16            | 116.16  |
| 3 × 3-6 × 6               | 90%    | 10                  | 10               | 9                 | 3.4           | 17.6             | 101.76               | 101.76  | 419.37            | 419.37  |
| 3 × 3-7 × 7               | 40%    | 5                   | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-7 × 7               | 40%    | 10                  | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-7 × 7               | 60%    | 5                   | 10               | 10                | 0.6           | 1.6              | 74.04                | 74.04   | 11.73             | 11.73   |
| 3 × 3-7 × 7               | 60%    | 10                  | 10               | 10                | 0.5           | 1.5              | 85.65                | 85.65   | 12.46             | 12.46   |
| 3 × 3-7 × 7               | 80%    | 5                   | 10               | 10                | 2             | 6.8              | 129                  | 129     | 36.77             | 36.77   |
| 3 × 3-7 × 7               | 80%    | 10                  | 10               | 10                | 2.4           | 7.6              | 169.58               | 169.58  | 52.28             | 52.28   |
| 3 × 3-7 × 7               | 90%    | 5                   | 10               | 10                | 3.1           | 16.2             | 233.86               | 233.86  | 436.21            | 436.21  |
| 3 × 3-7 × 7               | 90%    | 10                  | 7                | 7                 | 3.86          | 21               | 212.36               | 263.01  | 1027.18           | 1802.76 |
| 3 × 3-8 × 8               | 40%    | 5                   | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-8 × 8               | 40%    | 10                  | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-8 × 8               | 60%    | 5                   | 10               | 10                | 0.4           | 0.8              | 175.42               | 175.42  | 27.84             | 27.84   |
| 3 × 3-8 × 8               | 60%    | 10                  | 10               | 10                | 0.6           | 1.5              | 183.57               | 183.57  | 34.53             | 34.53   |
| 3 × 3-8 × 8               | 80%    | 5                   | 10               | 10                | 2.6           | 8.6              | 247.44               | 247.44  | 75.62             | 75.62   |
| 3 × 3-8 × 8               | 80%    | 10                  | 10               | 9                 | 3.4           | 10.9             | 330.63               | 330.63  | 869.04            | 869.04  |
| 3 × 3-8 × 8               | 90%    | 5                   | 7                | 5                 | 3.57          | 19.14            | 342.61               | 404.96  | 1097.71           | 1852.4  |
| 3 × 3-8 × 8               | 90%    | 10                  | 6                | 4                 | 5             | 24               | 472.05               | 1374.17 | 1564.24           | 2378.25 |
| 3 × 3-9 × 9               | 40%    | 5                   | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-9 × 9               | 40%    | 10                  | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-9 × 9               | 60%    | 5                   | 10               | 10                | 0.7           | 2                | 241.11               | 241.11  | 44.03             | 44.03   |
| 3 × 3-9 × 9               | 60%    | 10                  | 10               | 10                | 1.3           | 3.8              | 311.2                | 311.2   | 70.72             | 70.72   |
| 3 × 3-9 × 9               | 80%    | 5                   | 9                | 9                 | 3.67          | 11.11            | 522.64               | 1000.59 | 423.01            | 736.28  |
| 3 × 3-9 × 9               | 80%    | 10                  | 7                | 6                 | 3.86          | 10.71            | 570.28               | 1462.72 | 846.28            | 1676.38 |
| 3 × 3-9 × 9               | 90%    | 5                   | 6                | 5                 | 4             | 15.67            | 561.16               | 1579.6  | 863.1             | 1955.96 |
| 3 × 3-9 × 9               | 90%    | 10                  | 4                | 4                 | 4.5           | 19.25            | 734.26               | 3050.75 | 716.62            | 2433.85 |
| 3 × 3-10 × 10             | 40%    | 5                   | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-10 × 10             | 40%    | 10                  | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-10 × 10             | 60%    | 5                   | 10               | 10                | 1.1           | 3.3              | 255.22               | 255.22  | 38.02             | 38.02   |
| 3 × 3-10 × 10             | 60%    | 10                  | 10               | 10                | 1.5           | 4.2              | 374.04               | 374.04  | 68.28             | 68.28   |
| 3 × 3-10 × 10             | 80%    | 5                   | 7                | 5                 | 4.43          | 15               | 942.06               | 1649.37 | 1244.67           | 1946.85 |
| 3 × 3-10 × 10             | 80%    | 10                  | 6                | 3                 | 5             | 18.5             | 1097.4               | 3201.49 | 2221.12           | 2755.72 |
| 3 × 3-10 × 10             | 90%    | 5                   | 2                | 1                 | 5             | 14.5             | 1058.54              | 4626.94 | 1934.16           | 3233.6  |
| 3 × 3-10 × 10             | 90%    | 10                  | 1                | 0                 | 6             | 22               | 1464.67              | 5021.39 | 3616.94           | 3663.17 |
| 3 × 3-11 × 11             | 40%    | 5                   | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-11 × 11             | 40%    | 10                  | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-11 × 11             | 60%    | 5                   | 10               | 10                | 0.9           | 1.5              | 389.95               | 389.95  | 54.76             | 54.76   |
| 3 × 3-11 × 11             | 60%    | 10                  | 10               | 10                | 1.5           | 3.2              | 565.83               | 565.83  | 121.78            | 121.78  |
| 3 × 3-11 × 11             | 80%    | 5                   | 5                | 3                 | 4.6           | 13.6             | 1589.32              | 4067.93 | 1743.9            | 2669.01 |
| 3 × 3-11 × 11             | 80%    | 10                  | 4                | 1                 | 5.25          | 17               | 1734.45              | 5001.65 | 2837.93           | 3316.58 |

(continued on next page)

Table 13 (continued).

| Layout<br>(Bay-Warehouse) | Fill % | Priority<br>Classes | Number<br>Solved | Number<br>Optimal | Mean<br>Moves | Mean<br>Distance | Model build time [s] |         | Model runtime [s] |         |
|---------------------------|--------|---------------------|------------------|-------------------|---------------|------------------|----------------------|---------|-------------------|---------|
|                           |        |                     |                  |                   |               |                  | Solved               | All     | Solved            | All     |
| 3 × 3-11 × 11             | 90%    | 5                   | 1                | 1                 | 4             | 11               | 1993.87              | 6248.04 | 516.67            | 3322.09 |
| 3 × 3-11 × 11             | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | 7595.76 | –                 | 3495.12 |
| 3 × 3-12 × 12             | 40%    | 5                   | 10               | 10                | 0             | 0                | –                    | –       | –                 | –       |
| 3 × 3-12 × 12             | 40%    | 10                  | –                | –                 | –             | –                | –                    | –       | –                 | –       |
| 3 × 3-12 × 12             | 60%    | 5                   | 10               | 10                | 1.2           | 3.3              | 572.23               | 572.23  | 85.14             | 85.14   |
| 3 × 3-12 × 12             | 60%    | 10                  | –                | –                 | –             | –                | –                    | –       | –                 | –       |
| 3 × 3-12 × 12             | 80%    | 5                   | 4                | 3                 | 4.25          | 15.25            | 2094.34              | 6332.23 | 1378.22           | 2549.2  |
| 3 × 3-12 × 12             | 80%    | 10                  | –                | –                 | –             | –                | –                    | –       | –                 | –       |
| 3 × 3-12 × 12             | 90%    | 5                   | 1                | 1                 | 4             | 15               | 1891.16              | 5854.54 | 824.39            | 2232.68 |
| 3 × 3-12 × 12             | 90%    | 10                  | –                | –                 | –             | –                | –                    | –       | –                 | –       |
| 4 × 4-2 × 2               | 40%    | 5                   | 10               | 10                | 0.2           | 0.2              | 1.12                 | 1.12    | 0.12              | 0.12    |
| 4 × 4-2 × 2               | 40%    | 10                  | 10               | 10                | 0.2           | 0.2              | 1.17                 | 1.17    | 0.13              | 0.13    |
| 4 × 4-2 × 2               | 60%    | 5                   | 10               | 10                | 0.1           | 0.1              | 1.15                 | 1.15    | 0.12              | 0.12    |
| 4 × 4-2 × 2               | 60%    | 10                  | 10               | 10                | 0.3           | 1.1              | 1.22                 | 1.22    | 0.13              | 0.13    |
| 4 × 4-2 × 2               | 80%    | 5                   | 10               | 10                | 1.6           | 4.7              | 2.04                 | 2.04    | 1.79              | 1.79    |
| 4 × 4-2 × 2               | 80%    | 10                  | 10               | 10                | 2.3           | 9                | 2.61                 | 2.61    | 4.11              | 4.11    |
| 4 × 4-2 × 2               | 90%    | 5                   | 10               | 10                | 1.7           | 10               | 2.46                 | 2.46    | 3.91              | 3.91    |
| 4 × 4-2 × 2               | 90%    | 10                  | 10               | 10                | 2.2           | 13.5             | 2.79                 | 2.79    | 3.45              | 3.45    |
| 4 × 4-3 × 3               | 40%    | 5                   | 10               | 10                | 0.5           | 0.5              | 7.35                 | 7.35    | 0.8               | 0.8     |
| 4 × 4-3 × 3               | 40%    | 10                  | 10               | 10                | 0.5           | 0.5              | 6.71                 | 6.71    | 0.83              | 0.83    |
| 4 × 4-3 × 3               | 60%    | 5                   | 10               | 10                | 0.9           | 1.6              | 7.36                 | 7.36    | 0.88              | 0.88    |
| 4 × 4-3 × 3               | 60%    | 10                  | 10               | 10                | 1.2           | 2.5              | 9.18                 | 9.18    | 3.12              | 3.12    |
| 4 × 4-3 × 3               | 80%    | 5                   | 10               | 10                | 3             | 9                | 18.82                | 18.82   | 19.04             | 19.04   |
| 4 × 4-3 × 3               | 80%    | 10                  | 10               | 10                | 4.3           | 11.8             | 23.87                | 23.87   | 38.84             | 38.84   |
| 4 × 4-3 × 3               | 90%    | 5                   | 10               | 10                | 4.2           | 21.2             | 22.68                | 22.68   | 278.89            | 278.89  |
| 4 × 4-3 × 3               | 90%    | 10                  | 10               | 9                 | 5.6           | 25.6             | 32.34                | 32.34   | 1135.08           | 1135.08 |
| 4 × 4-4 × 4               | 40%    | 5                   | 10               | 10                | 0.5           | 0.5              | 28.09                | 28.09   | 6.21              | 6.21    |
| 4 × 4-4 × 4               | 40%    | 10                  | 10               | 10                | 0.6           | 0.7              | 27.41                | 27.41   | 5.42              | 5.42    |
| 4 × 4-4 × 4               | 60%    | 5                   | 10               | 10                | 2.1           | 3.3              | 45.47                | 45.47   | 12.32             | 12.32   |
| 4 × 4-4 × 4               | 60%    | 10                  | 10               | 10                | 2.5           | 4.5              | 49.97                | 49.97   | 19.61             | 19.61   |
| 4 × 4-4 × 4               | 80%    | 5                   | 10               | 8                 | 4.3           | 13.2             | 84.02                | 84.02   | 854.3             | 854.3   |
| 4 × 4-4 × 4               | 80%    | 10                  | 10               | 7                 | 5.6           | 17.7             | 100.25               | 100.25  | 1269.42           | 1269.42 |
| 4 × 4-4 × 4               | 90%    | 5                   | 8                | 4                 | 6.25          | 27.75            | 108.64               | 118.32  | 2073.2            | 2379.79 |
| 4 × 4-4 × 4               | 90%    | 10                  | 5                | 3                 | 7             | 29.6             | 130.32               | 154.46  | 2301.81           | 2954.73 |
| 4 × 4-5 × 5               | 40%    | 5                   | 10               | 10                | 0.9           | 0.9              | 69.7                 | 69.7    | 10.89             | 10.89   |
| 4 × 4-5 × 5               | 40%    | 10                  | 10               | 10                | 1.1           | 1.4              | 77.77                | 77.77   | 13.37             | 13.37   |
| 4 × 4-5 × 5               | 60%    | 5                   | 10               | 10                | 3.2           | 5.3              | 149.12               | 149.12  | 63.44             | 63.44   |
| 4 × 4-5 × 5               | 60%    | 10                  | 10               | 9                 | 3.7           | 6.2              | 161.21               | 161.21  | 417.62            | 417.62  |
| 4 × 4-5 × 5               | 80%    | 5                   | 4                | 2                 | 5.5           | 12.25            | 273.39               | 350.14  | 1823.63           | 2899.28 |
| 4 × 4-5 × 5               | 80%    | 10                  | 3                | 2                 | 6             | 15.33            | 258.74               | 420.07  | 1336.06           | 2939.9  |
| 4 × 4-5 × 5               | 90%    | 5                   | 1                | 0                 | 8             | 27               | 337.39               | 1145.73 | 3611.32           | 3427.68 |
| 4 × 4-5 × 5               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | 2155.33 | –                 | 3359.57 |
| 4 × 4-6 × 6               | 40%    | 5                   | 10               | 10                | 0.9           | 1.4              | 115.81               | 115.81  | 20.93             | 20.93   |
| 4 × 4-6 × 6               | 40%    | 10                  | 10               | 10                | 1.1           | 1.7              | 156.06               | 156.06  | 22.46             | 22.46   |
| 4 × 4-6 × 6               | 60%    | 5                   | 10               | 9                 | 3.9           | 5.9              | 369.12               | 369.12  | 597.78            | 597.78  |
| 4 × 4-6 × 6               | 60%    | 10                  | 9                | 8                 | 4.22          | 7.33             | 376.79               | 420.6   | 634.33            | 931.58  |
| 4 × 4-6 × 6               | 80%    | 5                   | 1                | 1                 | 5             | 5                | 533                  | 3438.81 | 144.97            | 3234.02 |
| 4 × 4-6 × 6               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | 4463.78 | –                 | 3617.62 |
| 4 × 4-6 × 6               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | 4758.33 | –                 | 3596.25 |
| 4 × 4-6 × 6               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | 4608.67 | –                 | 3633.29 |
| 4 × 4-7 × 7               | 40%    | 5                   | 10               | 10                | 1.2           | 1.3              | 280.76               | 280.76  | 46.36             | 46.36   |
| 4 × 4-7 × 7               | 40%    | 10                  | 10               | 10                | 1.6           | 1.7              | 317.15               | 317.15  | 59.3              | 59.3    |
| 4 × 4-7 × 7               | 60%    | 5                   | 7                | 7                 | 4.43          | 7.29             | 809.11               | 1528.97 | 676.15            | 1544.67 |
| 4 × 4-7 × 7               | 60%    | 10                  | 6                | 5                 | 6             | 11               | 1032.33              | 2212.51 | 1498.65           | 2326.8  |
| 4 × 4-7 × 7               | 80%    | 5                   | 1                | 0                 | 8             | 10               | 1455.04              | 5085.65 | 3612.17           | 3667.92 |
| 4 × 4-7 × 7               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | –       | –                 | –       |
| 4 × 4-7 × 7               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | 4356.87 | –                 | 3782.87 |
| 4 × 4-7 × 7               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | –       | –                 | –       |
| 4 × 4-8 × 8               | 40%    | 5                   | 10               | 10                | 1.3           | 2.1              | 517.87               | 517.87  | 100.96            | 100.96  |
| 4 × 4-8 × 8               | 40%    | 10                  | 10               | 10                | 1.5           | 2.4              | 588.7                | 588.7   | 124.77            | 124.77  |
| 4 × 4-8 × 8               | 60%    | 5                   | 6                | 6                 | 6             | 7.83             | 1622.96              | 4291.83 | 1693.18           | 2418.77 |
| 4 × 4-8 × 8               | 60%    | 10                  | 5                | 3                 | 7.4           | 9.8              | 2201.89              | 4501.86 | 2431.16           | 2953.2  |
| 4 × 4-8 × 8               | 80%    | 5                   | 0                | 0                 | –             | –                | –                    | 5056.85 | –                 | 3648.01 |
| 4 × 4-8 × 8               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | 8545.23 | –                 | 3819.07 |
| 4 × 4-8 × 8               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | 36987.4 | –                 | –       |
| 4 × 4-8 × 8               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | –       | –                 | –       |
| 5 × 5-2 × 2               | 40%    | 5                   | 10               | 10                | 0.2           | 0.2              | 2.9                  | 2.9     | 0.27              | 0.27    |
| 5 × 5-2 × 2               | 40%    | 10                  | 10               | 10                | 0.1           | 0.1              | 2.7                  | 2.7     | 0.34              | 0.34    |
| 5 × 5-2 × 2               | 60%    | 5                   | 10               | 10                | 1.4           | 2                | 4.77                 | 4.77    | 0.76              | 0.76    |
| 5 × 5-2 × 2               | 60%    | 10                  | 10               | 10                | 1.9           | 2.9              | 5.07                 | 5.07    | 1.93              | 1.93    |
| 5 × 5-2 × 2               | 80%    | 5                   | 10               | 10                | 4.8           | 16.4             | 13.23                | 13.23   | 436.51            | 436.51  |
| 5 × 5-2 × 2               | 80%    | 10                  | 10               | 9                 | 5.6           | 18.6             | 15.03                | 15.03   | 438.64            | 438.64  |
| 5 × 5-2 × 2               | 90%    | 5                   | 10               | 10                | 6.3           | 35.7             | 24.25                | 24.25   | 428.03            | 428.03  |
| 5 × 5-2 × 2               | 90%    | 10                  | 10               | 8                 | 6.5           | 35.6             | 18.8                 | 18.8    | 921.79            | 921.79  |

(continued on next page)

Table 13 (continued).

| Layout<br>(Bay-Warehouse) | Fill % | Priority<br>Classes | Number<br>Solved | Number<br>Optimal | Mean<br>Moves | Mean<br>Distance | Model build time [s] |          | Model runtime [s] |         |
|---------------------------|--------|---------------------|------------------|-------------------|---------------|------------------|----------------------|----------|-------------------|---------|
|                           |        |                     |                  |                   |               |                  | Solved               | All      | Solved            | All     |
| 5 × 5-3 × 3               | 40%    | 5                   | 10               | 10                | 0.8           | 1.4              | 20.82                | 20.82    | 2.92              | 2.92    |
| 5 × 5-3 × 3               | 40%    | 10                  | 10               | 10                | 0.9           | 1.5              | 22.97                | 22.97    | 3.79              | 3.79    |
| 5 × 5-3 × 3               | 60%    | 5                   | 10               | 10                | 4             | 5.4              | 52.16                | 52.16    | 128.76            | 128.76  |
| 5 × 5-3 × 3               | 60%    | 10                  | 10               | 10                | 5.1           | 8                | 70.62                | 70.62    | 306.87            | 306.87  |
| 5 × 5-3 × 3               | 80%    | 5                   | 5                | 3                 | 7             | 20.2             | 95.78                | 126.65   | 1893.9            | 2748.42 |
| 5 × 5-3 × 3               | 80%    | 10                  | 4                | 0                 | 8.75          | 27.5             | 169.3                | 178.79   | 3605.36           | 3607.13 |
| 5 × 5-3 × 3               | 90%    | 5                   | 1                | 0                 | 10            | 62               | 127.47               | 194.85   | 3602.96           | 3608.21 |
| 5 × 5-3 × 3               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | 202.12   | –                 | 3608.51 |
| 5 × 5-4 × 4               | 40%    | 5                   | 10               | 10                | 1.6           | 2                | 81.85                | 81.85    | 16.16             | 16.16   |
| 5 × 5-4 × 4               | 40%    | 10                  | 10               | 10                | 2             | 2.4              | 99.35                | 99.35    | 22.92             | 22.92   |
| 5 × 5-4 × 4               | 60%    | 5                   | 10               | 7                 | 6.4           | 10.4             | 257.08               | 257.08   | 1247.23           | 1247.23 |
| 5 × 5-4 × 4               | 60%    | 10                  | 8                | 1                 | 8.25          | 13.88            | 365.33               | 368.24   | 3170.97           | 3258.17 |
| 5 × 5-4 × 4               | 80%    | 5                   | 0                | 0                 | –             | –                | –                    | 2209.49  | –                 | 2936.74 |
| 5 × 5-4 × 4               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | 3658.71  | –                 | 3108.33 |
| 5 × 5-4 × 4               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | 4058.58  | –                 | 3408.84 |
| 5 × 5-4 × 4               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 5 × 5-5 × 5               | 40%    | 5                   | 10               | 10                | 2.6           | 2.9              | 284.35               | 284.35   | 58.25             | 58.25   |
| 5 × 5-5 × 5               | 40%    | 10                  | 10               | 10                | 3.2           | 3.7              | 320.39               | 320.39   | 77.78             | 77.78   |
| 5 × 5-5 × 5               | 60%    | 5                   | 4                | 1                 | 8.75          | 12.5             | 907.63               | 1431.99  | 3428.61           | 3539.99 |
| 5 × 5-5 × 5               | 60%    | 10                  | 0                | 0                 | –             | –                | –                    | 3795.2   | –                 | 3552.09 |
| 5 × 5-5 × 5               | 80%    | 5                   | 0                | 0                 | –             | –                | –                    | 5447.5   | –                 | 3730.5  |
| 5 × 5-5 × 5               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | 6135.13  | –                 | 3678.31 |
| 5 × 5-5 × 5               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | 5071.32  | –                 | 3969.73 |
| 5 × 5-5 × 5               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 5 × 5-6 × 6               | 40%    | 5                   | 10               | 9                 | 4.5           | 5.9              | 968.01               | 968.01   | 920.15            | 920.15  |
| 5 × 5-6 × 6               | 40%    | 10                  | 10               | 9                 | 5             | 6.1              | 1028.72              | 1028.72  | 866.77            | 866.77  |
| 5 × 5-6 × 6               | 60%    | 5                   | 0                | 0                 | –             | –                | –                    | 8179.91  | –                 | 3591.7  |
| 5 × 5-6 × 6               | 60%    | 10                  | 0                | 0                 | –             | –                | –                    | 7964.47  | –                 | 3627.83 |
| 5 × 5-6 × 6               | 80%    | 5                   | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 5 × 5-6 × 6               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 5 × 5-6 × 6               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 5 × 5-6 × 6               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-2 × 2               | 40%    | 5                   | 10               | 10                | 1.3           | 1.6              | 11.78                | 11.78    | 3.23              | 3.23    |
| 6 × 6-2 × 2               | 40%    | 10                  | 10               | 10                | 1.8           | 1.9              | 10.79                | 10.79    | 3.56              | 3.56    |
| 6 × 6-2 × 2               | 60%    | 5                   | 10               | 10                | 3.8           | 6.1              | 20.57                | 20.57    | 24.4              | 24.4    |
| 6 × 6-2 × 2               | 60%    | 10                  | 10               | 10                | 4.1           | 7.2              | 22.13                | 22.13    | 41.51             | 41.51   |
| 6 × 6-2 × 2               | 80%    | 5                   | 6                | 4                 | 7             | 21.67            | 37.45                | 56.52    | 1905.4            | 2582.87 |
| 6 × 6-2 × 2               | 80%    | 10                  | 6                | 2                 | 8.33          | 29               | 67.07                | 67.98    | 2933.08           | 3201.05 |
| 6 × 6-2 × 2               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | 89.45    | –                 | 3600.53 |
| 6 × 6-2 × 2               | 90%    | 10                  | 1                | 0                 | 14            | 148              | 77.42                | 99.21    | 3603.21           | 3602.85 |
| 6 × 6-3 × 3               | 40%    | 5                   | 10               | 10                | 2.5           | 3                | 70.33                | 70.33    | 17.13             | 17.13   |
| 6 × 6-3 × 3               | 40%    | 10                  | 10               | 10                | 3.4           | 3.6              | 98.12                | 98.12    | 38.97             | 38.97   |
| 6 × 6-3 × 3               | 60%    | 5                   | 7                | 1                 | 8.29          | 13               | 229.2                | 251.08   | 3111.47           | 3258.98 |
| 6 × 6-3 × 3               | 60%    | 10                  | 6                | 1                 | 9             | 12.67            | 251.07               | 314.45   | 3044.07           | 3270.57 |
| 6 × 6-3 × 3               | 80%    | 5                   | 0                | 0                 | –             | –                | –                    | 1036.94  | –                 | 3354.02 |
| 6 × 6-3 × 3               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | 2850.4   | –                 | 2692.97 |
| 6 × 6-3 × 3               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | 3542.83  | –                 | 3231.76 |
| 6 × 6-3 × 3               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-4 × 4               | 40%    | 5                   | 8                | 8                 | 4             | 4.75             | 366.35               | 470.71   | 120.5             | 815.27  |
| 6 × 6-4 × 4               | 40%    | 10                  | 8                | 7                 | 5.25          | 6                | 468.81               | 581.25   | 794.58            | 1356.79 |
| 6 × 6-4 × 4               | 60%    | 5                   | 0                | 0                 | –             | –                | –                    | 5359.21  | –                 | 3563.36 |
| 6 × 6-4 × 4               | 60%    | 10                  | 0                | 0                 | –             | –                | –                    | 5628.63  | –                 | 3587.41 |
| 6 × 6-4 × 4               | 80%    | 5                   | 0                | 0                 | –             | –                | –                    | 5786.41  | –                 | 3615.39 |
| 6 × 6-4 × 4               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | 6510.6   | –                 | 3705.79 |
| 6 × 6-4 × 4               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-4 × 4               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-5 × 5               | 40%    | 5                   | 6                | 4                 | 6.67          | 8                | 1450.83              | 2545.86  | 1807.87           | 2504.45 |
| 6 × 6-5 × 5               | 40%    | 10                  | 5                | 1                 | 7.8           | 9                | 1609.39              | 2549.4   | 3160.58           | 3346.92 |
| 6 × 6-5 × 5               | 60%    | 5                   | 0                | 0                 | –             | –                | –                    | 17 886.9 | –                 | 1868.99 |
| 6 × 6-5 × 5               | 60%    | 10                  | 0                | 0                 | –             | –                | –                    | 30 407   | –                 | –       |
| 6 × 6-5 × 5               | 80%    | 5                   | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-5 × 5               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-5 × 5               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-5 × 5               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-6 × 6               | 40%    | 5                   | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-6 × 6               | 40%    | 10                  | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-6 × 6               | 60%    | 5                   | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-6 × 6               | 60%    | 10                  | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-6 × 6               | 80%    | 5                   | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-6 × 6               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-6 × 6               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |
| 6 × 6-6 × 6               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | –        | –                 | –       |

**Table 14**

Step 2: Detailed Results for CP two-tier.

| Layout<br>(Bay-Warehouse) | Fill % | Priority<br>Classes | Number<br>Solved | Number<br>Optimal | Mean<br>Moves | Mean<br>Distance | Model build time [s] |        | Model runtime [s] |         |
|---------------------------|--------|---------------------|------------------|-------------------|---------------|------------------|----------------------|--------|-------------------|---------|
|                           |        |                     |                  |                   |               |                  | Solved               | All    | Solved            | All     |
| 3 × 3-2 × 2               | 40%    | 5                   | 10               | 10                | 2.90          | 4.60             | 4.04                 | 4.04   | 12.02             | 12.02   |
| 3 × 3-2 × 2               | 40%    | 10                  | 10               | 10                | 3.10          | 5.00             | 4.38                 | 4.38   | 14.89             | 14.89   |
| 3 × 3-2 × 2               | 60%    | 5                   | 10               | 8                 | 5.60          | 13.70            | 7.80                 | 7.80   | 906.34            | 906.34  |
| 3 × 3-2 × 2               | 60%    | 10                  | 10               | 6                 | 6.60          | 17.60            | 9.31                 | 9.31   | 1710.92           | 1710.92 |
| 3 × 3-2 × 2               | 80%    | 5                   | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 3 × 3-2 × 2               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 3 × 3-2 × 2               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 3 × 3-2 × 2               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 4 × 4-2 × 2               | 40%    | 5                   | 10               | 7                 | 6.70          | 9.60             | 25.52                | 25.52  | 1527.14           | 1527.14 |
| 4 × 4-2 × 2               | 40%    | 10                  | 9                | 4                 | 7.11          | 11.67            | 27.42                | 28.91  | 2437.92           | 2554.25 |
| 4 × 4-2 × 2               | 60%    | 5                   | 0                | 0                 | –             | –                | –                    | 64.62  | –                 | 3601.92 |
| 4 × 4-2 × 2               | 60%    | 10                  | 0                | 0                 | –             | –                | –                    | 65.64  | –                 | 3601.89 |
| 4 × 4-2 × 2               | 80%    | 5                   | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 4 × 4-2 × 2               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 4 × 4-2 × 2               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 4 × 4-2 × 2               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 5 × 5-2 × 2               | 40%    | 5                   | 2                | 0                 | 9.00          | 15.00            | 93.08                | 132.13 | 3606.67           | 3604.99 |
| 5 × 5-2 × 2               | 40%    | 10                  | 0                | 0                 | –             | –                | –                    | 148.07 | –                 | 3605.86 |
| 5 × 5-2 × 2               | 60%    | 5                   | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 5 × 5-2 × 2               | 60%    | 10                  | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 5 × 5-2 × 2               | 80%    | 5                   | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 5 × 5-2 × 2               | 80%    | 10                  | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 5 × 5-2 × 2               | 90%    | 5                   | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |
| 5 × 5-2 × 2               | 90%    | 10                  | 0                | 0                 | –             | –                | –                    | –      | –                 | –       |

**Table 15**

Step 3: Detailed results routing one-tier.

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |      |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best |
| 3 × 3-2 × 2         | 90%    | 5                   | 2      | MS   | 1      | 1       | 76.00     | 148.00      | 11.00  | 17.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 5                   | 2      | TT   | 1      | 1       | 76.00     | 148.00      | 11.00  | 17.00    | 0            | 0    |
| 3 × 3-2 × 2         | 90%    | 5                   | 3      | MS   | 1      | 1       | 73.00     | 145.00      | 11.00  | 14.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 5                   | 3      | TT   | 1      | 1       | 76.00     | 143.00      | 11.00  | 12.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 5                   | 4      | MS   | 1      | 1       | 73.00     | 144.00      | 11.00  | 13.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 5                   | 4      | TT   | 1      | 1       | 76.00     | 143.00      | 11.00  | 12.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 5                   | 5      | MS   | 1      | 1       | 73.00     | 144.00      | 11.00  | 13.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 5                   | 5      | TT   | 1      | 1       | 76.00     | 143.00      | 11.00  | 12.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 10                  | 2      | MS   | 1      | 1       | 76.00     | 148.00      | 11.00  | 17.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 10                  | 2      | TT   | 1      | 1       | 76.00     | 148.00      | 11.00  | 17.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 10                  | 3      | MS   | 1      | 1       | 73.00     | 145.00      | 11.00  | 14.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 10                  | 3      | TT   | 1      | 1       | 76.00     | 143.00      | 11.00  | 12.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 10                  | 4      | MS   | 1      | 1       | 73.00     | 144.00      | 11.00  | 13.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 10                  | 4      | TT   | 1      | 1       | 76.00     | 143.00      | 11.00  | 12.00    | 0.01         | 0.01 |
| 3 × 3-2 × 2         | 90%    | 10                  | 5      | MS   | 1      | 1       | 73.00     | 144.00      | 11.00  | 13.00    | 0.02         | 0.02 |
| 3 × 3-2 × 2         | 90%    | 10                  | 5      | TT   | 1      | 1       | 76.00     | 143.00      | 11.00  | 12.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 5                   | 2      | MS   | 1      | 1       | 78.00     | 154.00      | 9.00   | 25.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 5                   | 2      | TT   | 1      | 1       | 79.00     | 144.00      | 9.00   | 15.00    | 0            | 0    |
| 3 × 3-3 × 3         | 80%    | 5                   | 3      | MS   | 1      | 1       | 78.00     | 149.00      | 9.00   | 20       | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 5                   | 3      | TT   | 1      | 1       | 79.00     | 144.00      | 9.00   | 15.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 5                   | 4      | MS   | 1      | 1       | 78.00     | 154.00      | 9.00   | 25.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 5                   | 4      | TT   | 1      | 1       | 79.00     | 144.00      | 9.00   | 15.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 5                   | 5      | MS   | 1      | 1       | 78.00     | 154.00      | 9.00   | 25.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 5                   | 5      | TT   | 1      | 1       | 79.00     | 144.00      | 9.00   | 15.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 10                  | 2      | MS   | 1      | 1       | 78.00     | 154.00      | 9.00   | 25.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 10                  | 2      | TT   | 1      | 1       | 79.00     | 144.00      | 9.00   | 15.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 10                  | 3      | MS   | 1      | 1       | 78.00     | 149.00      | 9.00   | 20       | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 10                  | 3      | TT   | 1      | 1       | 79.00     | 144.00      | 9.00   | 15.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 10                  | 4      | MS   | 1      | 1       | 78.00     | 154.00      | 9.00   | 25.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 10                  | 4      | TT   | 1      | 1       | 79.00     | 144.00      | 9.00   | 15.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 10                  | 5      | MS   | 1      | 1       | 78.00     | 154.00      | 9.00   | 25.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 80%    | 10                  | 5      | TT   | 1      | 1       | 79.00     | 144.00      | 9.00   | 15.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 90%    | 5                   | 2      | MS   | 5      | 5       | 89.00     | 160.40      | 10.20  | 18.20    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 90%    | 5                   | 2      | TT   | 5      | 5       | 89.20     | 158.40      | 10.20  | 16.20    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 90%    | 5                   | 3      | MS   | 5      | 5       | 77.20     | 161.60      | 10.20  | 19.40    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 90%    | 5                   | 3      | TT   | 5      | 5       | 89.00     | 157.40      | 10.20  | 15.20    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 90%    | 5                   | 4      | MS   | 5      | 5       | 74.00     | 157.40      | 10.20  | 15.20    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 90%    | 5                   | 4      | TT   | 5      | 5       | 86.80     | 154.20      | 10.20  | 12.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 90%    | 5                   | 5      | MS   | 5      | 5       | 72.60     | 155.80      | 10.20  | 13.60    | 0.01         | 0.02 |
| 3 × 3-3 × 3         | 90%    | 5                   | 5      | TT   | 5      | 5       | 73.00     | 153.00      | 10.20  | 10.80    | 0.01         | 0.01 |

(continued on next page)

Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |      |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best |
| 3 × 3-3 × 3         | 90%    | 10                  | 2      | MS   | 5      | 5       | 89.00     | 160.40      | 10.20  | 18.20    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 90%    | 10                  | 2      | TT   | 5      | 5       | 89.20     | 158.40      | 10.20  | 16.20    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 90%    | 10                  | 3      | MS   | 5      | 5       | 77.20     | 162.20      | 10.20  | 20       | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 90%    | 10                  | 3      | TT   | 5      | 5       | 89.00     | 157.40      | 10.20  | 15.20    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 90%    | 10                  | 4      | MS   | 5      | 5       | 74.00     | 157.20      | 10.20  | 15.00    | 0.01         | 0.02 |
| 3 × 3-3 × 3         | 90%    | 10                  | 4      | TT   | 5      | 5       | 86.80     | 154.20      | 10.20  | 12.00    | 0.01         | 0.01 |
| 3 × 3-3 × 3         | 90%    | 10                  | 5      | MS   | 5      | 5       | 72.60     | 155.80      | 10.20  | 13.60    | 0.01         | 0.02 |
| 3 × 3-3 × 3         | 90%    | 10                  | 5      | TT   | 5      | 5       | 73.00     | 153.00      | 10.20  | 10.80    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 5                   | 2      | MS   | 2      | 2       | 79.00     | 156.00      | 8.00   | 28.00    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 5                   | 2      | TT   | 2      | 2       | 82.00     | 152.00      | 8.00   | 24.00    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 5                   | 3      | MS   | 2      | 2       | 73.00     | 143.00      | 8.00   | 15.00    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 5                   | 3      | TT   | 2      | 2       | 73.00     | 143.00      | 8.00   | 15.00    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 5                   | 4      | MS   | 2      | 2       | 73.00     | 143.00      | 8.00   | 15.00    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 5                   | 4      | TT   | 2      | 2       | 73.00     | 139.50      | 8.00   | 11.50    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 5                   | 5      | MS   | 2      | 2       | 73.00     | 143.00      | 8.00   | 15.00    | 0.01         | 0.02 |
| 3 × 3-4 × 4         | 80%    | 5                   | 5      | TT   | 2      | 2       | 73.00     | 139.50      | 8.00   | 11.50    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 10                  | 2      | MS   | 4      | 4       | 93.75     | 167.75      | 6.25   | 26.50    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 10                  | 2      | TT   | 4      | 4       | 95.25     | 165.75      | 6.25   | 24.50    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 10                  | 3      | MS   | 4      | 4       | 73.00     | 159.00      | 6.25   | 17.75    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 10                  | 3      | TT   | 4      | 4       | 90.25     | 158.75      | 6.25   | 17.50    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 10                  | 4      | MS   | 4      | 4       | 72.75     | 158.75      | 6.25   | 17.50    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 10                  | 4      | TT   | 4      | 4       | 90.25     | 157.00      | 6.25   | 15.75    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 80%    | 10                  | 5      | MS   | 4      | 4       | 72.00     | 158.00      | 6.25   | 16.75    | 0.01         | 0.02 |
| 3 × 3-4 × 4         | 80%    | 10                  | 5      | TT   | 4      | 4       | 72.25     | 155.25      | 6.25   | 14.00    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 90%    | 5                   | 2      | MS   | 5      | 5       | 119.80    | 194.80      | 15.60  | 23.20    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 90%    | 5                   | 2      | TT   | 5      | 5       | 135.00    | 193.80      | 15.60  | 22.20    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 90%    | 5                   | 3      | MS   | 5      | 5       | 80.20     | 195.60      | 15.60  | 24.00    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 90%    | 5                   | 3      | TT   | 5      | 5       | 120.60    | 191.40      | 15.60  | 19.80    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 90%    | 5                   | 4      | MS   | 5      | 5       | 78.20     | 193.20      | 15.60  | 21.60    | 0.01         | 0.02 |
| 3 × 3-4 × 4         | 90%    | 5                   | 4      | TT   | 5      | 5       | 120       | 188.80      | 15.60  | 17.20    | 0.01         | 0.02 |
| 3 × 3-4 × 4         | 90%    | 5                   | 5      | MS   | 5      | 5       | 78.00     | 191.80      | 15.60  | 20.20    | 0.02         | 0.03 |
| 3 × 3-4 × 4         | 90%    | 5                   | 5      | TT   | 5      | 5       | 104.80    | 188.00      | 15.60  | 16.40    | 0.01         | 0.02 |
| 3 × 3-4 × 4         | 90%    | 10                  | 2      | MS   | 5      | 5       | 119.80    | 194.80      | 14.80  | 24.00    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 90%    | 10                  | 2      | TT   | 5      | 5       | 135.00    | 193.80      | 14.80  | 23.00    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 90%    | 10                  | 3      | MS   | 5      | 5       | 79.40     | 194.80      | 14.80  | 24.00    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 90%    | 10                  | 3      | TT   | 5      | 5       | 120.20    | 191.00      | 14.80  | 20.20    | 0.01         | 0.01 |
| 3 × 3-4 × 4         | 90%    | 10                  | 4      | MS   | 5      | 5       | 77.40     | 191.60      | 14.80  | 20.80    | 0.01         | 0.03 |
| 3 × 3-4 × 4         | 90%    | 10                  | 4      | TT   | 5      | 5       | 119.20    | 188.00      | 14.80  | 17.20    | 0.01         | 0.02 |
| 3 × 3-4 × 4         | 90%    | 10                  | 5      | MS   | 5      | 5       | 77.20     | 190.60      | 14.80  | 19.80    | 0.02         | 0.03 |
| 3 × 3-4 × 4         | 90%    | 10                  | 5      | TT   | 5      | 5       | 104.00    | 187.20      | 14.80  | 16.40    | 0.01         | 0.03 |
| 3 × 3-5 × 5         | 80%    | 5                   | 2      | MS   | 2      | 2       | 80        | 152.50      | 8.50   | 24.00    | 0.01         | 0.01 |
| 3 × 3-5 × 5         | 80%    | 5                   | 2      | TT   | 2      | 2       | 80        | 152.50      | 8.50   | 24.00    | 0.01         | 0.01 |
| 3 × 3-5 × 5         | 80%    | 5                   | 3      | MS   | 2      | 2       | 75.50     | 148.00      | 8.50   | 19.50    | 0.01         | 0.01 |
| 3 × 3-5 × 5         | 80%    | 5                   | 3      | TT   | 2      | 2       | 75.50     | 148.00      | 8.50   | 19.50    | 0.01         | 0.01 |
| 3 × 3-5 × 5         | 80%    | 5                   | 4      | MS   | 2      | 2       | 75.00     | 144.00      | 8.50   | 15.50    | 0.01         | 0.01 |
| 3 × 3-5 × 5         | 80%    | 5                   | 4      | TT   | 2      | 2       | 75.00     | 144.00      | 8.50   | 15.50    | 0.01         | 0.01 |
| 3 × 3-5 × 5         | 80%    | 5                   | 5      | MS   | 2      | 2       | 71.50     | 138.00      | 8.50   | 9.50     | 0.01         | 0.02 |
| 3 × 3-5 × 5         | 80%    | 5                   | 5      | TT   | 2      | 2       | 71.50     | 138.00      | 8.50   | 9.50     | 0.01         | 0.01 |
| 3 × 3-5 × 5         | 80%    | 10                  | 2      | MS   | 4      | 4       | 110       | 190         | 8.75   | 31.25    | 0.01         | 0.01 |
| 3 × 3-5 × 5         | 80%    | 10                  | 2      | TT   | 4      | 4       | 146.75    | 184.50      | 8.75   | 25.75    | 0.01         | 0.01 |
| 3 × 3-5 × 5         | 80%    | 10                  | 3      | MS   | 4      | 4       | 77.75     | 186.50      | 8.75   | 27.75    | 0.01         | 0.02 |
| 3 × 3-5 × 5         | 80%    | 10                  | 3      | TT   | 4      | 4       | 108.25    | 180.75      | 8.75   | 22.00    | 0.01         | 0.01 |
| 3 × 3-5 × 5         | 80%    | 10                  | 4      | MS   | 4      | 4       | 75.00     | 178.50      | 8.75   | 19.75    | 0.01         | 0.02 |
| 3 × 3-5 × 5         | 80%    | 10                  | 4      | TT   | 4      | 4       | 90        | 177.75      | 8.75   | 19.00    | 0.01         | 0.02 |
| 3 × 3-5 × 5         | 80%    | 10                  | 5      | MS   | 4      | 4       | 73.25     | 175.50      | 8.75   | 16.75    | 0.02         | 0.03 |
| 3 × 3-5 × 5         | 80%    | 10                  | 5      | TT   | 4      | 4       | 73.25     | 175.50      | 8.75   | 16.75    | 0.01         | 0.02 |
| 3 × 3-5 × 5         | 90%    | 5                   | 2      | MS   | 7      | 7       | 139.14    | 242.00      | 15.57  | 37.86    | 0.01         | 0.02 |
| 3 × 3-5 × 5         | 90%    | 5                   | 2      | TT   | 7      | 7       | 191.57    | 233.43      | 15.57  | 29.29    | 0.01         | 0.01 |
| 3 × 3-5 × 5         | 90%    | 5                   | 3      | MS   | 7      | 7       | 98.57     | 237.43      | 15.57  | 33.29    | 0.02         | 0.03 |
| 3 × 3-5 × 5         | 90%    | 5                   | 3      | TT   | 7      | 7       | 168.14    | 229.57      | 15.57  | 25.43    | 0.01         | 0.02 |
| 3 × 3-5 × 5         | 90%    | 5                   | 4      | MS   | 7      | 7       | 86.57     | 235.00      | 15.57  | 30.86    | 0.02         | 0.04 |
| 3 × 3-5 × 5         | 90%    | 5                   | 4      | TT   | 7      | 7       | 156.00    | 227.29      | 15.57  | 23.14    | 0.02         | 0.02 |
| 3 × 3-5 × 5         | 90%    | 5                   | 5      | MS   | 7      | 7       | 78.00     | 234.29      | 15.57  | 30.14    | 0.03         | 0.05 |
| 3 × 3-5 × 5         | 90%    | 5                   | 5      | TT   | 7      | 7       | 144.29    | 225.86      | 15.57  | 21.71    | 0.02         | 0.04 |
| 3 × 3-5 × 5         | 90%    | 10                  | 2      | MS   | 9      | 9       | 135.22    | 247.00      | 15.89  | 37.78    | 0.01         | 0.02 |
| 3 × 3-5 × 5         | 90%    | 10                  | 2      | TT   | 9      | 9       | 189.33    | 238.78      | 15.89  | 29.56    | 0.01         | 0.01 |
| 3 × 3-5 × 5         | 90%    | 10                  | 3      | MS   | 9      | 9       | 108.56    | 247.89      | 15.89  | 38.33    | 0.02         | 0.03 |
| 3 × 3-5 × 5         | 90%    | 10                  | 3      | TT   | 9      | 9       | 162.89    | 235.56      | 15.89  | 26.33    | 0.01         | 0.02 |
| 3 × 3-5 × 5         | 90%    | 10                  | 4      | MS   | 9      | 9       | 86.56     | 248.22      | 15.89  | 39.00    | 0.02         | 0.04 |
| 3 × 3-5 × 5         | 90%    | 10                  | 4      | TT   | 9      | 9       | 162.22    | 234.33      | 15.89  | 25.11    | 0.02         | 0.03 |

(continued on next page)

Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |      |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best |
| 3 × 3-5 × 5         | 90%    | 10                  | 5      | MS   | 9      | 9       | 79.11     | 244.00      | 15.89  | 34.78    | 0.03         | 0.05 |
| 3 × 3-5 × 5         | 90%    | 10                  | 5      | TT   | 9      | 9       | 151.67    | 233.00      | 15.89  | 23.78    | 0.02         | 0.03 |
| 3 × 3-6 × 6         | 80%    | 5                   | 2      | MS   | 7      | 7       | 97.00     | 174.71      | 6.71   | 39.43    | 0.01         | 0.01 |
| 3 × 3-6 × 6         | 80%    | 5                   | 2      | TT   | 7      | 7       | 108.43    | 169.00      | 6.71   | 33.71    | 0.01         | 0.01 |
| 3 × 3-6 × 6         | 80%    | 5                   | 3      | MS   | 7      | 7       | 81.57     | 166.29      | 6.71   | 31.00    | 0.01         | 0.01 |
| 3 × 3-6 × 6         | 80%    | 5                   | 3      | TT   | 7      | 7       | 101.43    | 160.71      | 6.71   | 25.43    | 0.01         | 0.01 |
| 3 × 3-6 × 6         | 80%    | 5                   | 4      | MS   | 7      | 7       | 77.00     | 163.00      | 6.71   | 27.71    | 0.01         | 0.02 |
| 3 × 3-6 × 6         | 80%    | 5                   | 4      | TT   | 7      | 7       | 96.14     | 155.43      | 6.71   | 20.14    | 0.01         | 0.01 |
| 3 × 3-6 × 6         | 80%    | 5                   | 5      | MS   | 7      | 7       | 75.57     | 159.14      | 6.71   | 23.86    | 0.01         | 0.02 |
| 3 × 3-6 × 6         | 80%    | 5                   | 5      | TT   | 7      | 7       | 95.43     | 153.00      | 6.71   | 17.71    | 0.01         | 0.01 |
| 3 × 3-6 × 6         | 80%    | 10                  | 2      | MS   | 8      | 8       | 122.50    | 220.25      | 8.62   | 46.62    | 0.01         | 0.02 |
| 3 × 3-6 × 6         | 80%    | 10                  | 2      | TT   | 8      | 8       | 132.25    | 214.62      | 8.62   | 41.00    | 0.01         | 0.02 |
| 3 × 3-6 × 6         | 80%    | 10                  | 3      | MS   | 8      | 8       | 91.62     | 216.50      | 8.62   | 42.88    | 0.01         | 0.03 |
| 3 × 3-6 × 6         | 80%    | 10                  | 3      | TT   | 8      | 8       | 125.75    | 206.75      | 8.62   | 33.12    | 0.01         | 0.02 |
| 3 × 3-6 × 6         | 80%    | 10                  | 4      | MS   | 8      | 8       | 86.38     | 210.62      | 8.62   | 37.00    | 0.02         | 0.04 |
| 3 × 3-6 × 6         | 80%    | 10                  | 4      | TT   | 8      | 8       | 112.38    | 199.75      | 8.62   | 26.12    | 0.01         | 0.02 |
| 3 × 3-6 × 6         | 80%    | 10                  | 5      | MS   | 8      | 8       | 85.12     | 212.12      | 8.62   | 38.25    | 0.02         | 0.04 |
| 3 × 3-6 × 6         | 80%    | 10                  | 5      | TT   | 8      | 8       | 111.38    | 196.62      | 8.62   | 23.00    | 0.02         | 0.02 |
| 3 × 3-6 × 6         | 90%    | 5                   | 2      | MS   | 8      | 8       | 135.00    | 232.00      | 14.88  | 37.12    | 0.01         | 0.02 |
| 3 × 3-6 × 6         | 90%    | 5                   | 2      | TT   | 8      | 8       | 148.50    | 230.12      | 14.88  | 35.25    | 0.01         | 0.02 |
| 3 × 3-6 × 6         | 90%    | 5                   | 3      | MS   | 8      | 8       | 96.88     | 229.88      | 14.88  | 35.00    | 0.01         | 0.03 |
| 3 × 3-6 × 6         | 90%    | 5                   | 3      | TT   | 8      | 8       | 125.75    | 225.75      | 14.88  | 30.88    | 0.01         | 0.02 |
| 3 × 3-6 × 6         | 90%    | 5                   | 4      | MS   | 8      | 8       | 86.75     | 235.38      | 14.88  | 40.50    | 0.02         | 0.04 |
| 3 × 3-6 × 6         | 90%    | 5                   | 4      | TT   | 8      | 8       | 114.38    | 222.75      | 14.88  | 27.88    | 0.01         | 0.02 |
| 3 × 3-6 × 6         | 90%    | 5                   | 5      | MS   | 8      | 8       | 79.00     | 227.12      | 14.88  | 32.25    | 0.03         | 0.05 |
| 3 × 3-6 × 6         | 90%    | 5                   | 5      | TT   | 8      | 8       | 113.25    | 219.50      | 14.88  | 24.62    | 0.02         | 0.03 |
| 3 × 3-6 × 6         | 90%    | 10                  | 2      | MS   | 9      | 9       | 157.00    | 292.33      | 19.22  | 53.11    | 0.02         | 0.03 |
| 3 × 3-6 × 6         | 90%    | 10                  | 2      | TT   | 9      | 9       | 199.89    | 285.11      | 19.22  | 45.89    | 0.01         | 0.02 |
| 3 × 3-6 × 6         | 90%    | 10                  | 3      | MS   | 9      | 9       | 123.67    | 289.89      | 19.22  | 50.67    | 0.02         | 0.05 |
| 3 × 3-6 × 6         | 90%    | 10                  | 3      | TT   | 9      | 9       | 171.89    | 281.56      | 19.22  | 42.33    | 0.02         | 0.03 |
| 3 × 3-6 × 6         | 90%    | 10                  | 4      | MS   | 9      | 9       | 93.00     | 291.22      | 19.22  | 51.78    | 0.03         | 0.06 |
| 3 × 3-6 × 6         | 90%    | 10                  | 4      | TT   | 9      | 9       | 161.56    | 278.11      | 19.22  | 38.89    | 0.02         | 0.04 |
| 3 × 3-6 × 6         | 90%    | 10                  | 5      | MS   | 9      | 9       | 92.00     | 291.44      | 19.22  | 52.22    | 0.04         | 0.08 |
| 3 × 3-6 × 6         | 90%    | 10                  | 5      | TT   | 9      | 9       | 154.89    | 274.78      | 19.22  | 35.56    | 0.02         | 0.06 |
| 3 × 3-7 × 7         | 60%    | 5                   | 2      | MS   | 2      | 2       | 97.50     | 166.50      | 6.00   | 40.50    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 5                   | 2      | TT   | 2      | 2       | 97.50     | 166.50      | 6.00   | 40.50    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 5                   | 3      | MS   | 2      | 2       | 88.50     | 161.50      | 6.00   | 35.50    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 5                   | 3      | TT   | 2      | 2       | 88.50     | 157.50      | 6.00   | 31.50    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 5                   | 4      | MS   | 2      | 2       | 78.00     | 153.00      | 6.00   | 27.00    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 5                   | 4      | TT   | 2      | 2       | 78.00     | 147.00      | 6.00   | 21.00    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 5                   | 5      | MS   | 2      | 2       | 78.00     | 147.00      | 6.00   | 21.00    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 5                   | 5      | TT   | 2      | 2       | 78.00     | 146.00      | 6.00   | 20       | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 10                  | 2      | MS   | 2      | 2       | 97.50     | 172.50      | 6.00   | 46.50    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 10                  | 2      | TT   | 2      | 2       | 97.50     | 166.50      | 6.00   | 40.50    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 10                  | 3      | MS   | 2      | 2       | 88.50     | 163.50      | 6.00   | 37.50    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 10                  | 3      | TT   | 2      | 2       | 88.50     | 157.50      | 6.00   | 31.50    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 10                  | 4      | MS   | 2      | 2       | 78.00     | 153.00      | 6.00   | 27.00    | 0.01         | 0.02 |
| 3 × 3-7 × 7         | 60%    | 10                  | 4      | TT   | 2      | 2       | 78.00     | 147.00      | 6.00   | 21.00    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 60%    | 10                  | 5      | MS   | 2      | 2       | 78.00     | 152.00      | 6.00   | 26.00    | 0.01         | 0.02 |
| 3 × 3-7 × 7         | 60%    | 10                  | 5      | TT   | 2      | 2       | 78.00     | 146.00      | 6.00   | 20       | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 80%    | 5                   | 2      | MS   | 8      | 8       | 122.50    | 210.38      | 8.50   | 51.88    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 80%    | 5                   | 2      | TT   | 8      | 8       | 153.75    | 198.25      | 8.50   | 39.75    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 80%    | 5                   | 3      | MS   | 8      | 8       | 86.38     | 202.88      | 8.50   | 44.38    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 80%    | 5                   | 3      | TT   | 8      | 8       | 128.38    | 190.75      | 8.50   | 32.25    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 80%    | 5                   | 4      | MS   | 8      | 8       | 82.88     | 197.38      | 8.50   | 38.88    | 0.01         | 0.02 |
| 3 × 3-7 × 7         | 80%    | 5                   | 4      | TT   | 8      | 8       | 123.12    | 184.62      | 8.50   | 26.12    | 0.01         | 0.02 |
| 3 × 3-7 × 7         | 80%    | 5                   | 5      | MS   | 8      | 8       | 81.25     | 193.12      | 8.50   | 34.62    | 0.02         | 0.03 |
| 3 × 3-7 × 7         | 80%    | 5                   | 5      | TT   | 8      | 8       | 114.00    | 184.00      | 8.50   | 25.50    | 0.01         | 0.02 |
| 3 × 3-7 × 7         | 80%    | 10                  | 2      | MS   | 8      | 8       | 139.50    | 243.88      | 9.50   | 54.38    | 0.01         | 0.02 |
| 3 × 3-7 × 7         | 80%    | 10                  | 2      | TT   | 8      | 8       | 181.25    | 235.62      | 9.50   | 46.12    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 80%    | 10                  | 3      | MS   | 8      | 8       | 105.00    | 239.50      | 9.50   | 50       | 0.02         | 0.03 |
| 3 × 3-7 × 7         | 80%    | 10                  | 3      | TT   | 8      | 8       | 129.75    | 228.75      | 9.50   | 39.25    | 0.01         | 0.01 |
| 3 × 3-7 × 7         | 80%    | 10                  | 4      | MS   | 8      | 8       | 90.88     | 232.88      | 9.50   | 43.38    | 0.02         | 0.04 |
| 3 × 3-7 × 7         | 80%    | 10                  | 4      | TT   | 8      | 8       | 124.38    | 222.12      | 9.50   | 32.62    | 0.01         | 0.02 |
| 3 × 3-7 × 7         | 80%    | 10                  | 5      | MS   | 8      | 8       | 81.38     | 228.62      | 9.50   | 39.12    | 0.03         | 0.05 |
| 3 × 3-7 × 7         | 80%    | 10                  | 5      | TT   | 8      | 8       | 115.25    | 221.50      | 9.50   | 32.00    | 0.02         | 0.03 |
| 3 × 3-7 × 7         | 90%    | 5                   | 2      | MS   | 8      | 8       | 170       | 329.62      | 20.25  | 76.88    | 0.02         | 0.03 |
| 3 × 3-7 × 7         | 90%    | 5                   | 2      | TT   | 8      | 8       | 245.50    | 311.00      | 20.25  | 58.25    | 0.01         | 0.02 |
| 3 × 3-7 × 7         | 90%    | 5                   | 3      | MS   | 8      | 8       | 139.12    | 320.25      | 20.25  | 67.50    | 0.02         | 0.05 |
| 3 × 3-7 × 7         | 90%    | 5                   | 3      | TT   | 8      | 8       | 205.75    | 301.75      | 20.25  | 49.00    | 0.02         | 0.03 |
| 3 × 3-7 × 7         | 90%    | 5                   | 4      | MS   | 8      | 8       | 95.50     | 313.88      | 20.25  | 61.12    | 0.03         | 0.06 |
| 3 × 3-7 × 7         | 90%    | 5                   | 4      | TT   | 8      | 8       | 181.50    | 294.38      | 20.25  | 41.62    | 0.02         | 0.04 |
| 3 × 3-7 × 7         | 90%    | 5                   | 5      | MS   | 8      | 8       | 92.88     | 316.38      | 20.25  | 63.50    | 0.04         | 0.09 |

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Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |      |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best |
| 3 × 3-7 × 7         | 90%    | 5                   | 5      | TT   | 8      | 8       | 169.12    | 291.12      | 20.25  | 38.38    | 0.03         | 0.05 |
| 3 × 3-7 × 7         | 90%    | 10                  | 2      | MS   | 9      | 9       | 229.56    | 425.11      | 28.22  | 83.56    | 0.03         | 0.13 |
| 3 × 3-7 × 7         | 90%    | 10                  | 2      | TT   | 9      | 9       | 289.56    | 411.33      | 28.22  | 69.78    | 0.02         | 0.04 |
| 3 × 3-7 × 7         | 90%    | 10                  | 3      | MS   | 9      | 9       | 160       | 425.00      | 28.22  | 83.33    | 0.04         | 0.11 |
| 3 × 3-7 × 7         | 90%    | 10                  | 3      | TT   | 9      | 9       | 242.00    | 400.56      | 28.22  | 59.00    | 0.03         | 0.05 |
| 3 × 3-7 × 7         | 90%    | 10                  | 4      | MS   | 9      | 9       | 129.67    | 406.22      | 28.22  | 64.67    | 0.06         | 0.13 |
| 3 × 3-7 × 7         | 90%    | 10                  | 4      | TT   | 9      | 9       | 193.22    | 394.44      | 28.22  | 52.89    | 0.04         | 0.05 |
| 3 × 3-7 × 7         | 90%    | 10                  | 5      | MS   | 9      | 9       | 118.44    | 427.78      | 28.22  | 86.22    | 0.08         | 0.18 |
| 3 × 3-7 × 7         | 90%    | 10                  | 5      | TT   | 9      | 9       | 191.44    | 391.56      | 28.22  | 50       | 0.05         | 0.08 |
| 3 × 3-8 × 8         | 60%    | 5                   | 2      | MS   | 2      | 2       | 83.50     | 164.50      | 4.00   | 40.50    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 60%    | 5                   | 2      | TT   | 2      | 2       | 87.00     | 163.50      | 4.00   | 39.50    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 60%    | 5                   | 3      | MS   | 2      | 2       | 78.50     | 151.00      | 4.00   | 27.00    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 60%    | 5                   | 3      | TT   | 2      | 2       | 78.50     | 151.00      | 4.00   | 27.00    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 60%    | 5                   | 4      | MS   | 2      | 2       | 72.50     | 138.50      | 4.00   | 14.50    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 60%    | 5                   | 4      | TT   | 2      | 2       | 72.50     | 138.50      | 4.00   | 14.50    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 60%    | 5                   | 5      | MS   | 2      | 2       | 72.50     | 138.50      | 4.00   | 14.50    | 0.01         | 0.02 |
| 3 × 3-8 × 8         | 60%    | 5                   | 5      | TT   | 2      | 2       | 72.50     | 138.50      | 4.00   | 14.50    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 60%    | 10                  | 2      | MS   | 2      | 2       | 121.00    | 210         | 5.50   | 54.50    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 60%    | 10                  | 2      | TT   | 2      | 2       | 124.50    | 209.00      | 5.50   | 53.50    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 60%    | 10                  | 3      | MS   | 2      | 2       | 84.50     | 199.50      | 5.50   | 44.00    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 60%    | 10                  | 3      | TT   | 2      | 2       | 116.00    | 196.50      | 5.50   | 41.00    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 60%    | 10                  | 4      | MS   | 2      | 2       | 80.50     | 193.00      | 5.50   | 37.50    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 60%    | 10                  | 4      | TT   | 2      | 2       | 80.50     | 183.00      | 5.50   | 27.50    | 0.01         | 0.02 |
| 3 × 3-8 × 8         | 60%    | 10                  | 5      | MS   | 2      | 2       | 78.00     | 180.50      | 5.50   | 25.00    | 0.01         | 0.03 |
| 3 × 3-8 × 8         | 60%    | 10                  | 5      | TT   | 2      | 2       | 78.00     | 180.50      | 5.50   | 25.00    | 0.01         | 0.02 |
| 3 × 3-8 × 8         | 80%    | 5                   | 2      | MS   | 8      | 8       | 148.88    | 265.12      | 10.12  | 67.38    | 0.01         | 0.02 |
| 3 × 3-8 × 8         | 80%    | 5                   | 2      | TT   | 8      | 8       | 192.38    | 253.62      | 10.12  | 56.00    | 0.01         | 0.01 |
| 3 × 3-8 × 8         | 80%    | 5                   | 3      | MS   | 8      | 8       | 111.00    | 265.38      | 10.12  | 67.75    | 0.02         | 0.03 |
| 3 × 3-8 × 8         | 80%    | 5                   | 3      | TT   | 8      | 8       | 167.25    | 246.75      | 10.12  | 49.12    | 0.01         | 0.02 |
| 3 × 3-8 × 8         | 80%    | 5                   | 4      | MS   | 8      | 8       | 87.38     | 256.38      | 10.12  | 58.75    | 0.02         | 0.03 |
| 3 × 3-8 × 8         | 80%    | 5                   | 4      | TT   | 8      | 8       | 144.62    | 238.00      | 10.12  | 40.38    | 0.01         | 0.03 |
| 3 × 3-8 × 8         | 80%    | 5                   | 5      | MS   | 8      | 8       | 83.12     | 247.00      | 10.12  | 49.38    | 0.03         | 0.07 |
| 3 × 3-8 × 8         | 80%    | 5                   | 5      | TT   | 8      | 8       | 131.75    | 234.50      | 10.12  | 36.88    | 0.02         | 0.04 |
| 3 × 3-8 × 8         | 80%    | 10                  | 2      | MS   | 8      | 8       | 191.62    | 342.62      | 13.00  | 82.12    | 0.02         | 0.04 |
| 3 × 3-8 × 8         | 80%    | 10                  | 2      | TT   | 8      | 8       | 226.25    | 326.75      | 13.00  | 66.25    | 0.01         | 0.03 |
| 3 × 3-8 × 8         | 80%    | 10                  | 3      | MS   | 8      | 8       | 128.50    | 342.00      | 13.00  | 81.12    | 0.03         | 0.06 |
| 3 × 3-8 × 8         | 80%    | 10                  | 3      | TT   | 8      | 8       | 212.50    | 319.50      | 13.00  | 59.00    | 0.02         | 0.03 |
| 3 × 3-8 × 8         | 80%    | 10                  | 4      | MS   | 8      | 8       | 110.50    | 336.50      | 13.00  | 76.00    | 0.04         | 0.08 |
| 3 × 3-8 × 8         | 80%    | 10                  | 4      | TT   | 8      | 8       | 189.50    | 312.50      | 13.00  | 52.00    | 0.02         | 0.05 |
| 3 × 3-8 × 8         | 80%    | 10                  | 5      | MS   | 8      | 8       | 93.75     | 346.88      | 13.00  | 77.50    | 0.05         | 0.12 |
| 3 × 3-8 × 8         | 80%    | 10                  | 5      | TT   | 8      | 8       | 168.75    | 307.88      | 13.00  | 47.38    | 0.03         | 0.06 |
| 3 × 3-8 × 8         | 90%    | 5                   | 2      | MS   | 9      | 9       | 210.56    | 395.89      | 23.22  | 86.00    | 0.02         | 0.06 |
| 3 × 3-8 × 8         | 90%    | 5                   | 2      | TT   | 9      | 9       | 269.89    | 383.44      | 23.22  | 73.56    | 0.02         | 0.04 |
| 3 × 3-8 × 8         | 90%    | 5                   | 3      | MS   | 9      | 9       | 152.67    | 399.33      | 23.22  | 89.44    | 0.04         | 0.09 |
| 3 × 3-8 × 8         | 90%    | 5                   | 3      | TT   | 9      | 9       | 240.78    | 375.89      | 23.22  | 66.00    | 0.02         | 0.05 |
| 3 × 3-8 × 8         | 90%    | 5                   | 4      | MS   | 9      | 9       | 128.22    | 395.11      | 23.22  | 85.22    | 0.05         | 0.13 |
| 3 × 3-8 × 8         | 90%    | 5                   | 4      | TT   | 9      | 9       | 202.89    | 368.11      | 23.22  | 58.22    | 0.03         | 0.05 |
| 3 × 3-8 × 8         | 90%    | 5                   | 5      | MS   | 9      | 9       | 115.89    | 395.44      | 23.22  | 85.56    | 0.07         | 0.15 |
| 3 × 3-8 × 8         | 90%    | 5                   | 5      | TT   | 9      | 9       | 200.67    | 365.67      | 23.22  | 55.78    | 0.04         | 0.08 |
| 3 × 3-8 × 8         | 90%    | 10                  | 2      | MS   | 10     | 10      | 274.30    | 520.30      | 30.60  | 111.70   | 0.04         | 0.19 |
| 3 × 3-8 × 8         | 90%    | 10                  | 2      | TT   | 10     | 10      | 348.00    | 495.20      | 30.60  | 86.60    | 0.03         | 0.06 |
| 3 × 3-8 × 8         | 90%    | 10                  | 3      | MS   | 10     | 10      | 194.10    | 518.30      | 30.60  | 109.70   | 0.07         | 0.22 |
| 3 × 3-8 × 8         | 90%    | 10                  | 3      | TT   | 10     | 10      | 280.50    | 482.90      | 30.60  | 74.30    | 0.04         | 0.07 |
| 3 × 3-8 × 8         | 90%    | 10                  | 4      | MS   | 10     | 10      | 153.20    | 506.80      | 30.60  | 98.20    | 0.09         | 0.23 |
| 3 × 3-8 × 8         | 90%    | 10                  | 4      | TT   | 10     | 10      | 224.60    | 476.90      | 30.60  | 68.30    | 0.06         | 0.09 |
| 3 × 3-8 × 8         | 90%    | 10                  | 5      | MS   | 10     | 10      | 128.10    | 512.30      | 30.60  | 103.70   | 0.12         | 0.24 |
| 3 × 3-8 × 8         | 90%    | 10                  | 5      | TT   | 10     | 10      | 215.50    | 473.10      | 30.60  | 64.50    | 0.07         | 0.12 |
| 3 × 3-9 × 9         | 60%    | 5                   | 2      | MS   | 3      | 3       | 84.67     | 163.67      | 5.67   | 38.00    | 0.01         | 0.01 |
| 3 × 3-9 × 9         | 60%    | 5                   | 2      | TT   | 3      | 3       | 84.67     | 160.33      | 5.67   | 34.67    | 0.01         | 0.01 |
| 3 × 3-9 × 9         | 60%    | 5                   | 3      | MS   | 3      | 3       | 84.67     | 163.67      | 5.67   | 38.00    | 0.01         | 0.01 |
| 3 × 3-9 × 9         | 60%    | 5                   | 3      | TT   | 3      | 3       | 84.67     | 160.33      | 5.67   | 34.67    | 0.01         | 0.01 |
| 3 × 3-9 × 9         | 60%    | 5                   | 4      | MS   | 3      | 3       | 79.33     | 150.67      | 5.67   | 25.00    | 0.01         | 0.01 |
| 3 × 3-9 × 9         | 60%    | 5                   | 4      | TT   | 3      | 3       | 79.33     | 150.67      | 5.67   | 25.00    | 0.01         | 0.01 |
| 3 × 3-9 × 9         | 60%    | 5                   | 5      | MS   | 3      | 3       | 79.33     | 150.67      | 5.67   | 25.00    | 0.01         | 0.02 |
| 3 × 3-9 × 9         | 60%    | 5                   | 5      | TT   | 3      | 3       | 79.33     | 150.67      | 5.67   | 25.00    | 0.01         | 0.01 |
| 3 × 3-9 × 9         | 60%    | 10                  | 2      | MS   | 4      | 4       | 128.50    | 232.50      | 7.75   | 59.75    | 0.01         | 0.01 |
| 3 × 3-9 × 9         | 60%    | 10                  | 2      | TT   | 4      | 4       | 144.50    | 228.50      | 7.75   | 55.75    | 0.01         | 0.01 |
| 3 × 3-9 × 9         | 60%    | 10                  | 3      | MS   | 4      | 4       | 101.50    | 244.25      | 7.75   | 71.50    | 0.01         | 0.02 |
| 3 × 3-9 × 9         | 60%    | 10                  | 3      | TT   | 4      | 4       | 143.75    | 222.75      | 7.75   | 50       | 0.01         | 0.02 |
| 3 × 3-9 × 9         | 60%    | 10                  | 4      | MS   | 4      | 4       | 85.25     | 220.50      | 7.75   | 47.75    | 0.01         | 0.03 |
| 3 × 3-9 × 9         | 60%    | 10                  | 4      | TT   | 4      | 4       | 117.50    | 215.50      | 7.75   | 42.75    | 0.01         | 0.02 |
| 3 × 3-9 × 9         | 60%    | 10                  | 5      | MS   | 4      | 4       | 85.25     | 219.00      | 7.75   | 46.25    | 0.02         | 0.03 |

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Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |      |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best |
| 3 × 3-9 × 9         | 60%    | 10                  | 5      | TT   | 4      | 4       | 117.50    | 215.50      | 7.75   | 42.75    | 0.01         | 0.02 |
| 3 × 3-9 × 9         | 80%    | 5                   | 2      | MS   | 9      | 9       | 199.56    | 364.56      | 14.33  | 90.22    | 0.02         | 0.04 |
| 3 × 3-9 × 9         | 80%    | 5                   | 2      | TT   | 9      | 9       | 238.00    | 351.22      | 14.33  | 76.89    | 0.02         | 0.04 |
| 3 × 3-9 × 9         | 80%    | 5                   | 3      | MS   | 9      | 9       | 149.67    | 366.44      | 14.33  | 92.11    | 0.03         | 0.05 |
| 3 × 3-9 × 9         | 80%    | 5                   | 3      | TT   | 9      | 9       | 224.22    | 344.22      | 14.33  | 69.89    | 0.02         | 0.03 |
| 3 × 3-9 × 9         | 80%    | 5                   | 4      | MS   | 9      | 9       | 112.44    | 367.00      | 14.33  | 92.67    | 0.04         | 0.08 |
| 3 × 3-9 × 9         | 80%    | 5                   | 4      | TT   | 9      | 9       | 187.56    | 335.89      | 14.33  | 61.56    | 0.03         | 0.05 |
| 3 × 3-9 × 9         | 80%    | 5                   | 5      | MS   | 9      | 9       | 95.11     | 357.11      | 14.33  | 82.67    | 0.05         | 0.12 |
| 3 × 3-9 × 9         | 80%    | 5                   | 5      | TT   | 9      | 9       | 179.22    | 329.33      | 14.33  | 55.00    | 0.03         | 0.08 |
| 3 × 3-9 × 9         | 80%    | 10                  | 2      | MS   | 9      | 8       | 241.56    | 453.56      | 17.89  | 102.22   | 0.04         | 0.12 |
| 3 × 3-9 × 9         | 80%    | 10                  | 2      | TT   | 9      | 9       | 296.33    | 436.44      | 17.89  | 85.22    | 0.02         | 0.05 |
| 3 × 3-9 × 9         | 80%    | 10                  | 3      | MS   | 9      | 9       | 179.11    | 460.89      | 17.89  | 109.67   | 0.06         | 0.13 |
| 3 × 3-9 × 9         | 80%    | 10                  | 3      | TT   | 9      | 9       | 271.78    | 430.11      | 17.89  | 78.89    | 0.03         | 0.07 |
| 3 × 3-9 × 9         | 80%    | 10                  | 4      | MS   | 9      | 9       | 134.67    | 456.89      | 17.89  | 105.67   | 0.07         | 0.18 |
| 3 × 3-9 × 9         | 80%    | 10                  | 4      | TT   | 9      | 9       | 235.44    | 423.22      | 17.89  | 72.00    | 0.05         | 0.09 |
| 3 × 3-9 × 9         | 80%    | 10                  | 5      | MS   | 9      | 9       | 118.00    | 462.89      | 17.89  | 111.44   | 0.10         | 0.21 |
| 3 × 3-9 × 9         | 80%    | 10                  | 5      | TT   | 9      | 9       | 226.11    | 415.33      | 17.89  | 64.11    | 0.06         | 0.10 |
| 3 × 3-9 × 9         | 90%    | 5                   | 2      | MS   | 10     | 10      | 218.50    | 428.30      | 22.00  | 94.30    | 0.03         | 0.07 |
| 3 × 3-9 × 9         | 90%    | 5                   | 2      | TT   | 10     | 10      | 307.30    | 409.50      | 22.00  | 75.50    | 0.02         | 0.04 |
| 3 × 3-9 × 9         | 90%    | 5                   | 3      | MS   | 10     | 10      | 159.20    | 432.90      | 22.00  | 98.90    | 0.04         | 0.13 |
| 3 × 3-9 × 9         | 90%    | 5                   | 3      | TT   | 10     | 10      | 266.10    | 400         | 22.00  | 66.00    | 0.03         | 0.05 |
| 3 × 3-9 × 9         | 90%    | 5                   | 4      | MS   | 10     | 10      | 126.20    | 428.80      | 22.00  | 94.80    | 0.06         | 0.14 |
| 3 × 3-9 × 9         | 90%    | 5                   | 4      | TT   | 10     | 10      | 206.30    | 393.00      | 22.00  | 59.00    | 0.04         | 0.08 |
| 3 × 3-9 × 9         | 90%    | 5                   | 5      | MS   | 10     | 10      | 116.20    | 439.50      | 22.00  | 105.50   | 0.08         | 0.18 |
| 3 × 3-9 × 9         | 90%    | 5                   | 5      | TT   | 10     | 10      | 183.20    | 390.40      | 22.00  | 56.40    | 0.05         | 0.10 |
| 3 × 3-9 × 9         | 90%    | 10                  | 2      | MS   | 10     | 6       | 319.60    | 623.60      | 33.40  | 122.20   | 0.07         | 1.24 |
| 3 × 3-9 × 9         | 90%    | 10                  | 2      | TT   | 10     | 10      | 433.80    | 601.60      | 33.40  | 100.20   | 0.04         | 0.10 |
| 3 × 3-9 × 9         | 90%    | 10                  | 3      | MS   | 10     | 7       | 228.70    | 632.90      | 33.40  | 131.50   | 0.11         | 0.56 |
| 3 × 3-9 × 9         | 90%    | 10                  | 3      | TT   | 10     | 10      | 381.90    | 590.90      | 33.40  | 89.50    | 0.07         | 0.10 |
| 3 × 3-9 × 9         | 90%    | 10                  | 4      | MS   | 10     | 10      | 176.60    | 632.70      | 33.40  | 131.30   | 0.14         | 1.21 |
| 3 × 3-9 × 9         | 90%    | 10                  | 4      | TT   | 10     | 10      | 309.50    | 581.10      | 33.40  | 79.70    | 0.09         | 0.16 |
| 3 × 3-9 × 9         | 90%    | 10                  | 5      | MS   | 10     | 10      | 140.20    | 624.90      | 33.40  | 123.50   | 0.21         | 0.46 |
| 3 × 3-9 × 9         | 90%    | 10                  | 5      | TT   | 10     | 10      | 279.40    | 577.40      | 33.40  | 76.00    | 0.12         | 0.20 |
| 3 × 3-10 × 10       | 60%    | 5                   | 2      | MS   | 2      | 2       | 105.50    | 198.50      | 5.00   | 73.50    | 0.01         | 0.01 |
| 3 × 3-10 × 10       | 60%    | 5                   | 2      | TT   | 2      | 2       | 111.00    | 196.50      | 5.00   | 71.50    | 0.01         | 0.01 |
| 3 × 3-10 × 10       | 60%    | 5                   | 3      | MS   | 2      | 2       | 101.00    | 194.50      | 5.00   | 69.50    | 0.01         | 0.01 |
| 3 × 3-10 × 10       | 60%    | 5                   | 3      | TT   | 2      | 2       | 105.50    | 182.50      | 5.00   | 57.50    | 0.01         | 0.01 |
| 3 × 3-10 × 10       | 60%    | 5                   | 4      | MS   | 2      | 2       | 91.50     | 173.50      | 5.00   | 48.50    | 0.01         | 0.01 |
| 3 × 3-10 × 10       | 60%    | 5                   | 4      | TT   | 2      | 2       | 91.50     | 164.50      | 5.00   | 39.50    | 0.01         | 0.01 |
| 3 × 3-10 × 10       | 60%    | 5                   | 5      | MS   | 2      | 2       | 91.50     | 173.50      | 5.00   | 48.50    | 0.01         | 0.02 |
| 3 × 3-10 × 10       | 60%    | 5                   | 5      | TT   | 2      | 2       | 91.50     | 164.50      | 5.00   | 39.50    | 0.01         | 0.01 |
| 3 × 3-10 × 10       | 60%    | 10                  | 2      | MS   | 4      | 4       | 120       | 231.75      | 6.25   | 75.50    | 0.01         | 0.01 |
| 3 × 3-10 × 10       | 60%    | 10                  | 2      | TT   | 4      | 4       | 139.50    | 224.75      | 6.25   | 68.50    | 0.17         | 0.18 |
| 3 × 3-10 × 10       | 60%    | 10                  | 3      | MS   | 4      | 4       | 108.25    | 219.25      | 6.25   | 63.00    | 0.01         | 0.02 |
| 3 × 3-10 × 10       | 60%    | 10                  | 3      | TT   | 4      | 4       | 110.50    | 216.25      | 6.25   | 60       | 0.01         | 0.02 |
| 3 × 3-10 × 10       | 60%    | 10                  | 4      | MS   | 4      | 4       | 93.00     | 214.50      | 6.25   | 58.25    | 0.01         | 0.03 |
| 3 × 3-10 × 10       | 60%    | 10                  | 4      | TT   | 4      | 4       | 108.25    | 203.50      | 6.25   | 47.25    | 0.01         | 0.02 |
| 3 × 3-10 × 10       | 60%    | 10                  | 5      | MS   | 4      | 4       | 90.25     | 208.25      | 6.25   | 52.00    | 0.02         | 0.03 |
| 3 × 3-10 × 10       | 60%    | 10                  | 5      | TT   | 4      | 4       | 105.50    | 200.75      | 6.25   | 44.50    | 0.01         | 0.03 |
| 3 × 3-10 × 10       | 60%    | 10                  | 8      | TT   | 1      | 1       | 95.00     | 168.00      | 5.00   | 43.00    | 0.01         | 0.03 |
| 3 × 3-10 × 10       | 80%    | 5                   | 2      | MS   | 10     | 10      | 227.30    | 428.80      | 17.30  | 99.50    | 0.03         | 0.08 |
| 3 × 3-10 × 10       | 80%    | 5                   | 2      | TT   | 10     | 10      | 305.40    | 418.30      | 17.30  | 89.00    | 0.02         | 0.04 |
| 3 × 3-10 × 10       | 80%    | 5                   | 3      | MS   | 10     | 10      | 167.20    | 432.70      | 17.30  | 103.40   | 0.05         | 0.13 |
| 3 × 3-10 × 10       | 80%    | 5                   | 3      | TT   | 10     | 10      | 235.00    | 405.10      | 17.30  | 75.80    | 0.03         | 0.06 |
| 3 × 3-10 × 10       | 80%    | 5                   | 4      | MS   | 10     | 10      | 133.60    | 443.20      | 17.30  | 113.90   | 0.06         | 0.14 |
| 3 × 3-10 × 10       | 80%    | 5                   | 4      | TT   | 10     | 10      | 193.10    | 396.50      | 17.30  | 67.20    | 0.04         | 0.08 |
| 3 × 3-10 × 10       | 80%    | 5                   | 5      | MS   | 10     | 10      | 113.80    | 444.70      | 17.30  | 115.40   | 0.08         | 0.18 |
| 3 × 3-10 × 10       | 80%    | 5                   | 5      | TT   | 10     | 10      | 192.40    | 394.80      | 17.30  | 65.50    | 0.05         | 0.13 |
| 3 × 3-10 × 10       | 80%    | 10                  | 2      | MS   | 10     | 10      | 276.30    | 514.40      | 21.30  | 115.10   | 0.04         | 0.22 |
| 3 × 3-10 × 10       | 80%    | 10                  | 2      | TT   | 10     | 10      | 357.90    | 499.30      | 21.30  | 100      | 0.03         | 0.06 |
| 3 × 3-10 × 10       | 80%    | 10                  | 3      | MS   | 10     | 10      | 186.80    | 518.30      | 21.30  | 119.00   | 0.06         | 0.17 |
| 3 × 3-10 × 10       | 80%    | 10                  | 3      | TT   | 10     | 10      | 286.60    | 487.50      | 21.30  | 88.20    | 0.04         | 0.08 |
| 3 × 3-10 × 10       | 80%    | 10                  | 4      | MS   | 10     | 10      | 162.70    | 539.00      | 21.30  | 139.50   | 0.09         | 0.21 |
| 3 × 3-10 × 10       | 80%    | 10                  | 4      | TT   | 10     | 10      | 239.60    | 476.80      | 21.30  | 77.50    | 0.06         | 0.12 |
| 3 × 3-10 × 10       | 80%    | 10                  | 5      | MS   | 10     | 10      | 128.60    | 528.50      | 21.30  | 129.20   | 0.13         | 0.27 |
| 3 × 3-10 × 10       | 80%    | 10                  | 5      | TT   | 10     | 10      | 235.50    | 474.10      | 21.30  | 74.80    | 0.07         | 0.15 |
| 3 × 3-10 × 10       | 90%    | 5                   | 2      | MS   | 10     | 10      | 320.90    | 628.20      | 33.50  | 150.70   | 0.05         | 0.34 |
| 3 × 3-10 × 10       | 90%    | 5                   | 2      | TT   | 10     | 10      | 472.00    | 589.90      | 33.50  | 112.40   | 0.03         | 0.09 |
| 3 × 3-10 × 10       | 90%    | 5                   | 3      | MS   | 10     | 10      | 226.20    | 629.70      | 33.50  | 152.00   | 0.08         | 0.29 |
| 3 × 3-10 × 10       | 90%    | 5                   | 3      | TT   | 10     | 10      | 382.40    | 578.90      | 33.50  | 101.40   | 0.05         | 0.10 |
| 3 × 3-10 × 10       | 90%    | 5                   | 4      | MS   | 10     | 10      | 174.50    | 647.70      | 33.50  | 169.70   | 0.13         | 0.28 |
| 3 × 3-10 × 10       | 90%    | 5                   | 4      | TT   | 10     | 10      | 330.90    | 572.40      | 33.50  | 94.90    | 0.08         | 0.14 |

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Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |       |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|-------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best  |
| 3 × 3-10 × 10       | 90%    | 5                   | 5      | MS   | 10     | 10      | 151.50    | 629.70      | 33.50  | 152.20   | 0.16         | 0.36  |
| 3 × 3-10 × 10       | 90%    | 5                   | 5      | TT   | 10     | 10      | 307.30    | 567.30      | 33.50  | 89.80    | 0.09         | 0.18  |
| 3 × 3-10 × 10       | 90%    | 10                  | 2      | MS   | 10     | 4       | 423.10    | 835.20      | 49.00  | 168.20   | 0.12         | 1.91  |
| 3 × 3-10 × 10       | 90%    | 10                  | 2      | TT   | 10     | 10      | 599.30    | 803.10      | 49.00  | 136.10   | 0.07         | 0.15  |
| 3 × 3-10 × 10       | 90%    | 10                  | 3      | MS   | 10     | 5       | 292.50    | 846.80      | 49.00  | 179.80   | 0.19         | 3.41  |
| 3 × 3-10 × 10       | 90%    | 10                  | 3      | TT   | 10     | 10      | 428.00    | 792.50      | 49.00  | 125.50   | 0.11         | 0.21  |
| 3 × 3-10 × 10       | 90%    | 10                  | 4      | MS   | 10     | 8       | 228.50    | 865.80      | 49.00  | 198.80   | 0.25         | 0.81  |
| 3 × 3-10 × 10       | 90%    | 10                  | 4      | TT   | 10     | 10      | 366.70    | 785.90      | 49.00  | 118.90   | 0.15         | 0.24  |
| 3 × 3-10 × 10       | 90%    | 10                  | 5      | MS   | 10     | 10      | 192.00    | 864.00      | 49.00  | 197.00   | 0.34         | 1.54  |
| 3 × 3-10 × 10       | 90%    | 10                  | 5      | TT   | 10     | 10      | 377.30    | 780.20      | 49.00  | 113.20   | 0.20         | 0.36  |
| 3 × 3-11 × 11       | 60%    | 5                   | 2      | MS   | 2      | 2       | 105.50    | 201.00      | 4.00   | 77.00    | 0.01         | 0.01  |
| 3 × 3-11 × 11       | 60%    | 5                   | 2      | TT   | 2      | 2       | 109.00    | 179.00      | 4.00   | 55.00    | 0.01         | 0.01  |
| 3 × 3-11 × 11       | 60%    | 5                   | 3      | MS   | 2      | 2       | 92.00     | 175.00      | 4.00   | 51.00    | 0.01         | 0.01  |
| 3 × 3-11 × 11       | 60%    | 5                   | 3      | TT   | 2      | 2       | 96.50     | 166.50      | 4.00   | 42.50    | 0.01         | 0.01  |
| 3 × 3-11 × 11       | 60%    | 5                   | 4      | MS   | 2      | 2       | 84.50     | 154.50      | 4.00   | 30.50    | 0.01         | 0.01  |
| 3 × 3-11 × 11       | 60%    | 5                   | 4      | TT   | 2      | 2       | 84.50     | 154.50      | 4.00   | 30.50    | 0.01         | 0.01  |
| 3 × 3-11 × 11       | 60%    | 5                   | 5      | MS   | 2      | 2       | 84.50     | 160         | 4.00   | 36.00    | 0.01         | 0.01  |
| 3 × 3-11 × 11       | 60%    | 5                   | 5      | TT   | 2      | 2       | 84.50     | 154.50      | 4.00   | 30.50    | 0.01         | 0.01  |
| 3 × 3-11 × 11       | 60%    | 10                  | 2      | MS   | 4      | 4       | 131.75    | 237.50      | 6.00   | 66.50    | 0.01         | 0.02  |
| 3 × 3-11 × 11       | 60%    | 10                  | 2      | TT   | 4      | 4       | 150       | 229.25      | 6.00   | 58.25    | 0.01         | 0.01  |
| 3 × 3-11 × 11       | 60%    | 10                  | 3      | MS   | 4      | 4       | 103.75    | 237.00      | 6.00   | 66.00    | 0.01         | 0.02  |
| 3 × 3-11 × 11       | 60%    | 10                  | 3      | TT   | 4      | 4       | 141.00    | 216.25      | 6.00   | 45.25    | 0.01         | 0.01  |
| 3 × 3-11 × 11       | 60%    | 10                  | 4      | MS   | 4      | 4       | 85.75     | 219.50      | 6.00   | 48.50    | 0.02         | 0.03  |
| 3 × 3-11 × 11       | 60%    | 10                  | 4      | TT   | 4      | 4       | 118.75    | 211.00      | 6.00   | 40       | 0.01         | 0.02  |
| 3 × 3-11 × 11       | 60%    | 10                  | 5      | MS   | 4      | 4       | 85.75     | 223.75      | 6.00   | 52.75    | 0.02         | 0.04  |
| 3 × 3-11 × 11       | 60%    | 10                  | 5      | TT   | 4      | 4       | 118.75    | 211.00      | 6.00   | 40       | 0.01         | 0.03  |
| 3 × 3-11 × 11       | 80%    | 5                   | 2      | MS   | 10     | 10      | 257.60    | 496.80      | 19.60  | 129.20   | 0.03         | 0.12  |
| 3 × 3-11 × 11       | 80%    | 5                   | 2      | TT   | 10     | 10      | 336.20    | 473.50      | 19.60  | 105.90   | 0.02         | 0.05  |
| 3 × 3-11 × 11       | 80%    | 5                   | 3      | MS   | 10     | 10      | 184.50    | 509.80      | 19.60  | 141.30   | 0.05         | 0.14  |
| 3 × 3-11 × 11       | 80%    | 5                   | 3      | TT   | 10     | 10      | 285.20    | 464.00      | 19.60  | 96.40    | 0.03         | 0.05  |
| 3 × 3-11 × 11       | 80%    | 5                   | 4      | MS   | 10     | 10      | 148.90    | 504.50      | 19.60  | 136.90   | 0.07         | 0.18  |
| 3 × 3-11 × 11       | 80%    | 5                   | 4      | TT   | 10     | 10      | 253.60    | 453.20      | 19.60  | 85.60    | 0.05         | 0.06  |
| 3 × 3-11 × 11       | 80%    | 5                   | 5      | MS   | 10     | 10      | 131.30    | 504.80      | 19.60  | 137.20   | 0.10         | 0.20  |
| 3 × 3-11 × 11       | 80%    | 5                   | 5      | TT   | 10     | 10      | 231.00    | 448.20      | 19.60  | 80.60    | 0.05         | 0.11  |
| 3 × 3-11 × 11       | 80%    | 10                  | 2      | MS   | 10     | 10      | 316.20    | 611.20      | 25.40  | 147.80   | 0.05         | 0.54  |
| 3 × 3-11 × 11       | 80%    | 10                  | 2      | TT   | 10     | 10      | 428.90    | 588.30      | 25.40  | 124.90   | 0.03         | 0.09  |
| 3 × 3-11 × 11       | 80%    | 10                  | 3      | MS   | 10     | 9       | 223.20    | 629.30      | 25.40  | 165.90   | 0.09         | 0.29  |
| 3 × 3-11 × 11       | 80%    | 10                  | 3      | TT   | 10     | 10      | 337.60    | 576.30      | 25.40  | 112.90   | 0.06         | 0.09  |
| 3 × 3-11 × 11       | 80%    | 10                  | 4      | MS   | 10     | 10      | 182.20    | 633.80      | 25.40  | 170.40   | 0.13         | 0.31  |
| 3 × 3-11 × 11       | 80%    | 10                  | 4      | TT   | 10     | 10      | 314.80    | 565.90      | 25.40  | 102.50   | 0.07         | 0.14  |
| 3 × 3-11 × 11       | 80%    | 10                  | 5      | MS   | 10     | 10      | 147.50    | 620.60      | 25.40  | 157.10   | 0.15         | 0.37  |
| 3 × 3-11 × 11       | 80%    | 10                  | 5      | TT   | 10     | 10      | 305.40    | 559.60      | 25.40  | 96.20    | 0.09         | 0.17  |
| 3 × 3-11 × 11       | 90%    | 5                   | 2      | MS   | 10     | 8       | 357.50    | 704.00      | 37.20  | 168.80   | 0.08         | 1.37  |
| 3 × 3-11 × 11       | 90%    | 5                   | 2      | TT   | 10     | 10      | 455.10    | 673.60      | 37.20  | 138.40   | 0.05         | 0.13  |
| 3 × 3-11 × 11       | 90%    | 5                   | 3      | MS   | 10     | 9       | 249.00    | 711.30      | 37.20  | 176.10   | 0.12         | 1.52  |
| 3 × 3-11 × 11       | 90%    | 5                   | 3      | TT   | 10     | 10      | 382.90    | 665.80      | 37.20  | 130.60   | 0.08         | 0.17  |
| 3 × 3-11 × 11       | 90%    | 5                   | 4      | MS   | 10     | 10      | 201.60    | 743.10      | 37.20  | 206.50   | 0.17         | 0.55  |
| 3 × 3-11 × 11       | 90%    | 5                   | 4      | TT   | 10     | 10      | 348.20    | 656.60      | 37.20  | 121.40   | 0.10         | 0.18  |
| 3 × 3-11 × 11       | 90%    | 5                   | 5      | MS   | 10     | 10      | 166.00    | 726.30      | 37.20  | 190.90   | 0.22         | 0.51  |
| 3 × 3-11 × 11       | 90%    | 5                   | 5      | TT   | 10     | 10      | 320.50    | 648.90      | 37.20  | 113.70   | 0.12         | 0.26  |
| 3 × 3-11 × 11       | 90%    | 10                  | 2      | MS   | 10     | 3       | 480.70    | 956.30      | 53.30  | 201.00   | 0.16         | 13.15 |
| 3 × 3-11 × 11       | 90%    | 10                  | 2      | TT   | 10     | 10      | 658.90    | 925.80      | 53.30  | 170.50   | 0.10         | 0.31  |
| 3 × 3-11 × 11       | 90%    | 10                  | 3      | MS   | 10     | 4       | 332.00    | 971.80      | 53.30  | 216.50   | 0.26         | 28.21 |
| 3 × 3-11 × 11       | 90%    | 10                  | 3      | TT   | 10     | 10      | 494.50    | 915.60      | 53.30  | 160.30   | 0.15         | 0.30  |
| 3 × 3-11 × 11       | 90%    | 10                  | 4      | MS   | 10     | 6       | 248.40    | 959.80      | 53.30  | 204.50   | 0.37         | 14.61 |
| 3 × 3-11 × 11       | 90%    | 10                  | 4      | TT   | 10     | 10      | 449.20    | 906.40      | 53.30  | 151.10   | 0.21         | 0.35  |
| 3 × 3-11 × 11       | 90%    | 10                  | 5      | MS   | 10     | 8       | 217.60    | 996.30      | 53.30  | 235.30   | 0.50         | 1.48  |
| 3 × 3-11 × 11       | 90%    | 10                  | 5      | TT   | 10     | 10      | 403.20    | 897.90      | 53.30  | 142.60   | 0.28         | 0.58  |
| 3 × 3-12 × 12       | 60%    | 5                   | 2      | MS   | 3      | 3       | 102.67    | 190.33      | 5.00   | 65.33    | 0.01         | 0.01  |
| 3 × 3-12 × 12       | 60%    | 5                   | 2      | TT   | 3      | 3       | 102.67    | 190.33      | 5.00   | 65.33    | 0.01         | 0.01  |
| 3 × 3-12 × 12       | 60%    | 5                   | 3      | MS   | 3      | 3       | 91.67     | 171.33      | 5.00   | 46.33    | 0.01         | 0.01  |
| 3 × 3-12 × 12       | 60%    | 5                   | 3      | TT   | 3      | 3       | 95.00     | 171.33      | 5.00   | 46.33    | 0.01         | 0.01  |
| 3 × 3-12 × 12       | 60%    | 5                   | 4      | MS   | 3      | 3       | 90        | 169.67      | 5.00   | 44.67    | 0.01         | 0.01  |
| 3 × 3-12 × 12       | 60%    | 5                   | 4      | TT   | 3      | 3       | 97.67     | 168.67      | 5.00   | 43.67    | 0.01         | 0.01  |
| 3 × 3-12 × 12       | 60%    | 5                   | 5      | MS   | 3      | 3       | 86.67     | 162.67      | 5.00   | 37.67    | 0.01         | 0.02  |
| 3 × 3-12 × 12       | 60%    | 5                   | 5      | TT   | 3      | 3       | 90        | 162.67      | 5.00   | 37.67    | 0.01         | 0.01  |
| 3 × 3-12 × 12       | 60%    | 10                  | 2      | MS   | 6      | 6       | 127.67    | 238.50      | 7.67   | 80.83    | 0.01         | 0.01  |
| 3 × 3-12 × 12       | 60%    | 10                  | 2      | TT   | 6      | 6       | 165.00    | 230.67      | 7.67   | 73.00    | 0.01         | 0.01  |
| 3 × 3-12 × 12       | 60%    | 10                  | 3      | MS   | 6      | 6       | 107.17    | 234.17      | 7.67   | 76.50    | 0.01         | 0.02  |
| 3 × 3-12 × 12       | 60%    | 10                  | 3      | TT   | 6      | 6       | 161.00    | 220.83      | 7.67   | 63.17    | 0.01         | 0.02  |
| 3 × 3-12 × 12       | 60%    | 10                  | 4      | MS   | 6      | 6       | 100.17    | 233.33      | 7.67   | 75.67    | 0.01         | 0.02  |
| 3 × 3-12 × 12       | 60%    | 10                  | 4      | TT   | 6      | 6       | 146.17    | 211.33      | 7.67   | 53.67    | 0.01         | 0.02  |

(continued on next page)

Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |       |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|-------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best  |
| 3 × 3-12 × 12       | 60%    | 10                  | 5      | MS   | 6      | 6       | 89.50     | 213.67      | 7.67   | 56.00    | 0.02         | 0.04  |
| 3 × 3-12 × 12       | 60%    | 10                  | 5      | TT   | 6      | 6       | 134.83    | 200.17      | 7.67   | 42.50    | 0.01         | 0.02  |
| 3 × 3-12 × 12       | 80%    | 5                   | 2      | MS   | 9      | 9       | 263.11    | 514.89      | 21.33  | 126.89   | 0.04         | 0.14  |
| 3 × 3-12 × 12       | 80%    | 5                   | 2      | TT   | 9      | 9       | 333.44    | 485.67      | 21.33  | 97.67    | 0.03         | 0.05  |
| 3 × 3-12 × 12       | 80%    | 5                   | 3      | MS   | 9      | 9       | 201.11    | 540.33      | 21.33  | 152.33   | 0.06         | 0.16  |
| 3 × 3-12 × 12       | 80%    | 5                   | 3      | TT   | 9      | 9       | 310.22    | 481.22      | 21.33  | 93.22    | 0.04         | 0.06  |
| 3 × 3-12 × 12       | 80%    | 5                   | 4      | MS   | 9      | 9       | 152.89    | 552.44      | 21.33  | 159.78   | 0.09         | 0.20  |
| 3 × 3-12 × 12       | 80%    | 5                   | 4      | TT   | 9      | 9       | 303.89    | 474.56      | 21.33  | 86.56    | 0.05         | 0.11  |
| 3 × 3-12 × 12       | 80%    | 5                   | 5      | MS   | 9      | 9       | 130.56    | 523.33      | 21.33  | 135.33   | 0.11         | 0.28  |
| 3 × 3-12 × 12       | 80%    | 5                   | 5      | TT   | 9      | 9       | 282.33    | 468.89      | 21.33  | 80.89    | 0.07         | 0.16  |
| 3 × 3-12 × 12       | 80%    | 10                  | 2      | MS   | 8      | 8       | 316.00    | 609.25      | 26.12  | 135.12   | 0.05         | 0.34  |
| 3 × 3-12 × 12       | 80%    | 10                  | 2      | TT   | 8      | 8       | 385.88    | 575.00      | 26.12  | 106.38   | 0.03         | 0.07  |
| 3 × 3-12 × 12       | 80%    | 10                  | 3      | MS   | 8      | 8       | 221.12    | 619.00      | 26.12  | 150.38   | 0.09         | 0.29  |
| 3 × 3-12 × 12       | 80%    | 10                  | 3      | TT   | 8      | 8       | 324.50    | 569.12      | 26.12  | 100.50   | 0.05         | 0.10  |
| 3 × 3-12 × 12       | 80%    | 10                  | 4      | MS   | 8      | 8       | 181.25    | 644.50      | 26.12  | 175.75   | 0.12         | 0.26  |
| 3 × 3-12 × 12       | 80%    | 10                  | 4      | TT   | 8      | 8       | 316.75    | 564.12      | 26.12  | 95.50    | 0.07         | 0.14  |
| 3 × 3-12 × 12       | 80%    | 10                  | 5      | MS   | 8      | 8       | 148.88    | 641.88      | 26.12  | 172.00   | 0.15         | 0.35  |
| 3 × 3-12 × 12       | 80%    | 10                  | 5      | TT   | 8      | 8       | 305.25    | 559.50      | 26.12  | 90.88    | 0.09         | 0.17  |
| 3 × 3-12 × 12       | 90%    | 5                   | 2      | MS   | 10     | 5       | 397.40    | 783.80      | 43.00  | 188.80   | 0.09         | 23.75 |
| 3 × 3-12 × 12       | 90%    | 5                   | 2      | TT   | 10     | 10      | 526.40    | 757.30      | 43.00  | 162.30   | 0.06         | 0.15  |
| 3 × 3-12 × 12       | 90%    | 5                   | 3      | MS   | 10     | 8       | 284.00    | 807.10      | 43.00  | 212.10   | 0.16         | 3.18  |
| 3 × 3-12 × 12       | 90%    | 5                   | 3      | TT   | 10     | 10      | 442.20    | 744.60      | 43.00  | 149.60   | 0.09         | 0.16  |
| 3 × 3-12 × 12       | 90%    | 5                   | 4      | MS   | 10     | 9       | 218.70    | 819.80      | 43.00  | 224.50   | 0.20         | 4.02  |
| 3 × 3-12 × 12       | 90%    | 5                   | 4      | TT   | 10     | 10      | 389.60    | 732.00      | 43.00  | 137.00   | 0.12         | 0.24  |
| 3 × 3-12 × 12       | 90%    | 5                   | 5      | MS   | 10     | 10      | 181.80    | 826.00      | 43.00  | 231.00   | 0.28         | 0.69  |
| 3 × 3-12 × 12       | 90%    | 5                   | 5      | TT   | 10     | 10      | 358.40    | 724.80      | 43.00  | 129.80   | 0.16         | 0.30  |
| 3 × 3-12 × 12       | 90%    | 10                  | 2      | MS   | 10     | 2       | 556.60    | 1105.20     | 62.80  | 244.40   | 0.21         | 8.34  |
| 3 × 3-12 × 12       | 90%    | 10                  | 2      | TT   | 10     | 10      | 696.80    | 1069.60     | 62.80  | 208.80   | 0.14         | 0.47  |
| 3 × 3-12 × 12       | 90%    | 10                  | 3      | MS   | 10     | 2       | 378.80    | 1119.70     | 62.80  | 256.90   | 0.36         | 47.02 |
| 3 × 3-12 × 12       | 90%    | 10                  | 3      | TT   | 10     | 10      | 607.30    | 1056.00     | 62.80  | 195.20   | 0.21         | 0.56  |
| 3 × 3-12 × 12       | 90%    | 10                  | 4      | MS   | 10     | 5       | 293.80    | 1126.80     | 62.80  | 266.00   | 0.51         | 6.73  |
| 3 × 3-12 × 12       | 90%    | 10                  | 4      | TT   | 10     | 10      | 522.90    | 1043.40     | 62.80  | 182.60   | 0.30         | 0.78  |
| 3 × 3-12 × 12       | 90%    | 10                  | 5      | MS   | 10     | 7       | 241.60    | 1140.70     | 62.80  | 279.90   | 0.70         | 15.34 |
| 3 × 3-12 × 12       | 90%    | 10                  | 5      | TT   | 10     | 10      | 427.80    | 1037.90     | 62.80  | 177.10   | 0.39         | 0.88  |
| 4 × 4-2 × 2         | 80%    | 5                   | 2      | MS   | 4      | 4       | 107.50    | 194.50      | 8.00   | 21.50    | 0.01         | 0.01  |
| 4 × 4-2 × 2         | 80%    | 5                   | 2      | TT   | 4      | 4       | 108.25    | 190.25      | 8.00   | 17.25    | 0.01         | 0.01  |
| 4 × 4-2 × 2         | 80%    | 5                   | 3      | MS   | 4      | 4       | 87.25     | 189.25      | 8.00   | 16.25    | 0.01         | 0.02  |
| 4 × 4-2 × 2         | 80%    | 5                   | 3      | TT   | 4      | 4       | 103.75    | 186.75      | 8.00   | 13.75    | 0.01         | 0.01  |
| 4 × 4-2 × 2         | 80%    | 5                   | 4      | MS   | 4      | 4       | 70.75     | 189.00      | 8.00   | 16.00    | 0.01         | 0.02  |
| 4 × 4-2 × 2         | 80%    | 5                   | 4      | TT   | 4      | 4       | 102.50    | 185.50      | 8.00   | 12.50    | 0.01         | 0.02  |
| 4 × 4-2 × 2         | 80%    | 5                   | 5      | MS   | 4      | 4       | 69.75     | 186.25      | 8.00   | 13.25    | 0.02         | 0.04  |
| 4 × 4-2 × 2         | 80%    | 5                   | 5      | TT   | 4      | 4       | 102.00    | 184.75      | 8.00   | 11.75    | 0.01         | 0.03  |
| 4 × 4-2 × 2         | 80%    | 10                  | 2      | MS   | 7      | 7       | 114.14    | 207.00      | 12.00  | 23.14    | 0.01         | 0.01  |
| 4 × 4-2 × 2         | 80%    | 10                  | 2      | TT   | 7      | 7       | 153.71    | 203.43      | 12.00  | 20       | 0.01         | 0.01  |
| 4 × 4-2 × 2         | 80%    | 10                  | 3      | MS   | 7      | 7       | 91.29     | 204.14      | 12.00  | 20.71    | 0.01         | 0.02  |
| 4 × 4-2 × 2         | 80%    | 10                  | 3      | TT   | 7      | 7       | 112.57    | 200         | 12.00  | 16.57    | 0.01         | 0.02  |
| 4 × 4-2 × 2         | 80%    | 10                  | 4      | MS   | 7      | 7       | 72.71     | 201.86      | 12.00  | 18.43    | 0.02         | 0.03  |
| 4 × 4-2 × 2         | 80%    | 10                  | 4      | TT   | 7      | 7       | 110.57    | 197.86      | 12.00  | 14.43    | 0.01         | 0.02  |
| 4 × 4-2 × 2         | 80%    | 10                  | 5      | MS   | 7      | 7       | 70.86     | 197.43      | 12.00  | 14.00    | 0.02         | 0.04  |
| 4 × 4-2 × 2         | 80%    | 10                  | 5      | TT   | 7      | 7       | 90        | 195.29      | 12.00  | 11.86    | 0.01         | 0.03  |
| 4 × 4-2 × 2         | 90%    | 5                   | 2      | MS   | 4      | 4       | 141.50    | 237.75      | 20.50  | 22.25    | 0.01         | 0.02  |
| 4 × 4-2 × 2         | 90%    | 5                   | 2      | TT   | 4      | 4       | 183.50    | 231.75      | 20.50  | 16.25    | 0.01         | 0.01  |
| 4 × 4-2 × 2         | 90%    | 5                   | 3      | MS   | 4      | 4       | 93.25     | 252.75      | 20.50  | 21.00    | 0.02         | 0.02  |
| 4 × 4-2 × 2         | 90%    | 5                   | 3      | TT   | 4      | 4       | 144.25    | 229.25      | 20.50  | 13.75    | 0.01         | 0.02  |
| 4 × 4-2 × 2         | 90%    | 5                   | 4      | MS   | 4      | 4       | 76.25     | 235.00      | 20.50  | 19.50    | 0.02         | 0.03  |
| 4 × 4-2 × 2         | 90%    | 5                   | 4      | TT   | 4      | 4       | 111.00    | 227.25      | 20.50  | 11.75    | 0.01         | 0.02  |
| 4 × 4-2 × 2         | 90%    | 5                   | 5      | MS   | 4      | 4       | 74.75     | 232.50      | 20.50  | 17.00    | 0.03         | 0.04  |
| 4 × 4-2 × 2         | 90%    | 5                   | 5      | TT   | 4      | 4       | 92.75     | 225.25      | 20.50  | 9.75     | 0.02         | 0.04  |
| 4 × 4-2 × 2         | 90%    | 10                  | 2      | MS   | 8      | 8       | 110.50    | 196.25      | 17.38  | 21.25    | 0.01         | 0.01  |
| 4 × 4-2 × 2         | 90%    | 10                  | 2      | TT   | 8      | 8       | 131.38    | 192.88      | 17.38  | 18.00    | 0.01         | 0.01  |
| 4 × 4-2 × 2         | 90%    | 10                  | 3      | MS   | 8      | 8       | 84.12     | 200.88      | 17.38  | 17.88    | 0.01         | 0.02  |
| 4 × 4-2 × 2         | 90%    | 10                  | 3      | TT   | 8      | 8       | 101.00    | 189.38      | 17.38  | 14.50    | 0.01         | 0.01  |
| 4 × 4-2 × 2         | 90%    | 10                  | 4      | MS   | 8      | 8       | 75.38     | 189.25      | 17.38  | 14.38    | 0.01         | 0.02  |
| 4 × 4-2 × 2         | 90%    | 10                  | 4      | TT   | 8      | 8       | 84.25     | 186.62      | 17.38  | 11.75    | 0.01         | 0.02  |
| 4 × 4-2 × 2         | 90%    | 10                  | 5      | MS   | 8      | 8       | 74.50     | 187.62      | 17.38  | 12.75    | 0.02         | 0.03  |
| 4 × 4-2 × 2         | 90%    | 10                  | 5      | TT   | 8      | 8       | 83.50     | 184.75      | 17.38  | 9.88     | 0.01         | 0.02  |
| 4 × 4-3 × 3         | 40%    | 5                   | 2      | MS   | 1      | 1       | 78.00     | 155.00      | 2.00   | 33.00    | 0.01         | 0.01  |
| 4 × 4-3 × 3         | 40%    | 5                   | 2      | TT   | 1      | 1       | 81.00     | 147.00      | 2.00   | 25.00    | 0.01         | 0.01  |
| 4 × 4-3 × 3         | 40%    | 5                   | 3      | MS   | 1      | 1       | 70        | 136.00      | 2.00   | 14.00    | 0.01         | 0.01  |
| 4 × 4-3 × 3         | 40%    | 5                   | 3      | TT   | 1      | 1       | 70        | 136.00      | 2.00   | 14.00    | 0.01         | 0.01  |
| 4 × 4-3 × 3         | 40%    | 5                   | 4      | MS   | 1      | 1       | 70        | 136.00      | 2.00   | 14.00    | 0.01         | 0.02  |
| 4 × 4-3 × 3         | 40%    | 5                   | 4      | TT   | 1      | 1       | 70        | 136.00      | 2.00   | 14.00    | 0.01         | 0.01  |

(continued on next page)

Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |      |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best |
| 4 × 4-3 × 3         | 40%    | 5                   | 5      | MS   | 1      | 1       | 70        | 136.00      | 2.00   | 14.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 40%    | 5                   | 5      | TT   | 1      | 1       | 70        | 136.00      | 2.00   | 14.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 40%    | 10                  | 2      | MS   | 1      | 1       | 78.00     | 155.00      | 2.00   | 33.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 40%    | 10                  | 2      | TT   | 1      | 1       | 81.00     | 147.00      | 2.00   | 25.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 40%    | 10                  | 3      | MS   | 1      | 1       | 70        | 136.00      | 2.00   | 14.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 40%    | 10                  | 3      | TT   | 1      | 1       | 70        | 136.00      | 2.00   | 14.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 40%    | 10                  | 4      | MS   | 1      | 1       | 70        | 136.00      | 2.00   | 14.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 40%    | 10                  | 4      | TT   | 1      | 1       | 70        | 136.00      | 2.00   | 14.00    | 0.01         | 0.02 |
| 4 × 4-3 × 3         | 40%    | 10                  | 5      | MS   | 1      | 1       | 70        | 136.00      | 2.00   | 14.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 40%    | 10                  | 5      | TT   | 1      | 1       | 70        | 136.00      | 2.00   | 14.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 60%    | 5                   | 2      | MS   | 2      | 2       | 77.00     | 150         | 5.00   | 25.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 60%    | 5                   | 2      | TT   | 2      | 2       | 78.00     | 142.00      | 5.00   | 17.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 60%    | 5                   | 3      | MS   | 2      | 2       | 74.50     | 140         | 5.00   | 15.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 60%    | 5                   | 3      | TT   | 2      | 2       | 75.00     | 139.00      | 5.00   | 14.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 60%    | 5                   | 4      | MS   | 2      | 2       | 74.00     | 139.50      | 5.00   | 14.50    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 60%    | 5                   | 4      | TT   | 2      | 2       | 74.00     | 138.00      | 5.00   | 13.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 60%    | 5                   | 5      | MS   | 2      | 2       | 74.00     | 147.00      | 5.00   | 22.00    | 0.01         | 0.02 |
| 4 × 4-3 × 3         | 60%    | 5                   | 5      | TT   | 2      | 2       | 74.00     | 138.00      | 5.00   | 13.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 60%    | 10                  | 2      | MS   | 2      | 2       | 133.00    | 211.00      | 7.00   | 24.00    | 0.01         | 0.02 |
| 4 × 4-3 × 3         | 60%    | 10                  | 2      | TT   | 2      | 2       | 204.00    | 204.00      | 7.00   | 17.00    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 60%    | 10                  | 3      | MS   | 2      | 2       | 77.00     | 221.50      | 7.00   | 34.50    | 0.02         | 0.02 |
| 4 × 4-3 × 3         | 60%    | 10                  | 3      | TT   | 2      | 2       | 169.00    | 202.50      | 7.00   | 15.50    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 60%    | 10                  | 4      | MS   | 2      | 2       | 76.50     | 220.50      | 7.00   | 33.50    | 0.02         | 0.02 |
| 4 × 4-3 × 3         | 60%    | 10                  | 4      | TT   | 2      | 2       | 169.00    | 202.50      | 7.00   | 15.50    | 0.01         | 0.03 |
| 4 × 4-3 × 3         | 60%    | 10                  | 5      | MS   | 2      | 2       | 76.50     | 213.00      | 7.00   | 26.00    | 0.02         | 0.03 |
| 4 × 4-3 × 3         | 60%    | 10                  | 5      | TT   | 2      | 2       | 169.00    | 202.50      | 7.00   | 15.50    | 0.01         | 0.04 |
| 4 × 4-3 × 3         | 80%    | 5                   | 2      | MS   | 9      | 9       | 127.56    | 234.22      | 9.89   | 31.00    | 0.01         | 0.02 |
| 4 × 4-3 × 3         | 80%    | 5                   | 2      | TT   | 9      | 9       | 153.78    | 229.89      | 9.89   | 26.67    | 0.01         | 0.01 |
| 4 × 4-3 × 3         | 80%    | 5                   | 3      | MS   | 9      | 9       | 103.11    | 231.11      | 9.89   | 27.89    | 0.02         | 0.03 |
| 4 × 4-3 × 3         | 80%    | 5                   | 3      | TT   | 9      | 9       | 129.67    | 227.11      | 9.89   | 23.89    | 0.01         | 0.02 |
| 4 × 4-3 × 3         | 80%    | 5                   | 4      | MS   | 9      | 9       | 87.78     | 233.33      | 9.89   | 30.11    | 0.02         | 0.04 |
| 4 × 4-3 × 3         | 80%    | 5                   | 4      | TT   | 9      | 9       | 128.44    | 225.33      | 9.89   | 22.11    | 0.02         | 0.03 |
| 4 × 4-3 × 3         | 80%    | 5                   | 5      | MS   | 9      | 9       | 75.33     | 235.78      | 9.89   | 32.56    | 0.03         | 0.06 |
| 4 × 4-3 × 3         | 80%    | 5                   | 5      | TT   | 9      | 9       | 127.56    | 223.89      | 9.89   | 20.67    | 0.02         | 0.04 |
| 4 × 4-3 × 3         | 80%    | 10                  | 2      | MS   | 10     | 10      | 170.50    | 311.50      | 11.80  | 41.70    | 0.02         | 0.05 |
| 4 × 4-3 × 3         | 80%    | 10                  | 2      | TT   | 10     | 10      | 220.70    | 304.00      | 11.80  | 34.20    | 0.01         | 0.02 |
| 4 × 4-3 × 3         | 80%    | 10                  | 3      | MS   | 10     | 10      | 122.60    | 313.90      | 11.80  | 44.10    | 0.03         | 0.06 |
| 4 × 4-3 × 3         | 80%    | 10                  | 3      | TT   | 10     | 10      | 190.50    | 301.80      | 11.80  | 32.00    | 0.02         | 0.03 |
| 4 × 4-3 × 3         | 80%    | 10                  | 4      | MS   | 10     | 10      | 105.60    | 311.10      | 11.80  | 41.30    | 0.04         | 0.09 |
| 4 × 4-3 × 3         | 80%    | 10                  | 4      | TT   | 10     | 10      | 161.40    | 296.50      | 11.80  | 26.70    | 0.03         | 0.04 |
| 4 × 4-3 × 3         | 80%    | 10                  | 5      | MS   | 10     | 10      | 86.40     | 310.30      | 11.80  | 40.30    | 0.05         | 0.10 |
| 4 × 4-3 × 3         | 80%    | 10                  | 5      | TT   | 10     | 10      | 147.80    | 294.50      | 11.80  | 24.70    | 0.03         | 0.06 |
| 4 × 4-3 × 3         | 90%    | 5                   | 2      | MS   | 10     | 10      | 167.40    | 311.00      | 21.70  | 37.30    | 0.02         | 0.05 |
| 4 × 4-3 × 3         | 90%    | 5                   | 2      | TT   | 10     | 10      | 212.10    | 307.60      | 21.70  | 33.90    | 0.02         | 0.03 |
| 4 × 4-3 × 3         | 90%    | 5                   | 3      | MS   | 10     | 10      | 125.80    | 316.60      | 21.70  | 42.90    | 0.03         | 0.06 |
| 4 × 4-3 × 3         | 90%    | 5                   | 3      | TT   | 10     | 10      | 183.00    | 304.00      | 21.70  | 30.30    | 0.02         | 0.03 |
| 4 × 4-3 × 3         | 90%    | 5                   | 4      | MS   | 10     | 10      | 96.70     | 307.50      | 21.70  | 33.80    | 0.04         | 0.08 |
| 4 × 4-3 × 3         | 90%    | 5                   | 4      | TT   | 10     | 10      | 153.40    | 300.80      | 21.70  | 27.10    | 0.03         | 0.04 |
| 4 × 4-3 × 3         | 90%    | 5                   | 5      | MS   | 10     | 10      | 95.60     | 313.30      | 21.70  | 39.60    | 0.05         | 0.10 |
| 4 × 4-3 × 3         | 90%    | 5                   | 5      | TT   | 10     | 10      | 166.30    | 299.50      | 21.70  | 25.80    | 0.03         | 0.05 |
| 4 × 4-3 × 3         | 90%    | 10                  | 2      | MS   | 10     | 10      | 223.70    | 421.30      | 25.90  | 59.40    | 0.03         | 0.14 |
| 4 × 4-3 × 3         | 90%    | 10                  | 2      | TT   | 10     | 10      | 304.20    | 404.40      | 25.90  | 42.50    | 0.02         | 0.04 |
| 4 × 4-3 × 3         | 90%    | 10                  | 3      | MS   | 10     | 10      | 168.60    | 416.70      | 25.90  | 54.80    | 0.04         | 0.13 |
| 4 × 4-3 × 3         | 90%    | 10                  | 3      | TT   | 10     | 10      | 267.00    | 399.90      | 25.90  | 38.00    | 0.03         | 0.07 |
| 4 × 4-3 × 3         | 90%    | 10                  | 4      | MS   | 10     | 10      | 122.30    | 408.90      | 25.90  | 47.00    | 0.06         | 0.15 |
| 4 × 4-3 × 3         | 90%    | 10                  | 4      | TT   | 10     | 10      | 223.90    | 397.30      | 25.90  | 35.40    | 0.04         | 0.07 |
| 4 × 4-3 × 3         | 90%    | 10                  | 5      | MS   | 10     | 10      | 102.70    | 411.50      | 25.90  | 49.60    | 0.08         | 0.18 |
| 4 × 4-3 × 3         | 90%    | 10                  | 5      | TT   | 10     | 10      | 188.30    | 395.00      | 25.90  | 33.10    | 0.05         | 0.09 |
| 4 × 4-4 × 4         | 40%    | 5                   | 2      | MS   | 1      | 1       | 134.00    | 219.00      | 3.00   | 36.00    | 0.01         | 0.01 |
| 4 × 4-4 × 4         | 40%    | 5                   | 2      | TT   | 1      | 1       | 134.00    | 219.00      | 3.00   | 36.00    | 0.01         | 0.01 |
| 4 × 4-4 × 4         | 40%    | 5                   | 3      | MS   | 1      | 1       | 70        | 203.00      | 3.00   | 20       | 0.01         | 0.02 |
| 4 × 4-4 × 4         | 40%    | 5                   | 3      | TT   | 1      | 1       | 134.00    | 201.00      | 3.00   | 18.00    | 0.01         | 0.02 |
| 4 × 4-4 × 4         | 40%    | 5                   | 4      | MS   | 1      | 1       | 70        | 203.00      | 3.00   | 20       | 0.01         | 0.02 |
| 4 × 4-4 × 4         | 40%    | 5                   | 4      | TT   | 1      | 1       | 134.00    | 201.00      | 3.00   | 18.00    | 0.01         | 0.03 |
| 4 × 4-4 × 4         | 40%    | 5                   | 5      | MS   | 1      | 1       | 67.00     | 200         | 3.00   | 17.00    | 0.02         | 0.04 |
| 4 × 4-4 × 4         | 40%    | 5                   | 5      | TT   | 1      | 1       | 67.00     | 197.00      | 3.00   | 14.00    | 0.01         | 0.04 |
| 4 × 4-4 × 4         | 40%    | 10                  | 2      | MS   | 1      | 1       | 134.00    | 219.00      | 3.00   | 36.00    | 0.01         | 0.01 |
| 4 × 4-4 × 4         | 40%    | 10                  | 2      | TT   | 1      | 1       | 134.00    | 219.00      | 3.00   | 36.00    | 0.01         | 0.01 |
| 4 × 4-4 × 4         | 40%    | 10                  | 3      | MS   | 1      | 1       | 70        | 203.00      | 3.00   | 20       | 0.01         | 0.02 |
| 4 × 4-4 × 4         | 40%    | 10                  | 3      | TT   | 1      | 1       | 134.00    | 201.00      | 3.00   | 18.00    | 0.01         | 0.01 |
| 4 × 4-4 × 4         | 40%    | 10                  | 4      | MS   | 1      | 1       | 70        | 203.00      | 3.00   | 20       | 0.02         | 0.02 |
| 4 × 4-4 × 4         | 40%    | 10                  | 4      | TT   | 1      | 1       | 134.00    | 201.00      | 3.00   | 18.00    | 0.01         | 0.02 |
| 4 × 4-4 × 4         | 40%    | 10                  | 5      | MS   | 1      | 1       | 67.00     | 197.00      | 3.00   | 14.00    | 0.02         | 0.03 |

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Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |      |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best |
| 4 × 4-4 × 4         | 40%    | 10                  | 5      | TT   | 1      | 1       | 67.00     | 197.00      | 3.00   | 14.00    | 0.01         | 0.02 |
| 4 × 4-4 × 4         | 60%    | 5                   | 2      | MS   | 8      | 8       | 111.50    | 195.38      | 4.12   | 33.75    | 0.01         | 0.01 |
| 4 × 4-4 × 4         | 60%    | 5                   | 2      | TT   | 8      | 8       | 137.75    | 191.62      | 4.12   | 30       | 0.01         | 0.01 |
| 4 × 4-4 × 4         | 60%    | 5                   | 3      | MS   | 8      | 8       | 84.00     | 194.50      | 4.12   | 32.88    | 0.01         | 0.02 |
| 4 × 4-4 × 4         | 60%    | 5                   | 3      | TT   | 8      | 8       | 135.75    | 187.88      | 4.12   | 26.25    | 0.01         | 0.02 |
| 4 × 4-4 × 4         | 60%    | 5                   | 4      | MS   | 8      | 8       | 76.12     | 192.88      | 4.12   | 31.25    | 0.01         | 0.02 |
| 4 × 4-4 × 4         | 60%    | 5                   | 4      | TT   | 8      | 8       | 135.12    | 187.12      | 4.12   | 25.50    | 0.01         | 0.02 |
| 4 × 4-4 × 4         | 60%    | 5                   | 5      | MS   | 8      | 8       | 74.50     | 190.12      | 4.12   | 28.50    | 0.02         | 0.03 |
| 4 × 4-4 × 4         | 60%    | 5                   | 5      | TT   | 8      | 8       | 117.00    | 186.25      | 4.12   | 24.62    | 0.01         | 0.03 |
| 4 × 4-4 × 4         | 60%    | 10                  | 2      | MS   | 8      | 8       | 118.38    | 219.38      | 5.12   | 34.25    | 0.01         | 0.02 |
| 4 × 4-4 × 4         | 60%    | 10                  | 2      | TT   | 8      | 8       | 144.25    | 216.75      | 5.12   | 31.62    | 0.01         | 0.01 |
| 4 × 4-4 × 4         | 60%    | 10                  | 3      | MS   | 8      | 8       | 98.88     | 220.62      | 5.12   | 35.50    | 0.02         | 0.03 |
| 4 × 4-4 × 4         | 60%    | 10                  | 3      | TT   | 8      | 8       | 143.38    | 211.88      | 5.12   | 26.75    | 0.01         | 0.02 |
| 4 × 4-4 × 4         | 60%    | 10                  | 4      | MS   | 8      | 8       | 83.50     | 220.38      | 5.12   | 35.25    | 0.02         | 0.04 |
| 4 × 4-4 × 4         | 60%    | 10                  | 4      | TT   | 8      | 8       | 142.25    | 210.62      | 5.12   | 25.50    | 0.01         | 0.03 |
| 4 × 4-4 × 4         | 60%    | 10                  | 5      | MS   | 8      | 8       | 74.12     | 216.62      | 5.12   | 31.50    | 0.02         | 0.04 |
| 4 × 4-4 × 4         | 60%    | 10                  | 5      | TT   | 8      | 8       | 115.62    | 209.38      | 5.12   | 24.25    | 0.02         | 0.03 |
| 4 × 4-4 × 4         | 80%    | 5                   | 2      | MS   | 9      | 9       | 194.33    | 368.33      | 14.67  | 67.00    | 0.02         | 0.08 |
| 4 × 4-4 × 4         | 80%    | 5                   | 2      | TT   | 9      | 9       | 229.78    | 348.00      | 14.67  | 46.67    | 0.02         | 0.04 |
| 4 × 4-4 × 4         | 80%    | 5                   | 3      | MS   | 9      | 9       | 144.33    | 362.22      | 14.67  | 60.89    | 0.03         | 0.08 |
| 4 × 4-4 × 4         | 80%    | 5                   | 3      | TT   | 9      | 9       | 202.44    | 343.33      | 14.67  | 42.00    | 0.02         | 0.04 |
| 4 × 4-4 × 4         | 80%    | 5                   | 4      | MS   | 9      | 9       | 115.56    | 354.22      | 14.67  | 52.89    | 0.05         | 0.11 |
| 4 × 4-4 × 4         | 80%    | 5                   | 4      | TT   | 9      | 9       | 177.89    | 339.44      | 14.67  | 38.11    | 0.03         | 0.05 |
| 4 × 4-4 × 4         | 80%    | 5                   | 5      | MS   | 9      | 9       | 98.00     | 346.89      | 14.67  | 45.33    | 0.06         | 0.14 |
| 4 × 4-4 × 4         | 80%    | 5                   | 5      | TT   | 9      | 9       | 137.00    | 335.33      | 14.67  | 34.00    | 0.04         | 0.07 |
| 4 × 4-4 × 4         | 80%    | 10                  | 2      | MS   | 10     | 10      | 220.90    | 422.00      | 17.80  | 68.10    | 0.03         | 0.14 |
| 4 × 4-4 × 4         | 80%    | 10                  | 2      | TT   | 10     | 10      | 283.30    | 404.40      | 17.80  | 50.60    | 0.02         | 0.04 |
| 4 × 4-4 × 4         | 80%    | 10                  | 3      | MS   | 10     | 10      | 159.00    | 416.90      | 17.80  | 63.10    | 0.05         | 0.14 |
| 4 × 4-4 × 4         | 80%    | 10                  | 3      | TT   | 10     | 10      | 233.50    | 399.90      | 17.80  | 46.10    | 0.03         | 0.04 |
| 4 × 4-4 × 4         | 80%    | 10                  | 4      | MS   | 10     | 10      | 125.90    | 416.60      | 17.80  | 62.70    | 0.07         | 0.16 |
| 4 × 4-4 × 4         | 80%    | 10                  | 4      | TT   | 10     | 10      | 209.40    | 395.70      | 17.80  | 41.90    | 0.04         | 0.06 |
| 4 × 4-4 × 4         | 80%    | 10                  | 5      | MS   | 10     | 10      | 113.00    | 419.00      | 17.80  | 60.80    | 0.10         | 0.22 |
| 4 × 4-4 × 4         | 80%    | 10                  | 5      | TT   | 10     | 10      | 170.50    | 390         | 17.80  | 36.20    | 0.05         | 0.09 |
| 4 × 4-4 × 4         | 90%    | 5                   | 2      | MS   | 10     | 9       | 267.50    | 509.50      | 32.40  | 68.80    | 0.05         | 0.20 |
| 4 × 4-4 × 4         | 90%    | 5                   | 2      | TT   | 10     | 10      | 358.10    | 492.80      | 32.40  | 52.40    | 0.03         | 0.07 |
| 4 × 4-4 × 4         | 90%    | 5                   | 3      | MS   | 10     | 9       | 186.80    | 512.50      | 32.40  | 72.10    | 0.08         | 0.28 |
| 4 × 4-4 × 4         | 90%    | 5                   | 3      | TT   | 10     | 10      | 311.60    | 489.50      | 32.40  | 49.10    | 0.05         | 0.08 |
| 4 × 4-4 × 4         | 90%    | 5                   | 4      | MS   | 10     | 10      | 152.00    | 528.30      | 32.40  | 82.90    | 0.10         | 0.27 |
| 4 × 4-4 × 4         | 90%    | 5                   | 4      | TT   | 10     | 10      | 290.40    | 487.70      | 32.40  | 47.30    | 0.06         | 0.11 |
| 4 × 4-4 × 4         | 90%    | 5                   | 5      | MS   | 10     | 10      | 129.40    | 510.10      | 32.40  | 68.70    | 0.15         | 0.31 |
| 4 × 4-4 × 4         | 90%    | 5                   | 5      | TT   | 10     | 10      | 224.80    | 484.20      | 32.40  | 43.80    | 0.08         | 0.15 |
| 4 × 4-4 × 4         | 90%    | 10                  | 2      | MS   | 10     | 7       | 329.30    | 639.40      | 42.30  | 87.10    | 0.07         | 0.50 |
| 4 × 4-4 × 4         | 90%    | 10                  | 2      | TT   | 10     | 10      | 390.50    | 615.50      | 42.30  | 63.20    | 0.05         | 0.08 |
| 4 × 4-4 × 4         | 90%    | 10                  | 3      | MS   | 10     | 7       | 225.20    | 640.60      | 42.30  | 88.30    | 0.12         | 4.32 |
| 4 × 4-4 × 4         | 90%    | 10                  | 3      | TT   | 10     | 10      | 370.40    | 611.40      | 42.30  | 59.10    | 0.07         | 0.12 |
| 4 × 4-4 × 4         | 90%    | 10                  | 4      | MS   | 10     | 10      | 185.20    | 649.60      | 42.30  | 90.70    | 0.16         | 0.47 |
| 4 × 4-4 × 4         | 90%    | 10                  | 4      | TT   | 10     | 10      | 338.00    | 607.90      | 42.30  | 55.60    | 0.09         | 0.14 |
| 4 × 4-4 × 4         | 90%    | 10                  | 5      | MS   | 10     | 10      | 149.70    | 634.40      | 42.30  | 81.90    | 0.23         | 0.49 |
| 4 × 4-4 × 4         | 90%    | 10                  | 5      | TT   | 10     | 10      | 279.40    | 601.80      | 42.30  | 49.50    | 0.13         | 0.19 |
| 4 × 4-5 × 5         | 40%    | 5                   | 2      | MS   | 2      | 2       | 111.50    | 187.50      | 2.50   | 35.00    | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 40%    | 5                   | 2      | TT   | 2      | 2       | 118.50    | 184.00      | 2.50   | 31.50    | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 40%    | 5                   | 3      | MS   | 2      | 2       | 82.00     | 184.50      | 2.50   | 32.00    | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 40%    | 5                   | 3      | TT   | 2      | 2       | 118.50    | 184.00      | 2.50   | 31.50    | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 40%    | 5                   | 4      | MS   | 2      | 2       | 82.00     | 184.50      | 2.50   | 32.00    | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 40%    | 5                   | 4      | TT   | 2      | 2       | 117.00    | 182.50      | 2.50   | 30       | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 40%    | 5                   | 5      | MS   | 2      | 2       | 82.00     | 184.50      | 2.50   | 32.00    | 0.01         | 0.02 |
| 4 × 4-5 × 5         | 40%    | 5                   | 5      | TT   | 2      | 2       | 117.00    | 182.50      | 2.50   | 30       | 0.01         | 0.02 |
| 4 × 4-5 × 5         | 40%    | 10                  | 2      | MS   | 4      | 4       | 103.25    | 179.00      | 3.00   | 41.00    | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 40%    | 10                  | 2      | TT   | 4      | 4       | 108.00    | 177.25      | 3.00   | 39.25    | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 40%    | 10                  | 3      | MS   | 4      | 4       | 84.00     | 174.00      | 3.00   | 36.00    | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 40%    | 10                  | 3      | TT   | 4      | 4       | 102.50    | 170.75      | 3.00   | 32.75    | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 40%    | 10                  | 4      | MS   | 4      | 4       | 84.00     | 172.50      | 3.00   | 34.50    | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 40%    | 10                  | 4      | TT   | 4      | 4       | 101.75    | 170         | 3.00   | 32.00    | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 40%    | 10                  | 5      | MS   | 4      | 4       | 82.75     | 173.25      | 3.00   | 35.25    | 0.01         | 0.02 |
| 4 × 4-5 × 5         | 40%    | 10                  | 5      | TT   | 4      | 4       | 100.25    | 167.75      | 3.00   | 29.75    | 0.01         | 0.01 |
| 4 × 4-5 × 5         | 60%    | 5                   | 2      | MS   | 8      | 8       | 164.00    | 295.00      | 6.50   | 52.00    | 0.02         | 0.04 |
| 4 × 4-5 × 5         | 60%    | 5                   | 2      | TT   | 8      | 8       | 245.12    | 281.00      | 6.50   | 42.00    | 0.01         | 0.03 |
| 4 × 4-5 × 5         | 60%    | 5                   | 3      | MS   | 8      | 8       | 112.38    | 295.75      | 6.50   | 56.38    | 0.02         | 0.05 |
| 4 × 4-5 × 5         | 60%    | 5                   | 3      | TT   | 8      | 8       | 190.25    | 278.50      | 6.50   | 39.50    | 0.02         | 0.04 |
| 4 × 4-5 × 5         | 60%    | 5                   | 4      | MS   | 8      | 8       | 99.75     | 289.00      | 6.50   | 50       | 0.03         | 0.07 |
| 4 × 4-5 × 5         | 60%    | 5                   | 4      | TT   | 8      | 8       | 176.62    | 275.50      | 6.50   | 36.50    | 0.02         | 0.04 |
| 4 × 4-5 × 5         | 60%    | 5                   | 5      | MS   | 8      | 8       | 84.25     | 298.38      | 6.50   | 58.38    | 0.04         | 0.08 |
| 4 × 4-5 × 5         | 60%    | 5                   | 5      | TT   | 8      | 8       | 178.25    | 274.12      | 6.50   | 35.12    | 0.03         | 0.05 |

(continued on next page)

Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |       |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|-------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best  |
| 4 × 4.5 × 5         | 60%    | 10                  | 2      | MS   | 9      | 9       | 164.00    | 300.44      | 6.89   | 53.11    | 0.02         | 0.06  |
| 4 × 4.5 × 5         | 60%    | 10                  | 2      | TT   | 9      | 9       | 234.78    | 292.44      | 6.89   | 45.56    | 0.01         | 0.02  |
| 4 × 4.5 × 5         | 60%    | 10                  | 3      | MS   | 9      | 9       | 123.00    | 308.00      | 6.89   | 55.22    | 0.03         | 0.06  |
| 4 × 4.5 × 5         | 60%    | 10                  | 3      | TT   | 9      | 9       | 225.22    | 290.11      | 6.89   | 43.22    | 0.02         | 0.04  |
| 4 × 4.5 × 5         | 60%    | 10                  | 4      | MS   | 9      | 9       | 100       | 306.22      | 6.89   | 59.33    | 0.04         | 0.07  |
| 4 × 4.5 × 5         | 60%    | 10                  | 4      | TT   | 9      | 9       | 215.11    | 286.33      | 6.89   | 39.44    | 0.02         | 0.05  |
| 4 × 4.5 × 5         | 60%    | 10                  | 5      | MS   | 9      | 9       | 90.11     | 307.67      | 6.89   | 60.78    | 0.04         | 0.10  |
| 4 × 4.5 × 5         | 60%    | 10                  | 5      | TT   | 9      | 9       | 198.22    | 283.78      | 6.89   | 36.89    | 0.03         | 0.07  |
| 4 × 4.5 × 5         | 80%    | 5                   | 2      | MS   | 10     | 8       | 300.80    | 588.70      | 21.80  | 104.90   | 0.07         | 2.05  |
| 4 × 4.5 × 5         | 80%    | 5                   | 2      | TT   | 10     | 10      | 357.60    | 565.10      | 21.80  | 81.30    | 0.04         | 0.08  |
| 4 × 4.5 × 5         | 80%    | 5                   | 3      | MS   | 10     | 8       | 212.20    | 586.10      | 21.80  | 102.30   | 0.11         | 1.43  |
| 4 × 4.5 × 5         | 80%    | 5                   | 3      | TT   | 10     | 10      | 312.80    | 562.00      | 21.80  | 78.20    | 0.06         | 0.11  |
| 4 × 4.5 × 5         | 80%    | 5                   | 4      | MS   | 10     | 10      | 162.60    | 584.50      | 21.80  | 100.70   | 0.16         | 0.36  |
| 4 × 4.5 × 5         | 80%    | 5                   | 4      | TT   | 10     | 10      | 272.60    | 555.40      | 21.80  | 71.60    | 0.09         | 0.16  |
| 4 × 4.5 × 5         | 80%    | 5                   | 5      | MS   | 10     | 10      | 145.80    | 597.20      | 21.80  | 113.40   | 0.19         | 0.43  |
| 4 × 4.5 × 5         | 80%    | 5                   | 5      | TT   | 10     | 10      | 228.40    | 550.30      | 21.80  | 66.50    | 0.11         | 0.23  |
| 4 × 4.5 × 5         | 80%    | 10                  | 2      | MS   | 10     | 4       | 369.50    | 731.20      | 27.20  | 116.00   | 0.11         | 3.24  |
| 4 × 4.5 × 5         | 80%    | 10                  | 2      | TT   | 10     | 10      | 485.90    | 712.60      | 27.20  | 97.40    | 0.07         | 0.16  |
| 4 × 4.5 × 5         | 80%    | 10                  | 3      | MS   | 10     | 4       | 258.00    | 739.80      | 27.20  | 124.20   | 0.17         | 37.04 |
| 4 × 4.5 × 5         | 80%    | 10                  | 3      | TT   | 10     | 10      | 373.30    | 707.00      | 27.20  | 91.80    | 0.10         | 0.21  |
| 4 × 4.5 × 5         | 80%    | 10                  | 4      | MS   | 10     | 9       | 194.30    | 739.80      | 27.20  | 124.60   | 0.23         | 1.65  |
| 4 × 4.5 × 5         | 80%    | 10                  | 4      | TT   | 10     | 10      | 329.30    | 701.20      | 27.20  | 86.00    | 0.14         | 0.23  |
| 4 × 4.5 × 5         | 80%    | 10                  | 5      | MS   | 10     | 10      | 178.60    | 765.90      | 27.20  | 149.60   | 0.33         | 0.83  |
| 4 × 4.5 × 5         | 80%    | 10                  | 5      | TT   | 10     | 10      | 295.00    | 695.50      | 27.20  | 80.30    | 0.18         | 0.34  |
| 4 × 4.5 × 5         | 90%    | 5                   | 2      | MS   | 10     | 3       | 434.10    | 860.60      | 52.50  | 123.50   | 0.15         | 9.15  |
| 4 × 4.5 × 5         | 90%    | 5                   | 2      | TT   | 10     | 10      | 638.30    | 833.70      | 52.50  | 97.20    | 0.08         | 0.19  |
| 4 × 4.5 × 5         | 90%    | 5                   | 3      | MS   | 10     | 3       | 293.00    | 869.00      | 52.50  | 128.70   | 0.25         | 8.21  |
| 4 × 4.5 × 5         | 90%    | 5                   | 3      | TT   | 10     | 10      | 543.30    | 830         | 52.50  | 93.50    | 0.14         | 0.24  |
| 4 × 4.5 × 5         | 90%    | 5                   | 4      | MS   | 10     | 7       | 233.30    | 872.80      | 52.50  | 136.30   | 0.33         | 30.22 |
| 4 × 4.5 × 5         | 90%    | 5                   | 4      | TT   | 10     | 10      | 430.60    | 822.20      | 52.50  | 85.70    | 0.19         | 0.25  |
| 4 × 4.5 × 5         | 90%    | 5                   | 5      | MS   | 10     | 10      | 189.20    | 868.40      | 52.50  | 127.00   | 0.45         | 11.07 |
| 4 × 4.5 × 5         | 90%    | 5                   | 5      | TT   | 10     | 10      | 365.10    | 818.90      | 52.50  | 82.40    | 0.25         | 0.36  |
| 4 × 4.5 × 5         | 90%    | 10                  | 2      | MS   | 10     | 0       | 501.30    | 999.60      | 62.10  | 127.40   | 0.22         | 40.53 |
| 4 × 4.5 × 5         | 90%    | 10                  | 2      | TT   | 10     | 10      | 698.40    | 978.10      | 62.10  | 106.00   | 0.13         | 0.23  |
| 4 × 4.5 × 5         | 90%    | 10                  | 3      | MS   | 10     | 0       | 350.30    | 1027.10     | 62.10  | 154.80   | 0.36         | 20.94 |
| 4 × 4.5 × 5         | 90%    | 10                  | 3      | TT   | 10     | 10      | 595.00    | 974.40      | 62.10  | 102.30   | 0.20         | 0.51  |
| 4 × 4.5 × 5         | 90%    | 10                  | 4      | MS   | 10     | 3       | 269.40    | 1028.40     | 62.10  | 156.30   | 0.53         | 26.58 |
| 4 × 4.5 × 5         | 90%    | 10                  | 4      | TT   | 10     | 10      | 435.90    | 967.30      | 62.10  | 95.20    | 0.29         | 0.41  |
| 4 × 4.5 × 5         | 90%    | 10                  | 5      | MS   | 10     | 8       | 221.00    | 1039.10     | 62.10  | 167.00   | 0.70         | 24.33 |
| 4 × 4.5 × 5         | 90%    | 10                  | 5      | TT   | 10     | 10      | 405.80    | 964.20      | 62.10  | 92.10    | 0.38         | 0.61  |
| 4 × 4.6 × 6         | 40%    | 5                   | 2      | MS   | 1      | 1       | 153.00    | 244.00      | 7.00   | 57.00    | 0.01         | 0.02  |
| 4 × 4.6 × 6         | 40%    | 5                   | 2      | TT   | 1      | 1       | 161.00    | 243.00      | 7.00   | 56.00    | 0.01         | 0.01  |
| 4 × 4.6 × 6         | 40%    | 5                   | 3      | MS   | 1      | 1       | 82.00     | 222.00      | 7.00   | 35.00    | 0.01         | 0.02  |
| 4 × 4.6 × 6         | 40%    | 5                   | 3      | TT   | 1      | 1       | 153.00    | 215.00      | 7.00   | 28.00    | 0.01         | 0.01  |
| 4 × 4.6 × 6         | 40%    | 5                   | 4      | MS   | 1      | 1       | 82.00     | 222.00      | 7.00   | 35.00    | 0.01         | 0.02  |
| 4 × 4.6 × 6         | 40%    | 5                   | 4      | TT   | 1      | 1       | 144.00    | 206.00      | 7.00   | 19.00    | 0.01         | 0.02  |
| 4 × 4.6 × 6         | 40%    | 5                   | 5      | MS   | 1      | 1       | 82.00     | 223.00      | 7.00   | 36.00    | 0.02         | 0.03  |
| 4 × 4.6 × 6         | 40%    | 5                   | 5      | TT   | 1      | 1       | 144.00    | 206.00      | 7.00   | 19.00    | 0.01         | 0.03  |
| 4 × 4.6 × 6         | 40%    | 10                  | 2      | MS   | 3      | 3       | 111.67    | 196.33      | 4.33   | 52.00    | 0.01         | 0.01  |
| 4 × 4.6 × 6         | 40%    | 10                  | 2      | TT   | 3      | 3       | 116.33    | 194.00      | 4.33   | 49.67    | 0.01         | 0.01  |
| 4 × 4.6 × 6         | 40%    | 10                  | 3      | MS   | 3      | 3       | 83.00     | 184.33      | 4.33   | 40       | 0.01         | 0.01  |
| 4 × 4.6 × 6         | 40%    | 10                  | 3      | TT   | 3      | 3       | 110       | 181.33      | 4.33   | 37.00    | 0.01         | 0.01  |
| 4 × 4.6 × 6         | 40%    | 10                  | 4      | MS   | 3      | 3       | 83.00     | 184.33      | 4.33   | 40       | 0.01         | 0.01  |
| 4 × 4.6 × 6         | 40%    | 10                  | 4      | TT   | 3      | 3       | 107.00    | 178.33      | 4.33   | 34.00    | 0.01         | 0.01  |
| 4 × 4.6 × 6         | 40%    | 10                  | 5      | MS   | 3      | 3       | 81.67     | 182.67      | 4.33   | 38.33    | 0.01         | 0.02  |
| 4 × 4.6 × 6         | 40%    | 10                  | 5      | TT   | 3      | 3       | 104.33    | 175.67      | 4.33   | 31.33    | 0.01         | 0.02  |
| 4 × 4.6 × 6         | 60%    | 5                   | 2      | MS   | 9      | 9       | 176.44    | 334.33      | 6.56   | 67.78    | 0.02         | 0.06  |
| 4 × 4.6 × 6         | 60%    | 5                   | 2      | TT   | 9      | 9       | 257.78    | 320.78      | 6.56   | 54.22    | 0.02         | 0.04  |
| 4 × 4.6 × 6         | 60%    | 5                   | 3      | MS   | 9      | 9       | 138.22    | 346.44      | 6.56   | 79.89    | 0.03         | 0.08  |
| 4 × 4.6 × 6         | 60%    | 5                   | 3      | TT   | 9      | 9       | 229.44    | 316.33      | 6.56   | 49.78    | 0.02         | 0.06  |
| 4 × 4.6 × 6         | 60%    | 5                   | 4      | MS   | 9      | 9       | 112.44    | 339.22      | 6.56   | 72.67    | 0.04         | 0.11  |
| 4 × 4.6 × 6         | 60%    | 5                   | 4      | TT   | 9      | 9       | 187.33    | 311.00      | 6.56   | 44.44    | 0.03         | 0.06  |
| 4 × 4.6 × 6         | 60%    | 5                   | 5      | MS   | 9      | 9       | 105.33    | 345.00      | 6.56   | 78.44    | 0.05         | 0.10  |
| 4 × 4.6 × 6         | 60%    | 5                   | 5      | TT   | 9      | 9       | 185.11    | 308.22      | 6.56   | 41.67    | 0.04         | 0.08  |
| 4 × 4.6 × 6         | 60%    | 10                  | 2      | MS   | 9      | 9       | 207.33    | 404.78      | 8.89   | 89.22    | 0.03         | 0.09  |
| 4 × 4.6 × 6         | 60%    | 10                  | 2      | TT   | 9      | 9       | 314.44    | 379.44      | 8.89   | 63.89    | 0.02         | 0.06  |
| 4 × 4.6 × 6         | 60%    | 10                  | 3      | MS   | 9      | 9       | 164.44    | 403.56      | 8.89   | 88.00    | 0.05         | 0.12  |
| 4 × 4.6 × 6         | 60%    | 10                  | 3      | TT   | 9      | 9       | 285.56    | 373.78      | 8.89   | 58.22    | 0.03         | 0.08  |
| 4 × 4.6 × 6         | 60%    | 10                  | 4      | MS   | 9      | 9       | 121.44    | 412.78      | 8.89   | 97.22    | 0.06         | 0.14  |
| 4 × 4.6 × 6         | 60%    | 10                  | 4      | TT   | 9      | 9       | 233.44    | 369.22      | 8.89   | 53.67    | 0.04         | 0.07  |
| 4 × 4.6 × 6         | 60%    | 10                  | 5      | MS   | 9      | 9       | 107.56    | 397.67      | 8.89   | 82.11    | 0.08         | 0.18  |
| 4 × 4.6 × 6         | 60%    | 10                  | 5      | TT   | 9      | 9       | 231.33    | 365.33      | 8.89   | 49.78    | 0.05         | 0.11  |
| 4 × 4.6 × 6         | 80%    | 5                   | 2      | MS   | 10     | 4       | 417.60    | 826.50      | 32.50  | 146.00   | 0.13         | 1.74  |
| 4 × 4.6 × 6         | 80%    | 5                   | 2      | TT   | 10     | 10      | 606.60    | 799.40      | 32.50  | 118.90   | 0.08         | 0.21  |

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Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 4 × 4-6 × 6         | 80%    | 5                   | 3      | MS   | 10     | 4       | 282.80    | 824.50      | 32.50  | 144.00   | 0.21         | 17.83  |
| 4 × 4-6 × 6         | 80%    | 5                   | 3      | TT   | 10     | 10      | 477.80    | 792.10      | 32.50  | 111.60   | 0.12         | 0.31   |
| 4 × 4-6 × 6         | 80%    | 5                   | 4      | MS   | 10     | 8       | 225.60    | 841.70      | 32.50  | 161.00   | 0.30         | 7.27   |
| 4 × 4-6 × 6         | 80%    | 5                   | 4      | TT   | 10     | 10      | 415.50    | 784.00      | 32.50  | 103.50   | 0.18         | 0.39   |
| 4 × 4-6 × 6         | 80%    | 5                   | 5      | MS   | 10     | 9       | 188.60    | 857.30      | 32.50  | 176.80   | 0.41         | 1.44   |
| 4 × 4-6 × 6         | 80%    | 5                   | 5      | TT   | 10     | 10      | 412.50    | 777.20      | 32.50  | 96.70    | 0.23         | 0.58   |
| 4 × 4-6 × 6         | 80%    | 10                  | 2      | MS   | 10     | 2       | 538.90    | 1073.10     | 40.70  | 162.40   | 0.27         | 19.26  |
| 4 × 4-6 × 6         | 80%    | 10                  | 2      | TT   | 10     | 10      | 769.90    | 1052.60     | 40.70  | 141.90   | 0.16         | 0.54   |
| 4 × 4-6 × 6         | 80%    | 10                  | 3      | MS   | 10     | 2       | 371.70    | 1089.50     | 40.70  | 178.70   | 0.47         | 71.15  |
| 4 × 4-6 × 6         | 80%    | 10                  | 3      | TT   | 10     | 10      | 553.30    | 1043.50     | 40.70  | 132.80   | 0.27         | 0.69   |
| 4 × 4-6 × 6         | 80%    | 10                  | 4      | MS   | 10     | 2       | 290.30    | 1114.20     | 40.70  | 202.70   | 0.65         | 33.65  |
| 4 × 4-6 × 6         | 80%    | 10                  | 4      | TT   | 10     | 10      | 489.90    | 1034.90     | 40.70  | 124.20   | 0.37         | 0.81   |
| 4 × 4-6 × 6         | 80%    | 10                  | 5      | MS   | 10     | 5       | 231.20    | 1101.90     | 40.70  | 190.70   | 0.90         | 28.57  |
| 4 × 4-6 × 6         | 80%    | 10                  | 5      | TT   | 10     | 10      | 461.20    | 1028.60     | 40.70  | 117.90   | 0.46         | 1.25   |
| 4 × 4-6 × 6         | 90%    | 5                   | 2      | MS   | 10     | 0       | 586.70    | 1168.40     | 71.00  | 155.40   | 0.30         | 42.70  |
| 4 × 4-6 × 6         | 90%    | 5                   | 2      | TT   | 10     | 10      | 831.40    | 1148.20     | 71.00  | 135.20   | 0.19         | 0.53   |
| 4 × 4-6 × 6         | 90%    | 5                   | 3      | MS   | 10     | 0       | 407.30    | 1203.10     | 71.00  | 189.50   | 0.60         | 44.46  |
| 4 × 4-6 × 6         | 90%    | 5                   | 3      | TT   | 10     | 10      | 697.30    | 1140.60     | 71.00  | 127.60   | 0.32         | 0.82   |
| 4 × 4-6 × 6         | 90%    | 5                   | 4      | MS   | 10     | 2       | 307.60    | 1193.90     | 71.00  | 180.90   | 0.80         | 62.38  |
| 4 × 4-6 × 6         | 90%    | 5                   | 4      | TT   | 10     | 10      | 569.60    | 1135.00     | 71.00  | 122.00   | 0.45         | 1.13   |
| 4 × 4-6 × 6         | 90%    | 5                   | 5      | MS   | 10     | 3       | 255.30    | 1229.20     | 71.00  | 215.10   | 1.11         | 33.90  |
| 4 × 4-6 × 6         | 90%    | 5                   | 5      | TT   | 10     | 10      | 584.00    | 1131.60     | 71.00  | 118.60   | 0.60         | 1.28   |
| 4 × 4-6 × 6         | 90%    | 10                  | 2      | MS   | 10     | 0       | 707.60    | 1410.50     | 88.60  | 187.90   | 0.53         | 47.84  |
| 4 × 4-6 × 6         | 90%    | 10                  | 2      | TT   | 10     | 10      | 1023.10   | 1379.00     | 88.60  | 156.40   | 0.32         | 1.15   |
| 4 × 4-6 × 6         | 90%    | 10                  | 3      | MS   | 10     | 0       | 478.20    | 1426.00     | 88.60  | 202.60   | 0.96         | 91.12  |
| 4 × 4-6 × 6         | 90%    | 10                  | 3      | TT   | 10     | 10      | 862.30    | 1372.90     | 88.60  | 150.30   | 0.51         | 1.64   |
| 4 × 4-6 × 6         | 90%    | 10                  | 4      | MS   | 10     | 0       | 377.10    | 1463.90     | 88.60  | 240.80   | 1.46         | 40.58  |
| 4 × 4-6 × 6         | 90%    | 10                  | 4      | TT   | 10     | 10      | 764.30    | 1367.40     | 88.60  | 144.80   | 0.78         | 2.51   |
| 4 × 4-6 × 6         | 90%    | 10                  | 5      | MS   | 10     | 2       | 302.90    | 1473.60     | 88.60  | 251.00   | 1.94         | 47.99  |
| 4 × 4-6 × 6         | 90%    | 10                  | 5      | TT   | 10     | 10      | 720       | 1364.80     | 88.60  | 142.20   | 0.99         | 2.37   |
| 4 × 4-7 × 7         | 40%    | 5                   | 2      | MS   | 4      | 4       | 103.75    | 181.50      | 2.50   | 44.00    | 0.01         | 0.01   |
| 4 × 4-7 × 7         | 40%    | 5                   | 2      | TT   | 4      | 4       | 123.50    | 176.50      | 2.50   | 39.00    | 0.01         | 0.01   |
| 4 × 4-7 × 7         | 40%    | 5                   | 3      | MS   | 4      | 4       | 84.25     | 181.25      | 2.50   | 43.75    | 0.01         | 0.01   |
| 4 × 4-7 × 7         | 40%    | 5                   | 3      | TT   | 4      | 4       | 113.75    | 166.75      | 2.50   | 29.25    | 0.01         | 0.01   |
| 4 × 4-7 × 7         | 40%    | 5                   | 4      | MS   | 4      | 4       | 80.50     | 171.00      | 2.50   | 33.50    | 0.01         | 0.02   |
| 4 × 4-7 × 7         | 40%    | 5                   | 4      | TT   | 4      | 4       | 96.75     | 165.50      | 2.50   | 28.00    | 0.01         | 0.01   |
| 4 × 4-7 × 7         | 40%    | 5                   | 5      | MS   | 4      | 4       | 78.25     | 167.00      | 2.50   | 29.50    | 0.01         | 0.02   |
| 4 × 4-7 × 7         | 40%    | 5                   | 5      | TT   | 4      | 4       | 95.00     | 161.25      | 2.50   | 23.75    | 0.01         | 0.01   |
| 4 × 4-7 × 7         | 40%    | 10                  | 2      | MS   | 5      | 5       | 108.80    | 203.60      | 2.80   | 44.80    | 0.01         | 0.02   |
| 4 × 4-7 × 7         | 40%    | 10                  | 2      | TT   | 5      | 5       | 128.00    | 200.20      | 2.80   | 41.40    | 0.01         | 0.01   |
| 4 × 4-7 × 7         | 40%    | 10                  | 3      | MS   | 5      | 5       | 95.60     | 207.40      | 2.80   | 48.60    | 0.01         | 0.02   |
| 4 × 4-7 × 7         | 40%    | 10                  | 3      | TT   | 5      | 5       | 107.40    | 195.60      | 2.80   | 36.80    | 0.01         | 0.01   |
| 4 × 4-7 × 7         | 40%    | 10                  | 4      | MS   | 5      | 5       | 81.60     | 201.00      | 2.80   | 42.20    | 0.01         | 0.02   |
| 4 × 4-7 × 7         | 40%    | 10                  | 4      | TT   | 5      | 5       | 104.20    | 190.80      | 2.80   | 32.00    | 0.01         | 0.02   |
| 4 × 4-7 × 7         | 40%    | 10                  | 5      | MS   | 5      | 5       | 79.60     | 191.40      | 2.80   | 32.60    | 0.02         | 0.03   |
| 4 × 4-7 × 7         | 40%    | 10                  | 5      | TT   | 5      | 5       | 92.00     | 188.20      | 2.80   | 29.40    | 0.01         | 0.02   |
| 4 × 4-7 × 7         | 60%    | 5                   | 2      | MS   | 9      | 8       | 266.67    | 510.44      | 11.78  | 112.00   | 0.04         | 0.38   |
| 4 × 4-7 × 7         | 60%    | 5                   | 2      | TT   | 9      | 9       | 361.56    | 491.44      | 11.78  | 93.00    | 0.03         | 0.08   |
| 4 × 4-7 × 7         | 60%    | 5                   | 3      | MS   | 9      | 9       | 192.33    | 528.33      | 11.78  | 129.89   | 0.08         | 0.30   |
| 4 × 4-7 × 7         | 60%    | 5                   | 3      | TT   | 9      | 9       | 306.78    | 484.33      | 11.78  | 85.89    | 0.05         | 0.08   |
| 4 × 4-7 × 7         | 60%    | 5                   | 4      | MS   | 9      | 9       | 159.00    | 538.11      | 11.78  | 139.67   | 0.10         | 0.24   |
| 4 × 4-7 × 7         | 60%    | 5                   | 4      | TT   | 9      | 9       | 261.67    | 476.78      | 11.78  | 78.33    | 0.06         | 0.12   |
| 4 × 4-7 × 7         | 60%    | 5                   | 5      | MS   | 9      | 9       | 125.78    | 512.33      | 11.78  | 113.89   | 0.13         | 0.30   |
| 4 × 4-7 × 7         | 60%    | 5                   | 5      | TT   | 9      | 9       | 251.89    | 474.11      | 11.78  | 75.67    | 0.08         | 0.16   |
| 4 × 4-7 × 7         | 60%    | 10                  | 2      | MS   | 10     | 8       | 297.20    | 581.90      | 14.20  | 117.60   | 0.06         | 0.40   |
| 4 × 4-7 × 7         | 60%    | 10                  | 2      | TT   | 10     | 10      | 405.70    | 564.20      | 14.20  | 100      | 0.04         | 0.11   |
| 4 × 4-7 × 7         | 60%    | 10                  | 3      | MS   | 10     | 8       | 213.50    | 594.70      | 14.20  | 130.50   | 0.10         | 0.47   |
| 4 × 4-7 × 7         | 60%    | 10                  | 3      | TT   | 10     | 10      | 342.10    | 556.50      | 14.20  | 92.30    | 0.06         | 0.13   |
| 4 × 4-7 × 7         | 60%    | 10                  | 4      | MS   | 10     | 10      | 167.70    | 594.30      | 14.20  | 130.10   | 0.13         | 0.39   |
| 4 × 4-7 × 7         | 60%    | 10                  | 4      | TT   | 10     | 10      | 301.20    | 551.90      | 14.20  | 87.70    | 0.09         | 0.18   |
| 4 × 4-7 × 7         | 60%    | 10                  | 5      | MS   | 10     | 10      | 149.60    | 614.70      | 14.20  | 150.50   | 0.18         | 0.45   |
| 4 × 4-7 × 7         | 60%    | 10                  | 5      | TT   | 10     | 10      | 264.80    | 548.70      | 14.20  | 84.50    | 0.10         | 0.26   |
| 4 × 4-7 × 7         | 80%    | 5                   | 2      | MS   | 10     | 1       | 511.70    | 1015.00     | 35.70  | 175.20   | 0.22         | 68.28  |
| 4 × 4-7 × 7         | 80%    | 5                   | 2      | TT   | 10     | 10      | 702.80    | 982.10      | 35.70  | 142.40   | 0.12         | 0.38   |
| 4 × 4-7 × 7         | 80%    | 5                   | 3      | MS   | 10     | 1       | 349.70    | 1028.80     | 35.70  | 189.00   | 0.38         | 39.46  |
| 4 × 4-7 × 7         | 80%    | 5                   | 3      | TT   | 10     | 10      | 542.40    | 972.70      | 35.70  | 133.00   | 0.20         | 0.28   |
| 4 × 4-7 × 7         | 80%    | 5                   | 4      | MS   | 10     | 3       | 274.70    | 1054.90     | 35.70  | 215.10   | 0.48         | 11.48  |
| 4 × 4-7 × 7         | 80%    | 5                   | 4      | TT   | 10     | 10      | 460.30    | 967.90      | 35.70  | 128.20   | 0.28         | 0.56   |
| 4 × 4-7 × 7         | 80%    | 5                   | 5      | MS   | 10     | 7       | 220.70    | 1035.50     | 35.70  | 195.60   | 0.69         | 10.79  |
| 4 × 4-7 × 7         | 80%    | 5                   | 5      | TT   | 10     | 10      | 371.20    | 961.50      | 35.70  | 121.80   | 0.38         | 0.80   |
| 4 × 4-7 × 7         | 80%    | 10                  | 2      | MS   | 10     | 0       | 674.40    | 1342.70     | 46.40  | 216.10   | 0.45         | 61.72  |
| 4 × 4-7 × 7         | 80%    | 10                  | 2      | TT   | 10     | 10      | 983.00    | 1305.30     | 46.40  | 178.90   | 0.28         | 1.25   |
| 4 × 4-7 × 7         | 80%    | 10                  | 3      | MS   | 10     | 0       | 456.00    | 1360.90     | 46.40  | 233.30   | 0.83         | 121.02 |
| 4 × 4-7 × 7         | 80%    | 10                  | 3      | TT   | 10     | 10      | 744.90    | 1297.30     | 46.40  | 170.90   | 0.45         | 2.10   |

(continued on next page)

Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 4 × 4-7 × 7         | 80%    | 10                  | 4      | MS   | 10     | 2       | 349.20    | 1376.60     | 46.40  | 250.20   | 1.15         | 63.99  |
| 4 × 4-7 × 7         | 80%    | 10                  | 4      | TT   | 10     | 10      | 646.40    | 1288.70     | 46.40  | 162.30   | 0.62         | 2.50   |
| 4 × 4-7 × 7         | 80%    | 10                  | 5      | MS   | 10     | 2       | 286.30    | 1392.90     | 46.40  | 266.40   | 1.64         | 51.18  |
| 4 × 4-7 × 7         | 80%    | 10                  | 5      | TT   | 10     | 10      | 507.00    | 1281.10     | 46.40  | 154.70   | 0.86         | 2.68   |
| 4 × 4-7 × 7         | 90%    | 5                   | 2      | MS   | 10     | 0       | 787.10    | 1570.40     | 91.20  | 231.20   | 0.69         | 28.58  |
| 4 × 4-7 × 7         | 90%    | 5                   | 2      | TT   | 10     | 10      | 1089.90   | 1525.90     | 91.20  | 186.70   | 0.41         | 1.82   |
| 4 × 4-7 × 7         | 90%    | 5                   | 3      | MS   | 10     | 0       | 535.40    | 1594.00     | 91.20  | 254.80   | 1.26         | 105.14 |
| 4 × 4-7 × 7         | 90%    | 5                   | 3      | TT   | 10     | 10      | 856.40    | 1515.70     | 91.20  | 176.50   | 0.66         | 1.94   |
| 4 × 4-7 × 7         | 90%    | 5                   | 4      | MS   | 10     | 0       | 407.90    | 1617.10     | 91.20  | 277.90   | 1.82         | 49.15  |
| 4 × 4-7 × 7         | 90%    | 5                   | 4      | TT   | 10     | 10      | 792.10    | 1510.20     | 91.20  | 171.00   | 0.96         | 2.92   |
| 4 × 4-7 × 7         | 90%    | 5                   | 5      | MS   | 10     | 0       | 334.40    | 1628.10     | 91.20  | 287.10   | 2.68         | 124.37 |
| 4 × 4-7 × 7         | 90%    | 5                   | 5      | TT   | 10     | 10      | 738.50    | 1504.60     | 91.20  | 165.40   | 1.28         | 3.14   |
| 4 × 4-7 × 7         | 90%    | 10                  | 2      | MS   | 10     | 0       | 996.60    | 1990        | 125.50 | 268.50   | 1.54         | 98.20  |
| 4 × 4-7 × 7         | 90%    | 10                  | 2      | TT   | 10     | 10      | 1373.10   | 1945.10     | 125.50 | 223.60   | 0.73         | 5.42   |
| 4 × 4-7 × 7         | 90%    | 10                  | 3      | MS   | 10     | 0       | 678.80    | 2028.40     | 125.50 | 306.80   | 3.28         | 107.80 |
| 4 × 4-7 × 7         | 90%    | 10                  | 3      | TT   | 10     | 10      | 1124.00   | 1936.90     | 125.50 | 215.40   | 1.42         | 8.90   |
| 4 × 4-7 × 7         | 90%    | 10                  | 4      | MS   | 10     | 0       | 523.50    | 2074.70     | 125.50 | 353.20   | 4.75         | 75.38  |
| 4 × 4-7 × 7         | 90%    | 10                  | 4      | TT   | 10     | 10      | 919.80    | 1930.70     | 125.50 | 209.20   | 2.27         | 11.64  |
| 4 × 4-7 × 7         | 90%    | 10                  | 5      | MS   | 10     | 0       | 426.20    | 2110.80     | 125.50 | 388.90   | 7.17         | 85.84  |
| 4 × 4-7 × 7         | 90%    | 10                  | 5      | TT   | 10     | 10      | 907.20    | 1925.30     | 125.50 | 203.80   | 3.04         | 14.66  |
| 4 × 4-8 × 8         | 40%    | 5                   | 2      | MS   | 3      | 3       | 165.67    | 272.33      | 4.67   | 87.67    | 0.01         | 0.02   |
| 4 × 4-8 × 8         | 40%    | 5                   | 2      | TT   | 3      | 3       | 205.00    | 252.33      | 4.67   | 67.67    | 0.01         | 0.02   |
| 4 × 4-8 × 8         | 40%    | 5                   | 3      | MS   | 3      | 3       | 107.67    | 272.00      | 4.67   | 87.33    | 0.01         | 0.01   |
| 4 × 4-8 × 8         | 40%    | 5                   | 3      | TT   | 3      | 3       | 141.33    | 242.00      | 4.67   | 57.33    | 0.01         | 0.02   |
| 4 × 4-8 × 8         | 40%    | 5                   | 4      | MS   | 3      | 3       | 90        | 251.67      | 4.67   | 67.00    | 0.02         | 0.02   |
| 4 × 4-8 × 8         | 40%    | 5                   | 4      | TT   | 3      | 3       | 111.33    | 228.67      | 4.67   | 44.00    | 0.01         | 0.02   |
| 4 × 4-8 × 8         | 40%    | 5                   | 5      | MS   | 3      | 3       | 81.00     | 223.00      | 4.67   | 38.33    | 0.02         | 0.03   |
| 4 × 4-8 × 8         | 40%    | 5                   | 5      | TT   | 3      | 3       | 102.33    | 215.67      | 4.67   | 31.00    | 0.01         | 0.04   |
| 4 × 4-8 × 8         | 40%    | 10                  | 2      | MS   | 4      | 4       | 154.75    | 267.75      | 5.25   | 82.50    | 0.01         | 0.01   |
| 4 × 4-8 × 8         | 40%    | 10                  | 2      | TT   | 4      | 4       | 197.50    | 254.25      | 5.25   | 69.00    | 0.01         | 0.01   |
| 4 × 4-8 × 8         | 40%    | 10                  | 3      | MS   | 4      | 4       | 114.25    | 286.25      | 5.25   | 101.00   | 0.01         | 0.03   |
| 4 × 4-8 × 8         | 40%    | 10                  | 3      | TT   | 4      | 4       | 148.50    | 244.00      | 5.25   | 58.75    | 0.01         | 0.02   |
| 4 × 4-8 × 8         | 40%    | 10                  | 4      | MS   | 4      | 4       | 91.25     | 258.00      | 5.25   | 72.75    | 0.02         | 0.03   |
| 4 × 4-8 × 8         | 40%    | 10                  | 4      | TT   | 4      | 4       | 123.50    | 234.00      | 5.25   | 48.75    | 0.02         | 0.03   |
| 4 × 4-8 × 8         | 40%    | 10                  | 5      | MS   | 4      | 4       | 84.50     | 229.75      | 5.25   | 44.50    | 0.03         | 0.05   |
| 4 × 4-8 × 8         | 40%    | 10                  | 5      | TT   | 4      | 4       | 118.25    | 223.75      | 5.25   | 38.50    | 0.02         | 0.03   |
| 4 × 4-8 × 8         | 60%    | 5                   | 2      | MS   | 10     | 9       | 318.40    | 627.00      | 12.20  | 140.80   | 0.07         | 4.10   |
| 4 × 4-8 × 8         | 60%    | 5                   | 2      | TT   | 10     | 10      | 475.50    | 598.70      | 12.20  | 112.50   | 0.04         | 0.13   |
| 4 × 4-8 × 8         | 60%    | 5                   | 3      | MS   | 10     | 9       | 223.90    | 644.00      | 12.20  | 157.50   | 0.12         | 0.75   |
| 4 × 4-8 × 8         | 60%    | 5                   | 3      | TT   | 10     | 10      | 381.40    | 587.70      | 12.20  | 101.50   | 0.07         | 0.16   |
| 4 × 4-8 × 8         | 60%    | 5                   | 4      | MS   | 10     | 9       | 182.60    | 652.40      | 12.20  | 166.10   | 0.15         | 0.82   |
| 4 × 4-8 × 8         | 60%    | 5                   | 4      | TT   | 10     | 10      | 329.20    | 579.50      | 12.20  | 93.30    | 0.09         | 0.22   |
| 4 × 4-8 × 8         | 60%    | 5                   | 5      | MS   | 10     | 10      | 150.40    | 653.00      | 12.20  | 166.80   | 0.20         | 0.62   |
| 4 × 4-8 × 8         | 60%    | 5                   | 5      | TT   | 10     | 10      | 282.90    | 572.30      | 12.20  | 86.10    | 0.12         | 0.31   |
| 4 × 4-8 × 8         | 60%    | 10                  | 2      | MS   | 9      | 6       | 363.78    | 720.22      | 14.22  | 152.67   | 0.09         | 32.50  |
| 4 × 4-8 × 8         | 60%    | 10                  | 2      | TT   | 9      | 9       | 519.22    | 690         | 14.22  | 122.44   | 0.05         | 0.14   |
| 4 × 4-8 × 8         | 60%    | 10                  | 3      | MS   | 9      | 6       | 257.78    | 745.22      | 14.22  | 177.67   | 0.15         | 0.64   |
| 4 × 4-8 × 8         | 60%    | 10                  | 3      | TT   | 9      | 9       | 489.67    | 680.78      | 14.22  | 113.22   | 0.09         | 0.20   |
| 4 × 4-8 × 8         | 60%    | 10                  | 4      | MS   | 9      | 8       | 195.67    | 738.67      | 14.22  | 171.00   | 0.19         | 1.19   |
| 4 × 4-8 × 8         | 60%    | 10                  | 4      | TT   | 9      | 9       | 387.44    | 672.56      | 14.22  | 105.00   | 0.12         | 0.25   |
| 4 × 4-8 × 8         | 60%    | 10                  | 5      | MS   | 9      | 9       | 168.11    | 735.33      | 14.22  | 167.78   | 0.27         | 0.65   |
| 4 × 4-8 × 8         | 60%    | 10                  | 5      | TT   | 9      | 9       | 352.56    | 665.33      | 14.22  | 97.78    | 0.15         | 0.28   |
| 4 × 4-8 × 8         | 80%    | 5                   | 2      | MS   | 10     | 0       | 646.50    | 1290.30     | 47.70  | 222.50   | 0.37         | 33.40  |
| 4 × 4-8 × 8         | 80%    | 5                   | 2      | TT   | 10     | 10      | 992.40    | 1262.40     | 47.70  | 194.70   | 0.23         | 0.86   |
| 4 × 4-8 × 8         | 80%    | 5                   | 3      | MS   | 10     | 0       | 446.80    | 1328.90     | 47.70  | 260.80   | 0.64         | 22.82  |
| 4 × 4-8 × 8         | 80%    | 5                   | 3      | TT   | 10     | 10      | 727.70    | 1251.30     | 47.70  | 183.60   | 0.38         | 1.28   |
| 4 × 4-8 × 8         | 80%    | 5                   | 4      | MS   | 10     | 1       | 337.00    | 1326.70     | 47.70  | 256.60   | 0.94         | 78.74  |
| 4 × 4-8 × 8         | 80%    | 5                   | 4      | TT   | 10     | 10      | 627.50    | 1240.20     | 47.70  | 172.50   | 0.54         | 1.25   |
| 4 × 4-8 × 8         | 80%    | 5                   | 5      | MS   | 10     | 2       | 278.30    | 1340.70     | 47.70  | 273.00   | 1.29         | 47.23  |
| 4 × 4-8 × 8         | 80%    | 5                   | 5      | TT   | 10     | 10      | 540       | 1227.60     | 47.70  | 159.90   | 0.64         | 2.31   |
| 4 × 4-8 × 8         | 80%    | 10                  | 2      | MS   | 3      | 0       | 654.33    | 1303.67     | 39.00  | 244.67   | 0.38         | 8.00   |
| 4 × 4-8 × 8         | 80%    | 10                  | 2      | TT   | 3      | 3       | 890       | 1271.00     | 39.00  | 212.00   | 0.23         | 0.75   |
| 4 × 4-8 × 8         | 80%    | 10                  | 3      | MS   | 3      | 0       | 446.67    | 1323.67     | 39.00  | 264.67   | 0.63         | 5.54   |
| 4 × 4-8 × 8         | 80%    | 10                  | 3      | TT   | 3      | 3       | 617.33    | 1263.67     | 39.00  | 204.67   | 0.37         | 1.19   |
| 4 × 4-8 × 8         | 80%    | 10                  | 4      | MS   | 3      | 0       | 343.00    | 1355.33     | 39.00  | 291.00   | 0.94         | 106.50 |
| 4 × 4-8 × 8         | 80%    | 10                  | 4      | TT   | 3      | 3       | 644.00    | 1252.33     | 39.00  | 193.33   | 0.53         | 1.31   |
| 4 × 4-8 × 8         | 80%    | 10                  | 5      | MS   | 3      | 0       | 288.33    | 1381.67     | 39.00  | 322.67   | 1.21         | 44.20  |
| 4 × 4-8 × 8         | 80%    | 10                  | 5      | TT   | 3      | 3       | 514.67    | 1240.33     | 39.00  | 181.33   | 0.67         | 1.88   |
| 4 × 4-8 × 8         | 90%    | 5                   | 2      | MS   | 10     | 0       | 1080.20   | 2158.40     | 134.00 | 320.40   | 2.11         | 96.31  |
| 4 × 4-8 × 8         | 90%    | 5                   | 2      | TT   | 10     | 10      | 1541.90   | 2092.60     | 134.00 | 254.60   | 0.98         | 6.25   |
| 4 × 4-8 × 8         | 90%    | 5                   | 3      | MS   | 10     | 0       | 731.50    | 2191.50     | 134.00 | 353.30   | 3.45         | 89.25  |
| 4 × 4-8 × 8         | 90%    | 5                   | 3      | TT   | 10     | 10      | 1306.30   | 2081.90     | 134.00 | 243.90   | 1.65         | 7.88   |
| 4 × 4-8 × 8         | 90%    | 5                   | 4      | MS   | 10     | 0       | 561.00    | 2227.40     | 134.00 | 389.40   | 5.35         | 134.57 |
| 4 × 4-8 × 8         | 90%    | 5                   | 4      | TT   | 10     | 10      | 964.50    | 2071.50     | 134.00 | 233.50   | 2.49         | 9.01   |

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Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 4 × 4-8 × 8         | 90%    | 5                   | 5      | MS   | 10     | 0       | 455.80    | 2259.60     | 134.00 | 420.60   | 7.30         | 184.94 |
| 4 × 4-8 × 8         | 90%    | 5                   | 5      | TT   | 10     | 10      | 864.30    | 2065.40     | 134.00 | 227.40   | 3.56         | 14.00  |
| 4 × 4-8 × 8         | 90%    | 10                  | 2      | MS   | 9      | 0       | 1342.67   | 2683.33     | 170.11 | 386.56   | 4.17         | 183.84 |
| 4 × 4-8 × 8         | 90%    | 10                  | 2      | TT   | 9      | 9       | 1913.56   | 2600.89     | 170.11 | 304.11   | 1.89         | 16.21  |
| 4 × 4-8 × 8         | 90%    | 10                  | 3      | MS   | 9      | 0       | 910.67    | 2723.44     | 170.11 | 426.56   | 8.31         | 146.70 |
| 4 × 4-8 × 8         | 90%    | 10                  | 3      | TT   | 9      | 9       | 1535.89   | 2589.56     | 170.11 | 292.78   | 3.62         | 17.43  |
| 4 × 4-8 × 8         | 90%    | 10                  | 4      | MS   | 9      | 0       | 683.44    | 2724.33     | 170.11 | 426.00   | 12.50        | 184.45 |
| 4 × 4-8 × 8         | 90%    | 10                  | 4      | TT   | 9      | 9       | 1422.67   | 2579.22     | 170.11 | 282.44   | 5.88         | 25.53  |
| 4 × 4-8 × 8         | 90%    | 10                  | 5      | MS   | 9      | 0       | 567.44    | 2815.89     | 170.11 | 519.11   | 16.33        | 193.50 |
| 4 × 4-8 × 8         | 90%    | 10                  | 5      | TT   | 9      | 9       | 1230.33   | 2572.89     | 170.11 | 276.11   | 8.89         | 33.63  |
| 5 × 5-2 × 2         | 60%    | 5                   | 2      | MS   | 3      | 3       | 92.67     | 159.00      | 4.33   | 14.67    | 0.01         | 0.01   |
| 5 × 5-2 × 2         | 60%    | 5                   | 2      | TT   | 3      | 3       | 93.67     | 159.00      | 4.33   | 14.67    | 0.01         | 0.01   |
| 5 × 5-2 × 2         | 60%    | 5                   | 3      | MS   | 3      | 3       | 72.67     | 161.00      | 4.33   | 16.67    | 0.01         | 0.01   |
| 5 × 5-2 × 2         | 60%    | 5                   | 3      | TT   | 3      | 3       | 93.67     | 158.67      | 4.33   | 14.33    | 0.01         | 0.01   |
| 5 × 5-2 × 2         | 60%    | 5                   | 4      | MS   | 3      | 3       | 72.33     | 160.67      | 4.33   | 16.33    | 0.01         | 0.01   |
| 5 × 5-2 × 2         | 60%    | 5                   | 4      | TT   | 3      | 3       | 92.33     | 158.33      | 4.33   | 14.00    | 0.01         | 0.01   |
| 5 × 5-2 × 2         | 60%    | 5                   | 5      | MS   | 3      | 3       | 68.33     | 156.00      | 4.33   | 11.67    | 0.01         | 0.02   |
| 5 × 5-2 × 2         | 60%    | 5                   | 5      | TT   | 3      | 3       | 89.67     | 155.33      | 4.33   | 11.00    | 0.01         | 0.02   |
| 5 × 5-2 × 2         | 60%    | 10                  | 2      | MS   | 6      | 6       | 100.67    | 170         | 4.17   | 15.83    | 0.01         | 0.01   |
| 5 × 5-2 × 2         | 60%    | 10                  | 2      | TT   | 6      | 6       | 112.33    | 166.83      | 4.17   | 12.67    | 0.01         | 0.01   |
| 5 × 5-2 × 2         | 60%    | 10                  | 3      | MS   | 6      | 6       | 75.50     | 176.50      | 4.17   | 19.50    | 0.01         | 0.01   |
| 5 × 5-2 × 2         | 60%    | 10                  | 3      | TT   | 6      | 6       | 111.67    | 166.17      | 4.17   | 12.00    | 0.01         | 0.01   |
| 5 × 5-2 × 2         | 60%    | 10                  | 4      | MS   | 6      | 6       | 75.00     | 176.00      | 4.17   | 18.33    | 0.01         | 0.02   |
| 5 × 5-2 × 2         | 60%    | 10                  | 4      | TT   | 6      | 6       | 110.67    | 165.67      | 4.17   | 11.50    | 0.01         | 0.01   |
| 5 × 5-2 × 2         | 60%    | 10                  | 5      | MS   | 6      | 6       | 71.83     | 171.83      | 4.17   | 14.17    | 0.02         | 0.03   |
| 5 × 5-2 × 2         | 60%    | 10                  | 5      | TT   | 6      | 6       | 97.50     | 162.67      | 4.17   | 8.50     | 0.01         | 0.02   |
| 5 × 5-2 × 2         | 80%    | 5                   | 2      | MS   | 10     | 10      | 192.20    | 346.50      | 16.90  | 39.70    | 0.02         | 0.05   |
| 5 × 5-2 × 2         | 80%    | 5                   | 2      | TT   | 10     | 10      | 251.60    | 332.40      | 16.90  | 27.50    | 0.02         | 0.03   |
| 5 × 5-2 × 2         | 80%    | 5                   | 3      | MS   | 10     | 10      | 138.00    | 342.30      | 16.90  | 34.30    | 0.03         | 0.08   |
| 5 × 5-2 × 2         | 80%    | 5                   | 3      | TT   | 10     | 10      | 244.00    | 330.60      | 16.90  | 25.70    | 0.02         | 0.04   |
| 5 × 5-2 × 2         | 80%    | 5                   | 4      | MS   | 10     | 10      | 110.90    | 343.00      | 16.90  | 36.80    | 0.05         | 0.11   |
| 5 × 5-2 × 2         | 80%    | 5                   | 4      | TT   | 10     | 10      | 181.80    | 328.50      | 16.90  | 23.60    | 0.03         | 0.06   |
| 5 × 5-2 × 2         | 80%    | 5                   | 5      | MS   | 10     | 10      | 88.40     | 340.90      | 16.90  | 32.80    | 0.06         | 0.13   |
| 5 × 5-2 × 2         | 80%    | 5                   | 5      | TT   | 10     | 10      | 167.60    | 326.70      | 16.90  | 21.80    | 0.04         | 0.07   |
| 5 × 5-2 × 2         | 80%    | 10                  | 2      | MS   | 10     | 10      | 211.90    | 396.40      | 20.20  | 40.20    | 0.03         | 0.48   |
| 5 × 5-2 × 2         | 80%    | 10                  | 2      | TT   | 10     | 10      | 292.60    | 388.20      | 20.20  | 32.00    | 0.02         | 0.04   |
| 5 × 5-2 × 2         | 80%    | 10                  | 3      | MS   | 10     | 10      | 154.00    | 399.70      | 20.20  | 43.50    | 0.05         | 0.13   |
| 5 × 5-2 × 2         | 80%    | 10                  | 3      | TT   | 10     | 10      | 263.60    | 386.60      | 20.20  | 30.40    | 0.03         | 0.05   |
| 5 × 5-2 × 2         | 80%    | 10                  | 4      | MS   | 10     | 10      | 127.90    | 399.00      | 20.20  | 42.80    | 0.06         | 0.15   |
| 5 × 5-2 × 2         | 80%    | 10                  | 4      | TT   | 10     | 10      | 249.80    | 384.30      | 20.20  | 28.10    | 0.04         | 0.07   |
| 5 × 5-2 × 2         | 80%    | 10                  | 5      | MS   | 10     | 10      | 97.60     | 398.20      | 20.20  | 42.00    | 0.08         | 0.17   |
| 5 × 5-2 × 2         | 80%    | 10                  | 5      | TT   | 10     | 10      | 198.30    | 380.90      | 20.20  | 24.70    | 0.05         | 0.09   |
| 5 × 5-2 × 2         | 90%    | 5                   | 2      | MS   | 10     | 10      | 246.20    | 470.10      | 40.40  | 48.40    | 0.04         | 0.09   |
| 5 × 5-2 × 2         | 90%    | 5                   | 2      | TT   | 10     | 10      | 352.30    | 455.40      | 40.40  | 37.00    | 0.03         | 0.06   |
| 5 × 5-2 × 2         | 90%    | 5                   | 3      | MS   | 10     | 10      | 181.40    | 473.30      | 40.40  | 48.60    | 0.06         | 0.15   |
| 5 × 5-2 × 2         | 90%    | 5                   | 3      | TT   | 10     | 10      | 301.60    | 452.60      | 40.40  | 34.20    | 0.04         | 0.07   |
| 5 × 5-2 × 2         | 90%    | 5                   | 4      | MS   | 10     | 10      | 136.10    | 466.80      | 40.40  | 45.90    | 0.08         | 0.19   |
| 5 × 5-2 × 2         | 90%    | 5                   | 4      | TT   | 10     | 10      | 238.90    | 448.30      | 40.40  | 29.90    | 0.05         | 0.08   |
| 5 × 5-2 × 2         | 90%    | 5                   | 5      | MS   | 10     | 10      | 124.90    | 474.20      | 40.40  | 45.80    | 0.11         | 0.20   |
| 5 × 5-2 × 2         | 90%    | 5                   | 5      | TT   | 10     | 10      | 216.20    | 445.50      | 40.40  | 27.10    | 0.07         | 0.13   |
| 5 × 5-2 × 2         | 90%    | 10                  | 2      | MS   | 10     | 10      | 248.50    | 477.70      | 42.70  | 45.00    | 0.04         | 0.14   |
| 5 × 5-2 × 2         | 90%    | 10                  | 2      | TT   | 10     | 10      | 375.70    | 465.90      | 42.70  | 33.20    | 0.03         | 0.05   |
| 5 × 5-2 × 2         | 90%    | 10                  | 3      | MS   | 10     | 10      | 182.40    | 490.50      | 42.70  | 52.60    | 0.06         | 0.15   |
| 5 × 5-2 × 2         | 90%    | 10                  | 3      | TT   | 10     | 10      | 300.10    | 465.00      | 42.70  | 32.30    | 0.04         | 0.06   |
| 5 × 5-2 × 2         | 90%    | 10                  | 4      | MS   | 10     | 10      | 138.40    | 482.90      | 42.70  | 50       | 0.09         | 0.20   |
| 5 × 5-2 × 2         | 90%    | 10                  | 4      | TT   | 10     | 10      | 258.80    | 461.00      | 42.70  | 28.30    | 0.06         | 0.09   |
| 5 × 5-2 × 2         | 90%    | 10                  | 5      | MS   | 10     | 10      | 130.60    | 492.30      | 42.70  | 49.10    | 0.13         | 0.24   |
| 5 × 5-2 × 2         | 90%    | 10                  | 5      | TT   | 10     | 10      | 225.90    | 458.70      | 42.70  | 26.00    | 0.07         | 0.11   |
| 5 × 5-3 × 3         | 40%    | 5                   | 2      | MS   | 3      | 3       | 77.33     | 153.00      | 2.33   | 30.67    | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 5                   | 2      | TT   | 3      | 3       | 77.33     | 150.33      | 2.33   | 28.00    | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 5                   | 3      | MS   | 3      | 3       | 75.67     | 147.67      | 2.33   | 25.33    | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 5                   | 3      | TT   | 3      | 3       | 76.33     | 146.33      | 2.33   | 24.00    | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 5                   | 4      | MS   | 3      | 3       | 71.33     | 140.67      | 2.33   | 18.33    | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 5                   | 4      | TT   | 3      | 3       | 71.33     | 140.67      | 2.33   | 18.33    | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 5                   | 5      | MS   | 3      | 3       | 71.33     | 139.67      | 2.33   | 17.33    | 0.01         | 0.02   |
| 5 × 5-3 × 3         | 40%    | 5                   | 5      | TT   | 3      | 3       | 71.33     | 139.00      | 2.33   | 16.67    | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 10                  | 2      | MS   | 4      | 4       | 77.50     | 151.25      | 2.50   | 28.75    | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 10                  | 2      | TT   | 4      | 4       | 77.50     | 149.25      | 2.50   | 26.75    | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 10                  | 3      | MS   | 4      | 4       | 74.25     | 144.75      | 2.50   | 22.25    | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 10                  | 3      | TT   | 4      | 4       | 74.25     | 144.75      | 2.50   | 22.25    | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 10                  | 4      | MS   | 4      | 4       | 72.00     | 142.50      | 2.50   | 20       | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 10                  | 4      | TT   | 4      | 4       | 72.75     | 140.25      | 2.50   | 17.75    | 0.01         | 0.01   |
| 5 × 5-3 × 3         | 40%    | 10                  | 5      | MS   | 4      | 4       | 72.00     | 141.75      | 2.50   | 19.25    | 0.01         | 0.02   |

(continued on next page)

Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |       |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|-------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best  |
| 5 × 5-3 × 3         | 40%    | 10                  | 5      | TT   | 4      | 4       | 72.75     | 139.00      | 2.50   | 16.50    | 0.01         | 0.01  |
| 5 × 5-3 × 3         | 60%    | 5                   | 2      | MS   | 10     | 10      | 160.40    | 285.30      | 5.60   | 39.70    | 0.02         | 0.05  |
| 5 × 5-3 × 3         | 60%    | 5                   | 2      | TT   | 10     | 10      | 201.40    | 277.50      | 5.60   | 31.90    | 0.01         | 0.02  |
| 5 × 5-3 × 3         | 60%    | 5                   | 3      | MS   | 10     | 10      | 116.40    | 284.50      | 5.60   | 38.90    | 0.02         | 0.05  |
| 5 × 5-3 × 3         | 60%    | 5                   | 3      | TT   | 10     | 10      | 177.50    | 272.70      | 5.60   | 27.10    | 0.02         | 0.03  |
| 5 × 5-3 × 3         | 60%    | 5                   | 4      | MS   | 10     | 10      | 92.00     | 284.30      | 5.60   | 38.70    | 0.04         | 0.08  |
| 5 × 5-3 × 3         | 60%    | 5                   | 4      | TT   | 10     | 10      | 155.70    | 269.30      | 5.60   | 23.70    | 0.02         | 0.04  |
| 5 × 5-3 × 3         | 60%    | 5                   | 5      | MS   | 10     | 10      | 79.70     | 280.50      | 5.60   | 34.90    | 0.05         | 0.09  |
| 5 × 5-3 × 3         | 60%    | 5                   | 5      | TT   | 10     | 10      | 155.50    | 268.40      | 5.60   | 22.80    | 0.03         | 0.06  |
| 5 × 5-3 × 3         | 60%    | 10                  | 2      | MS   | 10     | 10      | 191.00    | 359.20      | 8.00   | 45.20    | 0.03         | 0.08  |
| 5 × 5-3 × 3         | 60%    | 10                  | 2      | TT   | 10     | 10      | 238.90    | 350.30      | 8.00   | 36.30    | 0.02         | 0.04  |
| 5 × 5-3 × 3         | 60%    | 10                  | 3      | MS   | 10     | 10      | 138.20    | 362.30      | 8.00   | 48.20    | 0.04         | 0.09  |
| 5 × 5-3 × 3         | 60%    | 10                  | 3      | TT   | 10     | 10      | 237.70    | 347.00      | 8.00   | 33.00    | 0.03         | 0.05  |
| 5 × 5-3 × 3         | 60%    | 10                  | 4      | MS   | 10     | 10      | 115.80    | 359.90      | 8.00   | 45.90    | 0.05         | 0.12  |
| 5 × 5-3 × 3         | 60%    | 10                  | 4      | TT   | 10     | 10      | 215.40    | 342.60      | 8.00   | 28.60    | 0.03         | 0.07  |
| 5 × 5-3 × 3         | 60%    | 10                  | 5      | MS   | 10     | 10      | 100.20    | 390.80      | 8.00   | 60.40    | 0.07         | 0.14  |
| 5 × 5-3 × 3         | 60%    | 10                  | 5      | TT   | 10     | 10      | 207.70    | 341.30      | 8.00   | 27.30    | 0.04         | 0.09  |
| 5 × 5-3 × 3         | 80%    | 5                   | 2      | MS   | 10     | 6       | 335.10    | 660.80      | 28.30  | 74.50    | 0.10         | 0.56  |
| 5 × 5-3 × 3         | 80%    | 5                   | 2      | TT   | 10     | 10      | 482.00    | 645.40      | 28.30  | 59.10    | 0.06         | 0.14  |
| 5 × 5-3 × 3         | 80%    | 5                   | 3      | MS   | 10     | 6       | 236.30    | 671.10      | 28.30  | 84.60    | 0.16         | 1.15  |
| 5 × 5-3 × 3         | 80%    | 5                   | 3      | TT   | 10     | 10      | 421.20    | 640.80      | 28.30  | 54.50    | 0.09         | 0.15  |
| 5 × 5-3 × 3         | 80%    | 5                   | 4      | MS   | 10     | 8       | 186.70    | 685.10      | 28.30  | 92.00    | 0.21         | 28.82 |
| 5 × 5-3 × 3         | 80%    | 5                   | 4      | TT   | 10     | 10      | 330.10    | 637.10      | 28.30  | 50.80    | 0.13         | 0.24  |
| 5 × 5-3 × 3         | 80%    | 5                   | 5      | MS   | 10     | 10      | 152.10    | 680         | 28.30  | 88.10    | 0.30         | 1.68  |
| 5 × 5-3 × 3         | 80%    | 5                   | 5      | TT   | 10     | 10      | 314.50    | 633.70      | 28.30  | 47.40    | 0.17         | 0.35  |
| 5 × 5-3 × 3         | 80%    | 10                  | 2      | MS   | 10     | 2       | 399.60    | 790.70      | 35.50  | 94.80    | 0.13         | 6.25  |
| 5 × 5-3 × 3         | 80%    | 10                  | 2      | TT   | 10     | 10      | 616.40    | 766.80      | 35.50  | 71.30    | 0.08         | 0.16  |
| 5 × 5-3 × 3         | 80%    | 10                  | 3      | MS   | 10     | 3       | 285.20    | 807.10      | 35.50  | 109.40   | 0.22         | 12.56 |
| 5 × 5-3 × 3         | 80%    | 10                  | 3      | TT   | 10     | 10      | 454.70    | 761.00      | 35.50  | 65.50    | 0.13         | 0.21  |
| 5 × 5-3 × 3         | 80%    | 10                  | 4      | MS   | 10     | 6       | 218.80    | 806.80      | 35.50  | 111.30   | 0.29         | 2.33  |
| 5 × 5-3 × 3         | 80%    | 10                  | 4      | TT   | 10     | 10      | 468.00    | 757.20      | 35.50  | 61.70    | 0.17         | 0.30  |
| 5 × 5-3 × 3         | 80%    | 10                  | 5      | MS   | 10     | 9       | 173.40    | 791.60      | 35.50  | 94.30    | 0.41         | 3.21  |
| 5 × 5-3 × 3         | 80%    | 10                  | 5      | TT   | 10     | 10      | 391.30    | 754.00      | 35.50  | 58.50    | 0.23         | 0.44  |
| 5 × 5-3 × 3         | 90%    | 5                   | 2      | MS   | 10     | 0       | 473.50    | 944.70      | 78.60  | 92.10    | 0.19         | 42.60 |
| 5 × 5-3 × 3         | 90%    | 5                   | 2      | TT   | 10     | 10      | 656.30    | 929.80      | 78.60  | 77.20    | 0.10         | 0.18  |
| 5 × 5-3 × 3         | 90%    | 5                   | 3      | MS   | 10     | 0       | 322.60    | 953.90      | 78.60  | 101.30   | 0.31         | 12.49 |
| 5 × 5-3 × 3         | 90%    | 5                   | 3      | TT   | 10     | 10      | 521.00    | 925.90      | 78.60  | 73.30    | 0.17         | 0.26  |
| 5 × 5-3 × 3         | 90%    | 5                   | 4      | MS   | 10     | 5       | 249.20    | 967.50      | 78.60  | 114.30   | 0.45         | 16.95 |
| 5 × 5-3 × 3         | 90%    | 5                   | 4      | TT   | 10     | 10      | 484.60    | 920.60      | 78.60  | 68.00    | 0.25         | 0.35  |
| 5 × 5-3 × 3         | 90%    | 5                   | 5      | MS   | 10     | 7       | 205.60    | 967.80      | 78.60  | 115.10   | 0.58         | 34.05 |
| 5 × 5-3 × 3         | 90%    | 5                   | 5      | TT   | 10     | 10      | 425.80    | 916.30      | 78.60  | 63.70    | 0.31         | 0.48  |
| 5 × 5-3 × 3         | 90%    | 10                  | 2      | MS   | 10     | 0       | 554.00    | 1105.20     | 103.60 | 101.60   | 0.29         | 25.58 |
| 5 × 5-3 × 3         | 90%    | 10                  | 2      | TT   | 10     | 10      | 797.80    | 1087.30     | 103.60 | 83.70    | 0.16         | 0.61  |
| 5 × 5-3 × 3         | 90%    | 10                  | 3      | MS   | 10     | 0       | 377.00    | 1118.40     | 103.60 | 114.80   | 0.44         | 63.65 |
| 5 × 5-3 × 3         | 90%    | 10                  | 3      | TT   | 10     | 10      | 707.60    | 1081.10     | 103.60 | 77.50    | 0.25         | 0.53  |
| 5 × 5-3 × 3         | 90%    | 10                  | 4      | MS   | 10     | 1       | 290.90    | 1132.30     | 103.60 | 126.10   | 0.65         | 35.92 |
| 5 × 5-3 × 3         | 90%    | 10                  | 4      | TT   | 10     | 10      | 582.50    | 1076.90     | 103.60 | 73.30    | 0.36         | 0.58  |
| 5 × 5-3 × 3         | 90%    | 10                  | 5      | MS   | 10     | 2       | 234.00    | 1134.80     | 103.60 | 128.60   | 0.88         | 9.75  |
| 5 × 5-3 × 3         | 90%    | 10                  | 5      | TT   | 10     | 10      | 517.80    | 1073.60     | 103.60 | 70       | 0.48         | 0.88  |
| 5 × 5-4 × 4         | 40%    | 5                   | 2      | MS   | 5      | 5       | 119.00    | 206.20      | 3.00   | 47.20    | 0.01         | 0.01  |
| 5 × 5-4 × 4         | 40%    | 5                   | 2      | TT   | 5      | 5       | 153.20    | 192.60      | 3.00   | 33.60    | 0.01         | 0.01  |
| 5 × 5-4 × 4         | 40%    | 5                   | 3      | MS   | 5      | 5       | 82.60     | 198.20      | 3.00   | 35.20    | 0.01         | 0.01  |
| 5 × 5-4 × 4         | 40%    | 5                   | 3      | TT   | 5      | 5       | 115.60    | 187.00      | 3.00   | 28.00    | 0.01         | 0.02  |
| 5 × 5-4 × 4         | 40%    | 5                   | 4      | MS   | 5      | 5       | 80.40     | 193.00      | 3.00   | 32.60    | 0.01         | 0.02  |
| 5 × 5-4 × 4         | 40%    | 5                   | 4      | TT   | 5      | 5       | 101.00    | 183.80      | 3.00   | 24.80    | 0.01         | 0.02  |
| 5 × 5-4 × 4         | 40%    | 5                   | 5      | MS   | 5      | 5       | 80.20     | 193.80      | 3.00   | 31.00    | 0.02         | 0.03  |
| 5 × 5-4 × 4         | 40%    | 5                   | 5      | TT   | 5      | 5       | 86.60     | 183.20      | 3.00   | 24.20    | 0.01         | 0.02  |
| 5 × 5-4 × 4         | 40%    | 10                  | 2      | MS   | 6      | 6       | 131.17    | 215.17      | 3.33   | 41.83    | 0.01         | 0.02  |
| 5 × 5-4 × 4         | 40%    | 10                  | 2      | TT   | 6      | 6       | 172.00    | 209.17      | 3.33   | 35.83    | 0.01         | 0.01  |
| 5 × 5-4 × 4         | 40%    | 10                  | 3      | MS   | 6      | 6       | 81.00     | 211.67      | 3.33   | 38.33    | 0.01         | 0.02  |
| 5 × 5-4 × 4         | 40%    | 10                  | 3      | TT   | 6      | 6       | 129.50    | 201.67      | 3.33   | 28.33    | 0.01         | 0.02  |
| 5 × 5-4 × 4         | 40%    | 10                  | 4      | MS   | 6      | 6       | 75.33     | 204.50      | 3.33   | 31.17    | 0.02         | 0.03  |
| 5 × 5-4 × 4         | 40%    | 10                  | 4      | TT   | 6      | 6       | 115.17    | 197.17      | 3.33   | 23.83    | 0.01         | 0.02  |
| 5 × 5-4 × 4         | 40%    | 10                  | 5      | MS   | 6      | 6       | 75.33     | 203.83      | 3.33   | 30.50    | 0.02         | 0.03  |
| 5 × 5-4 × 4         | 40%    | 10                  | 5      | TT   | 6      | 6       | 115.17    | 197.00      | 3.33   | 23.67    | 0.01         | 0.03  |
| 5 × 5-4 × 4         | 60%    | 5                   | 2      | MS   | 10     | 10      | 238.40    | 466.10      | 10.40  | 71.70    | 0.04         | 0.17  |
| 5 × 5-4 × 4         | 60%    | 5                   | 2      | TT   | 10     | 10      | 349.30    | 454.70      | 10.40  | 60.30    | 0.03         | 0.06  |
| 5 × 5-4 × 4         | 60%    | 5                   | 3      | MS   | 10     | 10      | 171.10    | 467.40      | 10.40  | 72.70    | 0.06         | 0.20  |
| 5 × 5-4 × 4         | 60%    | 5                   | 3      | TT   | 10     | 10      | 265.60    | 448.20      | 10.40  | 53.80    | 0.04         | 0.06  |
| 5 × 5-4 × 4         | 60%    | 5                   | 4      | MS   | 10     | 10      | 136.20    | 466.50      | 10.40  | 72.00    | 0.09         | 0.20  |
| 5 × 5-4 × 4         | 60%    | 5                   | 4      | TT   | 10     | 10      | 222.00    | 443.70      | 10.40  | 49.30    | 0.05         | 0.10  |
| 5 × 5-4 × 4         | 60%    | 5                   | 5      | MS   | 10     | 10      | 126.50    | 478.50      | 10.40  | 83.30    | 0.11         | 0.23  |
| 5 × 5-4 × 4         | 60%    | 5                   | 5      | TT   | 10     | 10      | 193.60    | 439.90      | 10.40  | 45.50    | 0.07         | 0.13  |
| 5 × 5-4 × 4         | 60%    | 10                  | 2      | MS   | 10     | 9       | 313.00    | 608.90      | 14.90  | 96.00    | 0.06         | 0.40  |

(continued on next page)

Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 5 × 5-4 × 4         | 60%    | 10                  | 2      | TT   | 10     | 10      | 417.20    | 582.70      | 14.90  | 69.80    | 0.04         | 0.10   |
| 5 × 5-4 × 4         | 60%    | 10                  | 3      | MS   | 10     | 10      | 216.20    | 614.10      | 14.90  | 101.10   | 0.11         | 0.40   |
| 5 × 5-4 × 4         | 60%    | 10                  | 3      | TT   | 10     | 10      | 351.40    | 576.50      | 14.90  | 63.60    | 0.07         | 0.14   |
| 5 × 5-4 × 4         | 60%    | 10                  | 4      | MS   | 10     | 10      | 172.70    | 622.60      | 14.90  | 106.80   | 0.15         | 0.36   |
| 5 × 5-4 × 4         | 60%    | 10                  | 4      | TT   | 10     | 10      | 276.60    | 571.20      | 14.90  | 58.30    | 0.09         | 0.16   |
| 5 × 5-4 × 4         | 60%    | 10                  | 5      | MS   | 10     | 10      | 142.00    | 613.70      | 14.90  | 100.50   | 0.21         | 0.40   |
| 5 × 5-4 × 4         | 60%    | 10                  | 5      | TT   | 10     | 10      | 255.20    | 566.20      | 14.90  | 53.30    | 0.12         | 0.23   |
| 5 × 5-4 × 4         | 80%    | 5                   | 2      | MS   | 10     | 0       | 590.10    | 1177.50     | 49.60  | 143.80   | 0.40         | 30.62  |
| 5 × 5-4 × 4         | 80%    | 5                   | 2      | TT   | 10     | 10      | 827.90    | 1147.90     | 49.60  | 114.30   | 0.26         | 1.73   |
| 5 × 5-4 × 4         | 80%    | 5                   | 3      | MS   | 10     | 0       | 402.80    | 1188.60     | 49.60  | 154.60   | 0.67         | 38.71  |
| 5 × 5-4 × 4         | 80%    | 5                   | 3      | TT   | 10     | 10      | 698.40    | 1140.60     | 49.60  | 107.00   | 0.39         | 2.53   |
| 5 × 5-4 × 4         | 80%    | 5                   | 4      | MS   | 10     | 1       | 308.80    | 1207.20     | 49.60  | 173.30   | 1.07         | 53.64  |
| 5 × 5-4 × 4         | 80%    | 5                   | 4      | TT   | 10     | 10      | 613.20    | 1135.20     | 49.60  | 101.60   | 0.57         | 1.75   |
| 5 × 5-4 × 4         | 80%    | 5                   | 5      | MS   | 10     | 2       | 247.40    | 1182.20     | 49.60  | 148.50   | 1.42         | 40.10  |
| 5 × 5-4 × 4         | 80%    | 5                   | 5      | TT   | 10     | 10      | 510       | 1130.90     | 49.60  | 97.30    | 0.72         | 2.01   |
| 5 × 5-4 × 4         | 80%    | 10                  | 2      | MS   | 10     | 0       | 689.00    | 1375.70     | 63.10  | 153.90   | 0.62         | 51.59  |
| 5 × 5-4 × 4         | 80%    | 10                  | 2      | TT   | 10     | 10      | 995.70    | 1348.50     | 63.10  | 127.40   | 0.35         | 1.11   |
| 5 × 5-4 × 4         | 80%    | 10                  | 3      | MS   | 10     | 0       | 473.20    | 1408.00     | 63.10  | 186.90   | 1.22         | 79.74  |
| 5 × 5-4 × 4         | 80%    | 10                  | 3      | TT   | 10     | 10      | 838.00    | 1340.90     | 63.10  | 119.80   | 0.59         | 1.92   |
| 5 × 5-4 × 4         | 80%    | 10                  | 4      | MS   | 10     | 0       | 352.10    | 1396.20     | 63.10  | 175.10   | 1.64         | 73.13  |
| 5 × 5-4 × 4         | 80%    | 10                  | 4      | TT   | 10     | 10      | 750.10    | 1335.90     | 63.10  | 114.80   | 0.92         | 2.43   |
| 5 × 5-4 × 4         | 80%    | 10                  | 5      | MS   | 10     | 0       | 298.30    | 1439.20     | 63.10  | 213.50   | 2.39         | 53.96  |
| 5 × 5-4 × 4         | 80%    | 10                  | 5      | TT   | 10     | 10      | 611.20    | 1330        | 63.10  | 108.90   | 1.14         | 2.51   |
| 5 × 5-4 × 4         | 90%    | 5                   | 2      | MS   | 10     | 0       | 825.30    | 1647.80     | 129.30 | 180.50   | 1.06         | 68.87  |
| 5 × 5-4 × 4         | 90%    | 5                   | 2      | TT   | 10     | 10      | 1243.20   | 1612.40     | 129.30 | 145.10   | 0.56         | 2.42   |
| 5 × 5-4 × 4         | 90%    | 5                   | 3      | MS   | 10     | 0       | 555.60    | 1662.40     | 129.30 | 195.10   | 2.02         | 124.65 |
| 5 × 5-4 × 4         | 90%    | 5                   | 3      | TT   | 10     | 10      | 1025.00   | 1605.50     | 129.30 | 138.20   | 0.93         | 3.41   |
| 5 × 5-4 × 4         | 90%    | 5                   | 4      | MS   | 10     | 0       | 419.10    | 1667.30     | 129.30 | 199.70   | 3.01         | 123.59 |
| 5 × 5-4 × 4         | 90%    | 5                   | 4      | TT   | 10     | 10      | 942.00    | 1598.10     | 129.30 | 130.80   | 1.41         | 4.05   |
| 5 × 5-4 × 4         | 90%    | 5                   | 5      | MS   | 10     | 0       | 341.30    | 1690        | 129.30 | 220.20   | 3.83         | 100.99 |
| 5 × 5-4 × 4         | 90%    | 5                   | 5      | TT   | 10     | 10      | 809.10    | 1594.60     | 129.30 | 127.30   | 1.91         | 4.82   |
| 5 × 5-4 × 4         | 90%    | 10                  | 2      | MS   | 9      | 0       | 970       | 1937.89     | 202.11 | 195.78   | 1.61         | 73.52  |
| 5 × 5-4 × 4         | 90%    | 10                  | 2      | TT   | 9      | 9       | 1567.67   | 1906.33     | 202.11 | 164.22   | 0.75         | 5.07   |
| 5 × 5-4 × 4         | 90%    | 10                  | 3      | MS   | 9      | 0       | 655.56    | 1963.78     | 202.11 | 220.67   | 3.14         | 147.66 |
| 5 × 5-4 × 4         | 90%    | 10                  | 3      | TT   | 9      | 9       | 1212.89   | 1898.56     | 202.11 | 156.44   | 1.32         | 5.55   |
| 5 × 5-4 × 4         | 90%    | 10                  | 4      | MS   | 9      | 0       | 496.11    | 1976.33     | 202.11 | 234.00   | 5.17         | 140.27 |
| 5 × 5-4 × 4         | 90%    | 10                  | 4      | TT   | 9      | 9       | 1191.22   | 1890.44     | 202.11 | 148.33   | 2.36         | 11.01  |
| 5 × 5-4 × 4         | 90%    | 10                  | 5      | MS   | 9      | 0       | 402.11    | 1996.22     | 202.11 | 252.56   | 7.38         | 96.68  |
| 5 × 5-4 × 4         | 90%    | 10                  | 5      | TT   | 9      | 9       | 944.33    | 1884.56     | 202.11 | 142.44   | 3.15         | 11.60  |
| 5 × 5-5 × 5         | 40%    | 5                   | 2      | MS   | 9      | 9       | 123.33    | 219.89      | 3.11   | 50.11    | 0.01         | 0.02   |
| 5 × 5-5 × 5         | 40%    | 5                   | 2      | TT   | 9      | 9       | 157.89    | 211.00      | 3.11   | 41.22    | 0.01         | 0.01   |
| 5 × 5-5 × 5         | 40%    | 5                   | 3      | MS   | 9      | 9       | 95.89     | 216.78      | 3.11   | 47.00    | 0.01         | 0.02   |
| 5 × 5-5 × 5         | 40%    | 5                   | 3      | TT   | 9      | 9       | 129.11    | 205.67      | 3.11   | 35.89    | 0.01         | 0.01   |
| 5 × 5-5 × 5         | 40%    | 5                   | 4      | MS   | 9      | 9       | 84.89     | 208.78      | 3.11   | 39.00    | 0.02         | 0.03   |
| 5 × 5-5 × 5         | 40%    | 5                   | 4      | TT   | 9      | 9       | 100.22    | 198.89      | 3.11   | 29.11    | 0.01         | 0.02   |
| 5 × 5-5 × 5         | 40%    | 5                   | 5      | MS   | 9      | 9       | 74.22     | 198.44      | 3.11   | 28.67    | 0.02         | 0.04   |
| 5 × 5-5 × 5         | 40%    | 5                   | 5      | TT   | 9      | 9       | 88.00     | 193.22      | 3.11   | 23.44    | 0.02         | 0.03   |
| 5 × 5-5 × 5         | 40%    | 10                  | 2      | MS   | 10     | 10      | 144.70    | 252.20      | 3.70   | 56.20    | 0.01         | 0.02   |
| 5 × 5-5 × 5         | 40%    | 10                  | 2      | TT   | 10     | 10      | 178.40    | 242.20      | 3.70   | 46.50    | 0.01         | 0.02   |
| 5 × 5-5 × 5         | 40%    | 10                  | 3      | MS   | 10     | 10      | 99.90     | 243.70      | 3.70   | 47.70    | 0.02         | 0.04   |
| 5 × 5-5 × 5         | 40%    | 10                  | 3      | TT   | 10     | 10      | 142.60    | 232.20      | 3.70   | 36.50    | 0.01         | 0.02   |
| 5 × 5-5 × 5         | 40%    | 10                  | 4      | MS   | 10     | 10      | 90.10     | 239.30      | 3.70   | 43.60    | 0.02         | 0.05   |
| 5 × 5-5 × 5         | 40%    | 10                  | 4      | TT   | 10     | 10      | 116.90    | 227.10      | 3.70   | 31.40    | 0.02         | 0.03   |
| 5 × 5-5 × 5         | 40%    | 10                  | 5      | MS   | 10     | 10      | 75.50     | 231.50      | 3.70   | 35.80    | 0.03         | 0.06   |
| 5 × 5-5 × 5         | 40%    | 10                  | 5      | TT   | 10     | 10      | 93.20     | 222.30      | 3.70   | 26.60    | 0.02         | 0.03   |
| 5 × 5-5 × 5         | 60%    | 5                   | 2      | MS   | 10     | 5       | 372.40    | 736.30      | 14.80  | 121.50   | 0.10         | 1.52   |
| 5 × 5-5 × 5         | 60%    | 5                   | 2      | TT   | 10     | 10      | 503.40    | 714.40      | 14.80  | 99.60    | 0.06         | 0.20   |
| 5 × 5-5 × 5         | 60%    | 5                   | 3      | MS   | 10     | 6       | 258.80    | 746.00      | 14.80  | 130.40   | 0.18         | 6.19   |
| 5 × 5-5 × 5         | 60%    | 5                   | 3      | TT   | 10     | 10      | 447.20    | 708.20      | 14.80  | 93.40    | 0.10         | 0.22   |
| 5 × 5-5 × 5         | 60%    | 5                   | 4      | MS   | 10     | 9       | 200.10    | 748.40      | 14.80  | 133.60   | 0.24         | 12.35  |
| 5 × 5-5 × 5         | 60%    | 5                   | 4      | TT   | 10     | 10      | 379.30    | 701.50      | 14.80  | 86.70    | 0.15         | 0.26   |
| 5 × 5-5 × 5         | 60%    | 5                   | 5      | MS   | 10     | 10      | 165.10    | 754.20      | 14.80  | 139.40   | 0.32         | 2.31   |
| 5 × 5-5 × 5         | 60%    | 5                   | 5      | TT   | 10     | 10      | 314.10    | 696.50      | 14.80  | 81.70    | 0.19         | 0.47   |
| 5 × 5-5 × 5         | 60%    | 10                  | 2      | MS   | 10     | 0       | 444.60    | 883.10      | 20.60  | 136.50   | 0.16         | 14.55  |
| 5 × 5-5 × 5         | 60%    | 10                  | 2      | TT   | 10     | 10      | 598.20    | 858.30      | 20.60  | 111.70   | 0.09         | 0.26   |
| 5 × 5-5 × 5         | 60%    | 10                  | 3      | MS   | 10     | 0       | 308.40    | 891.00      | 20.60  | 144.40   | 0.27         | 11.46  |
| 5 × 5-5 × 5         | 60%    | 10                  | 3      | TT   | 10     | 10      | 516.30    | 851.00      | 20.60  | 104.40   | 0.15         | 0.29   |
| 5 × 5-5 × 5         | 60%    | 10                  | 4      | MS   | 10     | 7       | 235.30    | 904.10      | 20.60  | 157.40   | 0.35         | 4.13   |
| 5 × 5-5 × 5         | 60%    | 10                  | 4      | TT   | 10     | 10      | 440.10    | 843.20      | 20.60  | 96.60    | 0.21         | 0.50   |
| 5 × 5-5 × 5         | 60%    | 10                  | 5      | MS   | 10     | 9       | 204.90    | 934.40      | 20.60  | 186.80   | 0.50         | 2.41   |
| 5 × 5-5 × 5         | 60%    | 10                  | 5      | TT   | 10     | 10      | 343.90    | 837.50      | 20.60  | 90.90    | 0.28         | 0.74   |
| 5 × 5-5 × 5         | 80%    | 5                   | 2      | MS   | 10     | 0       | 934.10    | 1865.20     | 74.90  | 236.30   | 1.53         | 122.66 |
| 5 × 5-5 × 5         | 80%    | 5                   | 2      | TT   | 10     | 10      | 1371.50   | 1812.60     | 74.90  | 183.70   | 0.78         | 3.66   |
| 5 × 5-5 × 5         | 80%    | 5                   | 3      | MS   | 10     | 0       | 633.40    | 1892.70     | 74.90  | 263.80   | 2.76         | 86.95  |

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Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 5 × 5-5 × 5         | 80%    | 5                   | 3      | TT   | 10     | 10      | 1131.90   | 1805.80     | 74.90  | 176.90   | 1.45         | 6.52   |
| 5 × 5-5 × 5         | 80%    | 5                   | 4      | MS   | 10     | 0       | 488.10    | 1940.20     | 74.90  | 310.50   | 4.78         | 102.46 |
| 5 × 5-5 × 5         | 80%    | 5                   | 4      | TT   | 10     | 10      | 811.10    | 1800.10     | 74.90  | 171.20   | 2.11         | 8.29   |
| 5 × 5-5 × 5         | 80%    | 5                   | 5      | MS   | 10     | 0       | 391.60    | 1934.60     | 74.90  | 305.70   | 6.89         | 119.59 |
| 5 × 5-5 × 5         | 80%    | 5                   | 5      | TT   | 10     | 10      | 660.10    | 1792.80     | 74.90  | 163.90   | 3.02         | 8.85   |
| 5 × 5-5 × 5         | 80%    | 10                  | 2      | MS   | 10     | 0       | 1091.70   | 2179.40     | 92.20  | 263.20   | 2.55         | 152.91 |
| 5 × 5-5 × 5         | 80%    | 10                  | 2      | TT   | 10     | 10      | 1645.60   | 2116.20     | 92.20  | 200      | 1.15         | 9.40   |
| 5 × 5-5 × 5         | 80%    | 10                  | 3      | MS   | 10     | 0       | 744.80    | 2227.60     | 92.20  | 311.40   | 4.88         | 137.96 |
| 5 × 5-5 × 5         | 80%    | 10                  | 3      | TT   | 10     | 9       | 1238.50   | 2109.40     | 92.20  | 193.20   | 2.16         | 19.82  |
| 5 × 5-5 × 5         | 80%    | 10                  | 4      | MS   | 10     | 0       | 559.60    | 2232.40     | 92.20  | 316.10   | 8.38         | 148.02 |
| 5 × 5-5 × 5         | 80%    | 10                  | 4      | TT   | 10     | 10      | 1017.60   | 2100.80     | 92.20  | 184.60   | 3.56         | 15.19  |
| 5 × 5-5 × 5         | 80%    | 10                  | 5      | MS   | 10     | 0       | 466.70    | 2308.80     | 92.20  | 392.40   | 11.92        | 69.80  |
| 5 × 5-5 × 5         | 80%    | 10                  | 5      | TT   | 10     | 10      | 924.80    | 2094.40     | 92.20  | 178.20   | 5.23         | 21.25  |
| 5 × 5-5 × 5         | 90%    | 5                   | 2      | MS   | 10     | 0       | 1280.30   | 2558.50     | 222.20 | 296.10   | 4.00         | 219.69 |
| 5 × 5-5 × 5         | 90%    | 5                   | 2      | TT   | 10     | 10      | 1995.60   | 2495.20     | 222.20 | 233.00   | 1.76         | 14.58  |
| 5 × 5-5 × 5         | 90%    | 5                   | 3      | MS   | 10     | 0       | 868.90    | 2602.70     | 222.20 | 340.50   | 7.44         | 144.10 |
| 5 × 5-5 × 5         | 90%    | 5                   | 3      | TT   | 10     | 10      | 1609.40   | 2486.40     | 222.20 | 224.20   | 3.34         | 22.81  |
| 5 × 5-5 × 5         | 90%    | 5                   | 4      | MS   | 10     | 0       | 656.60    | 2618.60     | 222.20 | 356.40   | 12.98        | 146.57 |
| 5 × 5-5 × 5         | 90%    | 5                   | 4      | TT   | 10     | 10      | 1164.10   | 2479.80     | 222.20 | 217.60   | 5.67         | 25.90  |
| 5 × 5-5 × 5         | 90%    | 5                   | 5      | MS   | 10     | 0       | 538.90    | 2678.80     | 222.20 | 416.50   | 16.72        | 116.74 |
| 5 × 5-5 × 5         | 90%    | 5                   | 5      | TT   | 10     | 10      | 1105.00   | 2474.60     | 222.20 | 212.40   | 8.38         | 25.22  |
| 5 × 5-5 × 5         | 90%    | 10                  | 2      | MS   | 10     | 0       | 1532.30   | 3063.00     | 320.20 | 342.80   | 7.80         | 175.20 |
| 5 × 5-5 × 5         | 90%    | 10                  | 2      | TT   | 10     | 10      | 2385.70   | 2988.00     | 320.20 | 267.80   | 3.22         | 21.15  |
| 5 × 5-5 × 5         | 90%    | 10                  | 3      | MS   | 10     | 0       | 1040.90   | 3118.20     | 320.20 | 398.00   | 15.93        | 152.09 |
| 5 × 5-5 × 5         | 90%    | 10                  | 3      | TT   | 10     | 10      | 2029.50   | 2978.60     | 320.20 | 258.40   | 6.50         | 37.66  |
| 5 × 5-5 × 5         | 90%    | 10                  | 4      | MS   | 10     | 0       | 785.60    | 3134.10     | 320.20 | 413.90   | 23.38        | 187.18 |
| 5 × 5-5 × 5         | 90%    | 10                  | 4      | TT   | 10     | 10      | 1463.80   | 2970.40     | 320.20 | 250.20   | 11.96        | 62.78  |
| 5 × 5-5 × 5         | 90%    | 10                  | 5      | MS   | 10     | 0       | 645.40    | 3218.70     | 320.20 | 498.50   | 29.61        | 150.10 |
| 5 × 5-5 × 5         | 90%    | 10                  | 5      | TT   | 10     | 10      | 1496.90   | 2964.40     | 320.20 | 244.20   | 16.85        | 88.65  |
| 5 × 5-6 × 6         | 40%    | 5                   | 2      | MS   | 10     | 10      | 186.90    | 356.10      | 5.90   | 80.20    | 0.02         | 0.05   |
| 5 × 5-6 × 6         | 40%    | 5                   | 2      | TT   | 10     | 10      | 253.40    | 349.80      | 5.90   | 73.90    | 0.02         | 0.04   |
| 5 × 5-6 × 6         | 40%    | 5                   | 3      | MS   | 10     | 10      | 146.60    | 367.80      | 5.90   | 91.90    | 0.03         | 0.07   |
| 5 × 5-6 × 6         | 40%    | 5                   | 3      | TT   | 10     | 10      | 212.00    | 338.00      | 5.90   | 62.10    | 0.02         | 0.04   |
| 5 × 5-6 × 6         | 40%    | 5                   | 4      | MS   | 10     | 10      | 107.50    | 354.10      | 5.90   | 78.20    | 0.04         | 0.10   |
| 5 × 5-6 × 6         | 40%    | 5                   | 4      | TT   | 10     | 10      | 193.50    | 332.90      | 5.90   | 57.00    | 0.03         | 0.07   |
| 5 × 5-6 × 6         | 40%    | 5                   | 5      | MS   | 10     | 10      | 99.10     | 362.40      | 5.90   | 86.50    | 0.06         | 0.13   |
| 5 × 5-6 × 6         | 40%    | 5                   | 5      | TT   | 10     | 10      | 172.60    | 329.50      | 5.90   | 53.60    | 0.04         | 0.08   |
| 5 × 5-6 × 6         | 40%    | 10                  | 2      | MS   | 10     | 10      | 212.20    | 400.70      | 6.10   | 94.60    | 0.02         | 0.07   |
| 5 × 5-6 × 6         | 40%    | 10                  | 2      | TT   | 10     | 10      | 294.90    | 387.50      | 6.10   | 81.40    | 0.02         | 0.04   |
| 5 × 5-6 × 6         | 40%    | 10                  | 3      | MS   | 10     | 10      | 159.80    | 408.80      | 6.10   | 102.60   | 0.04         | 0.09   |
| 5 × 5-6 × 6         | 40%    | 10                  | 3      | TT   | 10     | 10      | 228.40    | 377.00      | 6.10   | 70.90    | 0.03         | 0.05   |
| 5 × 5-6 × 6         | 40%    | 10                  | 4      | MS   | 10     | 10      | 123.20    | 411.30      | 6.10   | 105.20   | 0.05         | 0.13   |
| 5 × 5-6 × 6         | 40%    | 10                  | 4      | TT   | 10     | 10      | 210       | 372.30      | 6.10   | 66.20    | 0.03         | 0.06   |
| 5 × 5-6 × 6         | 40%    | 10                  | 5      | MS   | 10     | 10      | 102.50    | 408.90      | 6.10   | 99.90    | 0.07         | 0.14   |
| 5 × 5-6 × 6         | 40%    | 10                  | 5      | TT   | 10     | 10      | 186.30    | 366.80      | 6.10   | 60.70    | 0.04         | 0.08   |
| 5 × 5-6 × 6         | 60%    | 5                   | 2      | MS   | 10     | 0       | 534.70    | 1064.40     | 21.80  | 178.60   | 0.26         | 13.08  |
| 5 × 5-6 × 6         | 60%    | 5                   | 2      | TT   | 10     | 10      | 822.00    | 1035.00     | 21.80  | 149.20   | 0.15         | 0.55   |
| 5 × 5-6 × 6         | 60%    | 5                   | 3      | MS   | 10     | 1       | 369.50    | 1086.00     | 21.80  | 200.20   | 0.45         | 46.94  |
| 5 × 5-6 × 6         | 60%    | 5                   | 3      | TT   | 10     | 10      | 603.00    | 1022.90     | 21.80  | 137.10   | 0.26         | 0.79   |
| 5 × 5-6 × 6         | 60%    | 5                   | 4      | MS   | 10     | 3       | 282.30    | 1096.00     | 21.80  | 209.80   | 0.63         | 23.58  |
| 5 × 5-6 × 6         | 60%    | 5                   | 4      | TT   | 10     | 10      | 511.50    | 1015.60     | 21.80  | 129.80   | 0.35         | 0.89   |
| 5 × 5-6 × 6         | 60%    | 5                   | 5      | MS   | 10     | 5       | 236.60    | 1126.30     | 21.80  | 240.50   | 0.84         | 8.52   |
| 5 × 5-6 × 6         | 60%    | 5                   | 5      | TT   | 10     | 10      | 464.00    | 1011.10     | 21.80  | 125.30   | 0.46         | 1.15   |
| 5 × 5-6 × 6         | 60%    | 10                  | 2      | MS   | 10     | 0       | 642.30    | 1280.30     | 28.40  | 201.90   | 0.42         | 58.19  |
| 5 × 5-6 × 6         | 60%    | 10                  | 2      | TT   | 10     | 10      | 939.50    | 1246.60     | 28.40  | 168.20   | 0.27         | 1.72   |
| 5 × 5-6 × 6         | 60%    | 10                  | 3      | MS   | 10     | 0       | 439.10    | 1300.60     | 28.40  | 222.20   | 0.83         | 26.12  |
| 5 × 5-6 × 6         | 60%    | 10                  | 3      | TT   | 10     | 10      | 736.20    | 1238.70     | 28.40  | 160.30   | 0.43         | 1.36   |
| 5 × 5-6 × 6         | 60%    | 10                  | 4      | MS   | 10     | 0       | 339.60    | 1325.70     | 28.40  | 244.70   | 1.21         | 14.44  |
| 5 × 5-6 × 6         | 60%    | 10                  | 4      | TT   | 10     | 10      | 642.70    | 1231.50     | 28.40  | 153.10   | 0.65         | 2.28   |
| 5 × 5-6 × 6         | 60%    | 10                  | 5      | MS   | 10     | 1       | 277.70    | 1339.40     | 28.40  | 260.70   | 1.62         | 15.72  |
| 5 × 5-6 × 6         | 60%    | 10                  | 5      | TT   | 10     | 10      | 585.10    | 1224.30     | 28.40  | 145.90   | 0.80         | 2.40   |
| 5 × 5-6 × 6         | 80%    | 5                   | 2      | MS   | 5      | 0       | 1210.20   | 2419.20     | 95.80  | 319.40   | 3.00         | 194.94 |
| 5 × 5-6 × 6         | 80%    | 5                   | 2      | TT   | 5      | 5       | 1737.40   | 2357.60     | 95.80  | 257.80   | 1.55         | 14.25  |
| 5 × 5-6 × 6         | 80%    | 5                   | 3      | MS   | 5      | 0       | 836.20    | 2503.40     | 95.80  | 403.20   | 7.47         | 230.39 |
| 5 × 5-6 × 6         | 80%    | 5                   | 3      | TT   | 5      | 5       | 1409.40   | 2349.00     | 95.80  | 249.20   | 3.40         | 23.35  |
| 5 × 5-6 × 6         | 80%    | 5                   | 4      | MS   | 5      | 0       | 629.80    | 2503.40     | 95.80  | 403.60   | 11.68        | 150.35 |
| 5 × 5-6 × 6         | 80%    | 5                   | 4      | TT   | 5      | 5       | 1051.80   | 2341.00     | 95.80  | 241.20   | 5.21         | 28.82  |
| 5 × 5-6 × 6         | 80%    | 5                   | 5      | MS   | 5      | 0       | 519.40    | 2578.40     | 95.80  | 473.60   | 15.89        | 174.19 |
| 5 × 5-6 × 6         | 80%    | 5                   | 5      | TT   | 5      | 5       | 1073.60   | 2335.60     | 95.80  | 235.80   | 7.57         | 31.01  |
| 5 × 5-6 × 6         | 90%    | 5                   | 2      | MS   | 10     | 0       | 1879.90   | 3759.50     | 294.60 | 470.90   | 15.50        | 172.02 |
| 5 × 5-6 × 6         | 90%    | 5                   | 2      | TT   | 10     | 10      | 2571.00   | 3623.90     | 294.60 | 335.30   | 6.91         | 62.48  |
| 5 × 5-6 × 6         | 90%    | 5                   | 3      | MS   | 10     | 0       | 1285.70   | 3854.00     | 294.60 | 565.20   | 28.72        | 188.95 |
| 5 × 5-6 × 6         | 90%    | 5                   | 3      | TT   | 10     | 8       | 2147.00   | 3617.70     | 294.60 | 329.10   | 16.75        | 122.03 |

(continued on next page)

Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 5 × 5-6 × 6         | 90%    | 5                   | 4      | MS   | 10     | 0       | 980.30    | 3911.70     | 294.60 | 621.40   | 39.20        | 186.78 |
| 5 × 5-6 × 6         | 90%    | 5                   | 4      | TT   | 10     | 8       | 1816.00   | 3614.30     | 294.60 | 325.70   | 26.33        | 144.05 |
| 5 × 5-6 × 6         | 90%    | 5                   | 5      | MS   | 10     | 0       | 800.60    | 3985.10     | 294.60 | 694.30   | 42.38        | 202.27 |
| 5 × 5-6 × 6         | 90%    | 5                   | 5      | TT   | 10     | 8       | 1680.10   | 3606.60     | 294.60 | 318.00   | 31.63        | 163.14 |
| 5 × 5-6 × 6         | 90%    | 10                  | 2      | MS   | 4      | 0       | 2115.50   | 4230        | 398.75 | 531.25   | 23.15        | 253.08 |
| 5 × 5-6 × 6         | 90%    | 10                  | 2      | TT   | 4      | 4       | 2633.50   | 4069.50     | 398.75 | 370.75   | 8.78         | 95.65  |
| 5 × 5-6 × 6         | 90%    | 10                  | 3      | MS   | 4      | 0       | 1445.75   | 4334.75     | 398.75 | 636.00   | 42.63        | 204.46 |
| 5 × 5-6 × 6         | 90%    | 10                  | 3      | TT   | 4      | 4       | 2299.50   | 4063.50     | 398.75 | 364.75   | 22.36        | 142.53 |
| 5 × 5-6 × 6         | 90%    | 10                  | 4      | MS   | 4      | 0       | 1108.75   | 4422.25     | 398.75 | 723.50   | 48.58        | 230.78 |
| 5 × 5-6 × 6         | 90%    | 10                  | 4      | TT   | 4      | 3       | 1732.50   | 4057.50     | 398.75 | 358.75   | 33.73        | 158.80 |
| 5 × 5-6 × 6         | 90%    | 10                  | 5      | MS   | 4      | 0       | 896.00    | 4461.00     | 398.75 | 762.25   | 44.72        | 174.20 |
| 5 × 5-6 × 6         | 90%    | 10                  | 5      | TT   | 4      | 4       | 1661.00   | 4048.75     | 398.75 | 350      | 36.58        | 220.61 |
| 6 × 6-2 × 2         | 40%    | 5                   | 2      | MS   | 5      | 5       | 105.20    | 178.80      | 3.00   | 26.00    | 0.01         | 0.01   |
| 6 × 6-2 × 2         | 40%    | 5                   | 2      | TT   | 5      | 5       | 134.60    | 175.00      | 3.00   | 22.20    | 0.01         | 0.01   |
| 6 × 6-2 × 2         | 40%    | 5                   | 3      | MS   | 5      | 5       | 77.40     | 172.60      | 3.00   | 20.40    | 0.01         | 0.01   |
| 6 × 6-2 × 2         | 40%    | 5                   | 3      | TT   | 5      | 5       | 115.40    | 168.20      | 3.00   | 16.00    | 0.01         | 0.01   |
| 6 × 6-2 × 2         | 40%    | 5                   | 4      | MS   | 5      | 5       | 76.00     | 170.40      | 3.00   | 18.20    | 0.01         | 0.02   |
| 6 × 6-2 × 2         | 40%    | 5                   | 4      | TT   | 5      | 5       | 101.40    | 167.00      | 3.00   | 15.20    | 0.01         | 0.01   |
| 6 × 6-2 × 2         | 40%    | 5                   | 5      | MS   | 5      | 5       | 75.60     | 168.00      | 3.00   | 15.80    | 0.01         | 0.02   |
| 6 × 6-2 × 2         | 40%    | 5                   | 5      | TT   | 5      | 5       | 99.80     | 164.40      | 3.00   | 12.60    | 0.01         | 0.02   |
| 6 × 6-2 × 2         | 40%    | 10                  | 2      | MS   | 6      | 6       | 108.00    | 181.00      | 2.67   | 23.50    | 0.01         | 0.01   |
| 6 × 6-2 × 2         | 40%    | 10                  | 2      | TT   | 6      | 6       | 145.33    | 179.00      | 2.67   | 21.50    | 0.01         | 0.01   |
| 6 × 6-2 × 2         | 40%    | 10                  | 3      | MS   | 6      | 6       | 76.33     | 181.00      | 2.67   | 24.00    | 0.01         | 0.01   |
| 6 × 6-2 × 2         | 40%    | 10                  | 3      | TT   | 6      | 6       | 118.00    | 173.00      | 2.67   | 16.00    | 0.01         | 0.02   |
| 6 × 6-2 × 2         | 40%    | 10                  | 4      | MS   | 6      | 6       | 75.33     | 177.17      | 2.67   | 20.17    | 0.01         | 0.02   |
| 6 × 6-2 × 2         | 40%    | 10                  | 4      | TT   | 6      | 6       | 117.50    | 172.17      | 2.67   | 15.50    | 0.01         | 0.02   |
| 6 × 6-2 × 2         | 40%    | 10                  | 5      | MS   | 6      | 6       | 75.17     | 176.83      | 2.67   | 19.83    | 0.02         | 0.03   |
| 6 × 6-2 × 2         | 40%    | 10                  | 5      | TT   | 6      | 6       | 115.50    | 169.33      | 2.67   | 12.67    | 0.01         | 0.02   |
| 6 × 6-2 × 2         | 60%    | 5                   | 2      | MS   | 10     | 10      | 150.20    | 262.50      | 6.10   | 28.40    | 0.02         | 0.03   |
| 6 × 6-2 × 2         | 60%    | 5                   | 2      | TT   | 10     | 10      | 183.20    | 257.40      | 6.10   | 23.30    | 0.01         | 0.02   |
| 6 × 6-2 × 2         | 60%    | 5                   | 3      | MS   | 10     | 10      | 106.20    | 268.30      | 6.10   | 31.50    | 0.02         | 0.04   |
| 6 × 6-2 × 2         | 60%    | 5                   | 3      | TT   | 10     | 10      | 169.20    | 255.80      | 6.10   | 21.70    | 0.02         | 0.03   |
| 6 × 6-2 × 2         | 60%    | 5                   | 4      | MS   | 10     | 10      | 92.20     | 268.70      | 6.10   | 31.20    | 0.03         | 0.06   |
| 6 × 6-2 × 2         | 60%    | 5                   | 4      | TT   | 10     | 10      | 148.60    | 252.70      | 6.10   | 18.60    | 0.02         | 0.04   |
| 6 × 6-2 × 2         | 60%    | 5                   | 5      | MS   | 10     | 10      | 80.60     | 269.00      | 6.10   | 32.40    | 0.04         | 0.07   |
| 6 × 6-2 × 2         | 60%    | 5                   | 5      | TT   | 10     | 10      | 139.40    | 250         | 6.10   | 15.90    | 0.03         | 0.05   |
| 6 × 6-2 × 2         | 60%    | 10                  | 2      | MS   | 10     | 10      | 151.40    | 279.40      | 7.20   | 26.20    | 0.02         | 0.04   |
| 6 × 6-2 × 2         | 60%    | 10                  | 2      | TT   | 10     | 10      | 185.90    | 278.00      | 7.20   | 24.80    | 0.01         | 0.02   |
| 6 × 6-2 × 2         | 60%    | 10                  | 3      | MS   | 10     | 10      | 123.90    | 289.30      | 7.20   | 33.50    | 0.02         | 0.06   |
| 6 × 6-2 × 2         | 60%    | 10                  | 3      | TT   | 10     | 10      | 149.70    | 275.10      | 7.20   | 21.90    | 0.02         | 0.03   |
| 6 × 6-2 × 2         | 60%    | 10                  | 4      | MS   | 10     | 10      | 92.30     | 286.00      | 7.20   | 30.90    | 0.03         | 0.06   |
| 6 × 6-2 × 2         | 60%    | 10                  | 4      | TT   | 10     | 10      | 155.00    | 272.60      | 7.20   | 19.40    | 0.02         | 0.04   |
| 6 × 6-2 × 2         | 60%    | 10                  | 5      | MS   | 10     | 10      | 80.80     | 285.90      | 7.20   | 30.80    | 0.04         | 0.10   |
| 6 × 6-2 × 2         | 60%    | 10                  | 5      | TT   | 10     | 10      | 154.20    | 270.10      | 7.20   | 16.90    | 0.03         | 0.06   |
| 6 × 6-2 × 2         | 80%    | 5                   | 2      | MS   | 10     | 6       | 325.90    | 637.10      | 30.80  | 66.20    | 0.09         | 21.99  |
| 6 × 6-2 × 2         | 80%    | 5                   | 2      | TT   | 10     | 10      | 453.00    | 618.30      | 30.80  | 47.50    | 0.06         | 0.16   |
| 6 × 6-2 × 2         | 80%    | 5                   | 3      | MS   | 10     | 6       | 224.20    | 633.80      | 30.80  | 60.30    | 0.15         | 2.86   |
| 6 × 6-2 × 2         | 80%    | 5                   | 3      | TT   | 10     | 10      | 375.60    | 615.00      | 30.80  | 44.20    | 0.09         | 0.20   |
| 6 × 6-2 × 2         | 80%    | 5                   | 4      | MS   | 10     | 9       | 177.40    | 644.10      | 30.80  | 69.90    | 0.21         | 0.74   |
| 6 × 6-2 × 2         | 80%    | 5                   | 4      | TT   | 10     | 10      | 334.40    | 611.50      | 30.80  | 40.70    | 0.12         | 0.26   |
| 6 × 6-2 × 2         | 80%    | 5                   | 5      | MS   | 10     | 10      | 154.20    | 646.40      | 30.80  | 72.70    | 0.29         | 0.67   |
| 6 × 6-2 × 2         | 80%    | 5                   | 5      | TT   | 10     | 10      | 286.80    | 608.20      | 30.80  | 37.40    | 0.16         | 0.30   |
| 6 × 6-2 × 2         | 80%    | 10                  | 2      | MS   | 10     | 4       | 357.60    | 702.10      | 38.40  | 63.50    | 0.11         | 4.34   |
| 6 × 6-2 × 2         | 80%    | 10                  | 2      | TT   | 10     | 10      | 500.60    | 690.70      | 38.40  | 52.30    | 0.07         | 0.21   |
| 6 × 6-2 × 2         | 80%    | 10                  | 3      | MS   | 10     | 4       | 248.90    | 719.80      | 38.40  | 77.70    | 0.19         | 4.37   |
| 6 × 6-2 × 2         | 80%    | 10                  | 3      | TT   | 10     | 10      | 434.60    | 686.50      | 38.40  | 48.10    | 0.11         | 0.20   |
| 6 × 6-2 × 2         | 80%    | 10                  | 4      | MS   | 10     | 8       | 195.30    | 719.90      | 38.40  | 78.10    | 0.26         | 3.14   |
| 6 × 6-2 × 2         | 80%    | 10                  | 4      | TT   | 10     | 10      | 359.30    | 683.40      | 38.40  | 45.00    | 0.15         | 0.31   |
| 6 × 6-2 × 2         | 80%    | 10                  | 5      | MS   | 10     | 9       | 163.90    | 709.50      | 38.40  | 70.90    | 0.34         | 0.95   |
| 6 × 6-2 × 2         | 80%    | 10                  | 5      | TT   | 10     | 10      | 339.10    | 681.10      | 38.40  | 42.70    | 0.20         | 0.33   |
| 6 × 6-2 × 2         | 90%    | 5                   | 2      | MS   | 9      | 0       | 565.44    | 1127.56     | 109.22 | 104.89   | 0.39         | 56.26  |
| 6 × 6-2 × 2         | 90%    | 5                   | 2      | TT   | 9      | 8       | 811.33    | 1110.67     | 109.22 | 88.11    | 0.25         | 2.40   |
| 6 × 6-2 × 2         | 90%    | 5                   | 3      | MS   | 9      | 0       | 386.44    | 1143.22     | 109.22 | 115.44   | 0.77         | 19.10  |
| 6 × 6-2 × 2         | 90%    | 5                   | 3      | TT   | 9      | 8       | 581.11    | 1105.11     | 109.22 | 82.56    | 0.46         | 15.05  |
| 6 × 6-2 × 2         | 90%    | 5                   | 4      | MS   | 9      | 1       | 300.33    | 1162.89     | 109.22 | 128.89   | 1.19         | 9.95   |
| 6 × 6-2 × 2         | 90%    | 5                   | 4      | TT   | 9      | 8       | 525.67    | 1099.11     | 109.22 | 76.56    | 0.64         | 16.30  |
| 6 × 6-2 × 2         | 90%    | 5                   | 5      | MS   | 9      | 5       | 246.33    | 1172.67     | 109.22 | 128.89   | 1.59         | 17.83  |
| 6 × 6-2 × 2         | 90%    | 5                   | 5      | TT   | 9      | 8       | 475.56    | 1094.11     | 109.22 | 71.56    | 0.98         | 7.21   |
| 6 × 6-2 × 2         | 90%    | 10                  | 2      | MS   | 10     | 0       | 661.50    | 1321.50     | 134.90 | 118.30   | 0.62         | 42.22  |
| 6 × 6-2 × 2         | 90%    | 10                  | 2      | TT   | 10     | 10      | 907.10    | 1305.00     | 134.90 | 102.10   | 0.48         | 5.37   |
| 6 × 6-2 × 2         | 90%    | 10                  | 3      | MS   | 10     | 0       | 451.40    | 1343.10     | 134.90 | 133.40   | 1.14         | 27.86  |
| 6 × 6-2 × 2         | 90%    | 10                  | 3      | TT   | 10     | 10      | 852.40    | 1298.20     | 134.90 | 95.30    | 0.85         | 29.11  |
| 6 × 6-2 × 2         | 90%    | 10                  | 4      | MS   | 10     | 0       | 343.40    | 1351.30     | 134.90 | 134.10   | 1.98         | 33.36  |
| 6 × 6-2 × 2         | 90%    | 10                  | 4      | TT   | 10     | 8       | 742.80    | 1296.40     | 134.90 | 93.50    | 1.45         | 38.34  |

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Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 6 × 6-2 × 2         | 90%    | 10                  | 5      | MS   | 10     | 0       | 286.70    | 1378.90     | 134.90 | 145.80   | 2.91         | 30.42  |
| 6 × 6-2 × 2         | 90%    | 10                  | 5      | TT   | 10     | 9       | 664.00    | 1291.50     | 134.90 | 88.60    | 1.69         | 36.12  |
| 6 × 6-3 × 3         | 40%    | 5                   | 2      | MS   | 7      | 7       | 128.00    | 239.71      | 3.86   | 47.29    | 0.01         | 0.02   |
| 6 × 6-3 × 3         | 40%    | 5                   | 2      | TT   | 7      | 7       | 177.14    | 228.71      | 3.86   | 36.29    | 0.01         | 0.02   |
| 6 × 6-3 × 3         | 40%    | 5                   | 3      | MS   | 7      | 7       | 101.71    | 226.29      | 3.86   | 33.86    | 0.02         | 0.03   |
| 6 × 6-3 × 3         | 40%    | 5                   | 3      | TT   | 7      | 7       | 160.86    | 219.14      | 3.86   | 26.71    | 0.01         | 0.02   |
| 6 × 6-3 × 3         | 40%    | 5                   | 4      | MS   | 7      | 7       | 84.86     | 228.43      | 3.86   | 36.00    | 0.02         | 0.04   |
| 6 × 6-3 × 3         | 40%    | 5                   | 4      | TT   | 7      | 7       | 148.71    | 215.57      | 3.86   | 23.14    | 0.02         | 0.02   |
| 6 × 6-3 × 3         | 40%    | 5                   | 5      | MS   | 7      | 7       | 72.86     | 222.00      | 3.86   | 29.57    | 0.03         | 0.05   |
| 6 × 6-3 × 3         | 40%    | 5                   | 5      | TT   | 7      | 7       | 135.43    | 210.14      | 3.86   | 17.71    | 0.02         | 0.04   |
| 6 × 6-3 × 3         | 40%    | 10                  | 2      | MS   | 10     | 10      | 144.30    | 258.30      | 3.60   | 46.40    | 0.01         | 0.03   |
| 6 × 6-3 × 3         | 40%    | 10                  | 2      | TT   | 10     | 10      | 194.70    | 245.20      | 3.60   | 37.60    | 0.01         | 0.02   |
| 6 × 6-3 × 3         | 40%    | 10                  | 3      | MS   | 10     | 10      | 99.50     | 253.30      | 3.60   | 45.70    | 0.02         | 0.04   |
| 6 × 6-3 × 3         | 40%    | 10                  | 3      | TT   | 10     | 10      | 185.00    | 239.90      | 3.60   | 32.30    | 0.01         | 0.03   |
| 6 × 6-3 × 3         | 40%    | 10                  | 4      | MS   | 10     | 10      | 93.60     | 248.10      | 3.60   | 40.50    | 0.02         | 0.05   |
| 6 × 6-3 × 3         | 40%    | 10                  | 4      | TT   | 10     | 10      | 161.30    | 235.30      | 3.60   | 27.70    | 0.02         | 0.04   |
| 6 × 6-3 × 3         | 40%    | 10                  | 5      | MS   | 10     | 10      | 78.80     | 248.80      | 3.60   | 41.20    | 0.03         | 0.07   |
| 6 × 6-3 × 3         | 40%    | 10                  | 5      | TT   | 10     | 10      | 137.20    | 229.90      | 3.60   | 22.30    | 0.02         | 0.05   |
| 6 × 6-3 × 3         | 60%    | 5                   | 2      | MS   | 10     | 7       | 332.00    | 649.80      | 14.90  | 82.90    | 0.09         | 1.09   |
| 6 × 6-3 × 3         | 60%    | 5                   | 2      | TT   | 10     | 10      | 444.30    | 630.30      | 14.90  | 63.40    | 0.05         | 0.12   |
| 6 × 6-3 × 3         | 60%    | 5                   | 3      | MS   | 10     | 7       | 227.60    | 657.50      | 14.90  | 86.50    | 0.14         | 41.14  |
| 6 × 6-3 × 3         | 60%    | 5                   | 3      | TT   | 10     | 10      | 373.50    | 625.80      | 14.90  | 58.90    | 0.08         | 0.18   |
| 6 × 6-3 × 3         | 60%    | 5                   | 4      | MS   | 10     | 10      | 178.80    | 668.40      | 14.90  | 95.40    | 0.20         | 0.66   |
| 6 × 6-3 × 3         | 60%    | 5                   | 4      | TT   | 10     | 10      | 331.40    | 620.50      | 14.90  | 53.60    | 0.12         | 0.18   |
| 6 × 6-3 × 3         | 60%    | 5                   | 5      | MS   | 10     | 10      | 152.50    | 664.00      | 14.90  | 89.50    | 0.26         | 0.62   |
| 6 × 6-3 × 3         | 60%    | 5                   | 5      | TT   | 10     | 10      | 277.90    | 618.10      | 14.90  | 51.20    | 0.16         | 0.31   |
| 6 × 6-3 × 3         | 60%    | 10                  | 2      | MS   | 10     | 6       | 384.00    | 749.50      | 17.90  | 89.60    | 0.12         | 4.14   |
| 6 × 6-3 × 3         | 60%    | 10                  | 2      | TT   | 10     | 10      | 560.50    | 732.20      | 17.90  | 72.30    | 0.08         | 0.22   |
| 6 × 6-3 × 3         | 60%    | 10                  | 3      | MS   | 10     | 6       | 261.20    | 765.60      | 17.90  | 105.70   | 0.22         | 19.11  |
| 6 × 6-3 × 3         | 60%    | 10                  | 3      | TT   | 10     | 10      | 476.30    | 728.20      | 17.90  | 68.30    | 0.12         | 0.31   |
| 6 × 6-3 × 3         | 60%    | 10                  | 4      | MS   | 10     | 7       | 214.30    | 771.00      | 17.90  | 111.00   | 0.29         | 1.29   |
| 6 × 6-3 × 3         | 60%    | 10                  | 4      | TT   | 10     | 10      | 384.90    | 723.50      | 17.90  | 63.60    | 0.16         | 0.40   |
| 6 × 6-3 × 3         | 60%    | 10                  | 5      | MS   | 10     | 9       | 166.70    | 760.40      | 17.90  | 100.40   | 0.39         | 1.39   |
| 6 × 6-3 × 3         | 60%    | 10                  | 5      | TT   | 10     | 10      | 330.90    | 721.00      | 17.90  | 61.10    | 0.22         | 0.55   |
| 6 × 6-3 × 3         | 80%    | 5                   | 2      | MS   | 10     | 0       | 752.80    | 1504.20     | 76.70  | 143.50   | 0.89         | 108.95 |
| 6 × 6-3 × 3         | 80%    | 5                   | 2      | TT   | 10     | 10      | 1015.70   | 1478.40     | 76.70  | 117.70   | 0.51         | 2.20   |
| 6 × 6-3 × 3         | 80%    | 5                   | 3      | MS   | 10     | 0       | 508.80    | 1520.80     | 76.70  | 159.40   | 1.90         | 50.38  |
| 6 × 6-3 × 3         | 80%    | 5                   | 3      | TT   | 10     | 10      | 799.80    | 1472.00     | 76.70  | 111.30   | 0.87         | 2.52   |
| 6 × 6-3 × 3         | 80%    | 5                   | 4      | MS   | 10     | 0       | 389.50    | 1536.40     | 76.70  | 171.00   | 2.70         | 65.92  |
| 6 × 6-3 × 3         | 80%    | 5                   | 4      | TT   | 10     | 10      | 603.60    | 1464.50     | 76.70  | 103.80   | 1.38         | 3.77   |
| 6 × 6-3 × 3         | 80%    | 5                   | 5      | MS   | 10     | 0       | 319.00    | 1562.20     | 76.70  | 198.10   | 3.79         | 95.88  |
| 6 × 6-3 × 3         | 80%    | 5                   | 5      | TT   | 10     | 10      | 582.10    | 1459.70     | 76.70  | 99.00    | 1.98         | 4.01   |
| 6 × 6-3 × 3         | 80%    | 10                  | 2      | MS   | 10     | 0       | 830.80    | 1659.50     | 90.60  | 152.90   | 1.30         | 114.56 |
| 6 × 6-3 × 3         | 80%    | 10                  | 2      | TT   | 10     | 10      | 1178.70   | 1627.80     | 90.60  | 121.20   | 0.66         | 2.23   |
| 6 × 6-3 × 3         | 80%    | 10                  | 3      | MS   | 10     | 0       | 567.50    | 1694.60     | 90.60  | 187.40   | 2.36         | 74.16  |
| 6 × 6-3 × 3         | 80%    | 10                  | 3      | TT   | 10     | 10      | 959.10    | 1623.60     | 90.60  | 117.00   | 1.16         | 4.13   |
| 6 × 6-3 × 3         | 80%    | 10                  | 4      | MS   | 10     | 0       | 434.10    | 1709.60     | 90.60  | 202.90   | 4.26         | 84.42  |
| 6 × 6-3 × 3         | 80%    | 10                  | 4      | TT   | 10     | 10      | 784.80    | 1618.30     | 90.60  | 111.70   | 1.86         | 5.95   |
| 6 × 6-3 × 3         | 80%    | 10                  | 5      | MS   | 10     | 0       | 354.70    | 1740.50     | 90.60  | 233.90   | 5.35         | 97.74  |
| 6 × 6-3 × 3         | 80%    | 10                  | 5      | TT   | 10     | 10      | 782.80    | 1613.80     | 90.60  | 107.20   | 2.57         | 6.66   |
| 6 × 6-3 × 3         | 90%    | 5                   | 2      | MS   | 7      | 0       | 1122.71   | 2244.86     | 243.14 | 209.71   | 3.32         | 78.66  |
| 6 × 6-3 × 3         | 90%    | 5                   | 2      | TT   | 7      | 7       | 1735.57   | 2193.00     | 243.14 | 158.43   | 2.07         | 23.23  |
| 6 × 6-3 × 3         | 90%    | 5                   | 3      | MS   | 7      | 0       | 755.29    | 2262.86     | 243.14 | 228.29   | 7.04         | 146.44 |
| 6 × 6-3 × 3         | 90%    | 5                   | 3      | TT   | 7      | 7       | 1353.14   | 2188.29     | 243.14 | 153.71   | 3.93         | 29.12  |
| 6 × 6-3 × 3         | 90%    | 5                   | 4      | MS   | 7      | 0       | 573.71    | 2284.71     | 243.14 | 249.29   | 12.16        | 135.73 |
| 6 × 6-3 × 3         | 90%    | 5                   | 4      | TT   | 7      | 7       | 1205.43   | 2183.14     | 243.14 | 148.57   | 6.01         | 37.35  |
| 6 × 6-3 × 3         | 90%    | 5                   | 5      | MS   | 7      | 0       | 465.86    | 2320.29     | 243.14 | 279.00   | 15.27        | 137.26 |
| 6 × 6-3 × 3         | 90%    | 5                   | 5      | TT   | 7      | 6       | 1025.43   | 2179.14     | 243.14 | 144.57   | 7.51         | 72.53  |
| 6 × 6-3 × 3         | 90%    | 10                  | 2      | MS   | 7      | 0       | 1317.00   | 2632.71     | 309.57 | 240.29   | 5.40         | 207.69 |
| 6 × 6-3 × 3         | 90%    | 10                  | 2      | TT   | 7      | 5       | 1765.14   | 2578.29     | 309.57 | 185.86   | 3.95         | 116.76 |
| 6 × 6-3 × 3         | 90%    | 10                  | 3      | MS   | 7      | 0       | 885.57    | 2652.57     | 309.57 | 260.14   | 11.72        | 127.29 |
| 6 × 6-3 × 3         | 90%    | 10                  | 3      | TT   | 7      | 5       | 1418.14   | 2571.00     | 309.57 | 178.57   | 7.69         | 107.15 |
| 6 × 6-3 × 3         | 90%    | 10                  | 4      | MS   | 7      | 0       | 674.00    | 2686.71     | 309.57 | 294.29   | 21.83        | 174.64 |
| 6 × 6-3 × 3         | 90%    | 10                  | 4      | TT   | 7      | 4       | 1238.71   | 2571.57     | 309.57 | 179.14   | 11.90        | 151.47 |
| 6 × 6-3 × 3         | 90%    | 10                  | 5      | MS   | 7      | 0       | 547.14    | 2719.57     | 309.57 | 323.43   | 32.60        | 170.03 |
| 6 × 6-3 × 3         | 90%    | 10                  | 5      | TT   | 7      | 4       | 1184.00   | 2567.57     | 309.57 | 175.14   | 19.30        | 118.56 |
| 6 × 6-4 × 4         | 40%    | 5                   | 2      | MS   | 10     | 9       | 209.10    | 390.20      | 6.30   | 71.90    | 0.04         | 0.11   |
| 6 × 6-4 × 4         | 40%    | 5                   | 2      | TT   | 10     | 10      | 291.30    | 376.40      | 6.30   | 58.10    | 0.02         | 0.06   |
| 6 × 6-4 × 4         | 40%    | 5                   | 3      | MS   | 10     | 9       | 147.40    | 389.00      | 6.30   | 70.60    | 0.05         | 0.24   |
| 6 × 6-4 × 4         | 40%    | 5                   | 3      | TT   | 10     | 10      | 234.60    | 370.50      | 6.30   | 52.20    | 0.03         | 0.09   |
| 6 × 6-4 × 4         | 40%    | 5                   | 4      | MS   | 10     | 10      | 117.80    | 387.70      | 6.30   | 69.30    | 0.08         | 0.29   |
| 6 × 6-4 × 4         | 40%    | 5                   | 4      | TT   | 10     | 10      | 203.60    | 366.30      | 6.30   | 48.00    | 0.05         | 0.11   |
| 6 × 6-4 × 4         | 40%    | 5                   | 5      | MS   | 10     | 10      | 104.70    | 399.00      | 6.30   | 80.30    | 0.10         | 0.22   |
| 6 × 6-4 × 4         | 40%    | 5                   | 5      | TT   | 10     | 10      | 203.50    | 359.80      | 6.30   | 41.50    | 0.06         | 0.14   |

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Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 6 × 6-4 × 4         | 40%    | 10                  | 2      | MS   | 10     | 8       | 252.20    | 485.90      | 8.30   | 81.60    | 0.06         | 0.30   |
| 6 × 6-4 × 4         | 40%    | 10                  | 2      | TT   | 10     | 10      | 349.70    | 471.00      | 8.30   | 66.70    | 0.04         | 0.09   |
| 6 × 6-4 × 4         | 40%    | 10                  | 3      | MS   | 10     | 8       | 177.30    | 493.00      | 8.30   | 88.70    | 0.09         | 0.51   |
| 6 × 6-4 × 4         | 40%    | 10                  | 3      | TT   | 10     | 10      | 303.30    | 464.30      | 8.30   | 60       | 0.05         | 0.12   |
| 6 × 6-4 × 4         | 40%    | 10                  | 4      | MS   | 10     | 10      | 140.10    | 495.90      | 8.30   | 91.50    | 0.11         | 0.66   |
| 6 × 6-4 × 4         | 40%    | 10                  | 4      | TT   | 10     | 10      | 271.90    | 460.10      | 8.30   | 55.80    | 0.07         | 0.16   |
| 6 × 6-4 × 4         | 40%    | 10                  | 5      | MS   | 10     | 10      | 127.30    | 496.00      | 8.30   | 91.60    | 0.16         | 0.43   |
| 6 × 6-4 × 4         | 40%    | 10                  | 5      | TT   | 10     | 10      | 249.90    | 455.00      | 8.30   | 50.70    | 0.09         | 0.21   |
| 6 × 6-4 × 4         | 60%    | 5                   | 2      | MS   | 10     | 0       | 598.00    | 1194.40     | 28.60  | 151.80   | 0.41         | 39.48  |
| 6 × 6-4 × 4         | 60%    | 5                   | 2      | TT   | 10     | 10      | 900.20    | 1173.10     | 28.60  | 130.50   | 0.24         | 1.29   |
| 6 × 6-4 × 4         | 60%    | 5                   | 3      | MS   | 10     | 0       | 423.00    | 1243.10     | 28.60  | 200.30   | 0.77         | 33.97  |
| 6 × 6-4 × 4         | 60%    | 5                   | 3      | TT   | 10     | 10      | 653.90    | 1165.30     | 28.60  | 122.70   | 0.44         | 1.56   |
| 6 × 6-4 × 4         | 60%    | 5                   | 4      | MS   | 10     | 1       | 310       | 1217.50     | 28.60  | 173.90   | 1.21         | 57.72  |
| 6 × 6-4 × 4         | 60%    | 5                   | 4      | TT   | 10     | 10      | 598.40    | 1159.70     | 28.60  | 117.10   | 0.60         | 2.51   |
| 6 × 6-4 × 4         | 60%    | 5                   | 5      | MS   | 10     | 2       | 262.70    | 1280.30     | 28.60  | 232.40   | 1.52         | 31.38  |
| 6 × 6-4 × 4         | 60%    | 5                   | 5      | TT   | 10     | 10      | 511.90    | 1154.60     | 28.60  | 112.00   | 0.83         | 3.76   |
| 6 × 6-4 × 4         | 60%    | 10                  | 2      | MS   | 10     | 0       | 713.90    | 1424.90     | 34.70  | 183.50   | 0.76         | 78.23  |
| 6 × 6-4 × 4         | 60%    | 10                  | 2      | TT   | 10     | 10      | 1014.20   | 1379.90     | 34.70  | 139.20   | 0.41         | 2.21   |
| 6 × 6-4 × 4         | 60%    | 10                  | 3      | MS   | 10     | 0       | 482.50    | 1439.30     | 34.70  | 198.40   | 1.31         | 102.85 |
| 6 × 6-4 × 4         | 60%    | 10                  | 3      | TT   | 10     | 10      | 811.30    | 1372.70     | 34.70  | 132.00   | 0.71         | 4.13   |
| 6 × 6-4 × 4         | 60%    | 10                  | 4      | MS   | 10     | 0       | 375.60    | 1478.00     | 34.70  | 236.00   | 2.09         | 43.70  |
| 6 × 6-4 × 4         | 60%    | 10                  | 4      | TT   | 10     | 10      | 664.40    | 1365.40     | 34.70  | 124.70   | 0.99         | 6.29   |
| 6 × 6-4 × 4         | 60%    | 10                  | 5      | MS   | 10     | 1       | 306.50    | 1503.00     | 34.70  | 256.00   | 2.88         | 68.29  |
| 6 × 6-4 × 4         | 60%    | 10                  | 5      | TT   | 10     | 10      | 620.90    | 1361.20     | 34.70  | 120.50   | 1.36         | 5.37   |
| 6 × 6-4 × 4         | 80%    | 5                   | 2      | MS   | 10     | 0       | 1317.80   | 2634.00     | 127.60 | 268.40   | 6.32         | 207.59 |
| 6 × 6-4 × 4         | 80%    | 5                   | 2      | TT   | 10     | 10      | 2064.10   | 2569.70     | 127.60 | 204.10   | 2.65         | 21.29  |
| 6 × 6-4 × 4         | 80%    | 5                   | 3      | MS   | 10     | 0       | 894.20    | 2678.40     | 127.60 | 312.80   | 12.61        | 220.91 |
| 6 × 6-4 × 4         | 80%    | 5                   | 3      | TT   | 10     | 10      | 1668.20   | 2561.80     | 127.60 | 196.20   | 5.79         | 34.12  |
| 6 × 6-4 × 4         | 80%    | 5                   | 4      | MS   | 10     | 0       | 682.70    | 2718.20     | 127.60 | 352.40   | 20.17        | 179.13 |
| 6 × 6-4 × 4         | 80%    | 5                   | 4      | TT   | 10     | 10      | 1436.30   | 2555.70     | 127.60 | 190.10   | 8.87         | 44.14  |
| 6 × 6-4 × 4         | 80%    | 5                   | 5      | MS   | 10     | 0       | 558.50    | 2775.00     | 127.60 | 409.40   | 26.96        | 144.71 |
| 6 × 6-4 × 4         | 80%    | 5                   | 5      | TT   | 10     | 10      | 1317.70   | 2551.90     | 127.60 | 186.30   | 12.88        | 71.64  |
| 6 × 6-4 × 4         | 80%    | 10                  | 2      | MS   | 10     | 0       | 1506.30   | 3010.90     | 160.30 | 312.60   | 9.90         | 231.64 |
| 6 × 6-4 × 4         | 80%    | 10                  | 2      | TT   | 10     | 9       | 1899.80   | 2921.20     | 160.30 | 222.90   | 4.53         | 27.13  |
| 6 × 6-4 × 4         | 80%    | 10                  | 3      | MS   | 10     | 0       | 1023.50   | 3068.00     | 160.30 | 369.70   | 19.53        | 144.63 |
| 6 × 6-4 × 4         | 80%    | 10                  | 3      | TT   | 10     | 9       | 1783.70   | 2915.60     | 160.30 | 217.30   | 8.90         | 81.63  |
| 6 × 6-4 × 4         | 80%    | 10                  | 4      | MS   | 10     | 0       | 778.50    | 3100.60     | 160.30 | 402.30   | 27.18        | 200.11 |
| 6 × 6-4 × 4         | 80%    | 10                  | 4      | TT   | 10     | 9       | 1457.70   | 2910.10     | 160.30 | 211.80   | 15.63        | 103.44 |
| 6 × 6-4 × 4         | 80%    | 10                  | 5      | MS   | 10     | 0       | 633.40    | 3150.90     | 160.30 | 452.20   | 34.65        | 210.41 |
| 6 × 6-4 × 4         | 80%    | 10                  | 5      | TT   | 10     | 9       | 1261.90   | 2904.20     | 160.30 | 205.90   | 21.92        | 118.45 |
| 6 × 6-4 × 4         | 90%    | 5                   | 2      | MS   | 6      | 0       | 1951.67   | 3899.83     | 420    | 399.83   | 19.70        | 167.08 |
| 6 × 6-4 × 4         | 90%    | 5                   | 2      | TT   | 6      | 4       | 2540.83   | 3794.17     | 420    | 294.17   | 11.78        | 107.97 |
| 6 × 6-4 × 4         | 90%    | 5                   | 3      | MS   | 6      | 0       | 1327.50   | 3979.00     | 420    | 479.00   | 36.51        | 230.61 |
| 6 × 6-4 × 4         | 90%    | 5                   | 3      | TT   | 6      | 3       | 2416.33   | 3785.67     | 420    | 285.67   | 24.70        | 172.58 |
| 6 × 6-4 × 4         | 90%    | 5                   | 4      | MS   | 6      | 0       | 1009.67   | 4028.33     | 420    | 528.33   | 52.20        | 242.37 |
| 6 × 6-4 × 4         | 90%    | 5                   | 4      | TT   | 6      | 3       | 1924.17   | 3780.83     | 420    | 280.83   | 38.01        | 205.95 |
| 6 × 6-4 × 4         | 90%    | 5                   | 5      | MS   | 6      | 0       | 830.83    | 4138.83     | 420    | 637.67   | 56.46        | 269.85 |
| 6 × 6-4 × 4         | 90%    | 5                   | 5      | TT   | 6      | 2       | 1760.17   | 3783.17     | 420    | 283.17   | 52.89        | 215.87 |
| 6 × 6-4 × 4         | 90%    | 10                  | 2      | MS   | 1      | 0       | 2203.00   | 4405.00     | 561.00 | 424.00   | 19.04        | 145.17 |
| 6 × 6-4 × 4         | 90%    | 10                  | 2      | TT   | 1      | 1       | 2572.00   | 4266.00     | 561.00 | 285.00   | 8.95         | 194.47 |
| 6 × 6-4 × 4         | 90%    | 10                  | 3      | MS   | 1      | 0       | 1514.00   | 4540        | 561.00 | 559.00   | 50.51        | 179.39 |
| 6 × 6-4 × 4         | 90%    | 10                  | 3      | TT   | 1      | 0       | 3784.00   | 4275.00     | 561.00 | 294.00   | 38.04        | 257.40 |
| 6 × 6-4 × 4         | 90%    | 10                  | 4      | MS   | 1      | 0       | 1165.00   | 4658.00     | 561.00 | 677.00   | 55.40        | 138.06 |
| 6 × 6-4 × 4         | 90%    | 10                  | 4      | TT   | 1      | 0       | 1880      | 4306.00     | 561.00 | 325.00   | 55.24        | 290.67 |
| 6 × 6-4 × 4         | 90%    | 10                  | 5      | MS   | 1      | 0       | 953.00    | 4738.00     | 561.00 | 757.00   | 44.82        | 225.00 |
| 6 × 6-4 × 4         | 90%    | 10                  | 5      | TT   | 1      | 0       | 1576.00   | 4280        | 561.00 | 299.00   | 60.13        | 278.09 |
| 6 × 6-5 × 5         | 40%    | 5                   | 2      | MS   | 10     | 9       | 296.60    | 582.60      | 9.10   | 111.50   | 0.06         | 3.73   |
| 6 × 6-5 × 5         | 40%    | 5                   | 2      | TT   | 10     | 10      | 445.00    | 562.90      | 9.10   | 91.80    | 0.04         | 0.10   |
| 6 × 6-5 × 5         | 40%    | 5                   | 3      | MS   | 10     | 9       | 209.30    | 595.60      | 9.10   | 124.50   | 0.10         | 0.39   |
| 6 × 6-5 × 5         | 40%    | 5                   | 3      | TT   | 10     | 10      | 382.80    | 556.10      | 9.10   | 85.00    | 0.06         | 0.13   |
| 6 × 6-5 × 5         | 40%    | 5                   | 4      | MS   | 10     | 10      | 166.90    | 604.50      | 9.10   | 133.40   | 0.13         | 0.61   |
| 6 × 6-5 × 5         | 40%    | 5                   | 4      | TT   | 10     | 10      | 307.70    | 549.80      | 9.10   | 78.70    | 0.08         | 0.18   |
| 6 × 6-5 × 5         | 40%    | 5                   | 5      | MS   | 10     | 10      | 144.50    | 597.70      | 9.10   | 124.60   | 0.18         | 0.37   |
| 6 × 6-5 × 5         | 40%    | 5                   | 5      | TT   | 10     | 10      | 288.90    | 541.70      | 9.10   | 70.60    | 0.10         | 0.24   |
| 6 × 6-5 × 5         | 40%    | 10                  | 2      | MS   | 10     | 5       | 377.00    | 744.90      | 12.00  | 138.90   | 0.10         | 25.45  |
| 6 × 6-5 × 5         | 40%    | 10                  | 2      | TT   | 10     | 10      | 545.50    | 716.10      | 12.00  | 110.10   | 0.07         | 0.25   |
| 6 × 6-5 × 5         | 40%    | 10                  | 3      | MS   | 10     | 6       | 257.30    | 753.40      | 12.00  | 147.40   | 0.18         | 8.05   |
| 6 × 6-5 × 5         | 40%    | 10                  | 3      | TT   | 10     | 10      | 481.30    | 709.50      | 12.00  | 103.50   | 0.11         | 0.39   |
| 6 × 6-5 × 5         | 40%    | 10                  | 4      | MS   | 10     | 9       | 203.60    | 756.80      | 12.00  | 147.30   | 0.24         | 1.21   |
| 6 × 6-5 × 5         | 40%    | 10                  | 4      | TT   | 10     | 10      | 373.80    | 701.70      | 12.00  | 95.70    | 0.14         | 0.34   |
| 6 × 6-5 × 5         | 40%    | 10                  | 5      | MS   | 10     | 9       | 173.00    | 766.20      | 12.00  | 160.10   | 0.32         | 1.50   |
| 6 × 6-5 × 5         | 40%    | 10                  | 5      | TT   | 10     | 10      | 359.40    | 695.70      | 12.00  | 89.70    | 0.19         | 0.39   |
| 6 × 6-5 × 5         | 60%    | 5                   | 2      | MS   | 5      | 0       | 876.20    | 1750.40     | 37.40  | 249.00   | 0.93         | 117.61 |
| 6 × 6-5 × 5         | 60%    | 5                   | 2      | TT   | 5      | 5       | 1352.60   | 1708.80     | 37.40  | 207.40   | 0.64         | 4.30   |

(continued on next page)

Table 15 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |       |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|-------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best  |
| 6 × 6-5 × 5         | 60%    | 5                   | 3      | MS   | 5      | 0       | 598.60    | 1787.40     | 37.40  | 286.00   | 2.33         | 98.50 |
| 6 × 6-5 × 5         | 60%    | 5                   | 3      | TT   | 5      | 5       | 899.80    | 1698.60     | 37.40  | 197.20   | 1.05         | 4.20  |
| 6 × 6-5 × 5         | 60%    | 5                   | 4      | MS   | 5      | 0       | 462.80    | 1831.40     | 37.40  | 330      | 3.05         | 36.56 |
| 6 × 6-5 × 5         | 60%    | 5                   | 4      | TT   | 5      | 5       | 835.40    | 1690.80     | 37.40  | 189.40   | 1.65         | 11.43 |
| 6 × 6-5 × 5         | 60%    | 5                   | 5      | MS   | 5      | 0       | 379.80    | 1858.00     | 37.40  | 356.60   | 4.06         | 80.40 |
| 6 × 6-5 × 5         | 60%    | 5                   | 5      | TT   | 5      | 5       | 819.40    | 1681.80     | 37.40  | 180.40   | 2.24         | 13.43 |
| 6 × 6-5 × 5         | 60%    | 10                  | 2      | MS   | 2      | 0       | 956.50    | 1911.00     | 48.00  | 243.00   | 1.77         | 44.13 |
| 6 × 6-5 × 5         | 60%    | 10                  | 2      | TT   | 2      | 2       | 1150      | 1888.00     | 48.00  | 220      | 0.84         | 5.61  |
| 6 × 6-5 × 5         | 60%    | 10                  | 3      | MS   | 2      | 0       | 669.50    | 2007.00     | 48.00  | 339.00   | 3.75         | 37.20 |
| 6 × 6-5 × 5         | 60%    | 10                  | 3      | TT   | 2      | 2       | 858.00    | 1879.50     | 48.00  | 211.50   | 1.35         | 8.27  |
| 6 × 6-5 × 5         | 60%    | 10                  | 4      | MS   | 2      | 0       | 514.00    | 2022.00     | 48.00  | 354.00   | 5.76         | 47.85 |
| 6 × 6-5 × 5         | 60%    | 10                  | 4      | TT   | 2      | 2       | 784.50    | 1868.00     | 48.00  | 200      | 2.20         | 8.72  |
| 6 × 6-5 × 5         | 60%    | 10                  | 5      | MS   | 2      | 0       | 421.00    | 2098.00     | 48.00  | 430      | 6.87         | 78.87 |
| 6 × 6-5 × 5         | 60%    | 10                  | 5      | TT   | 2      | 2       | 612.00    | 1853.00     | 48.00  | 185.00   | 3.37         | 10.03 |
| 6 × 6-6 × 6         | 40%    | 5                   | 2      | MS   | 3      | 3       | 311.00    | 617.67      | 8.67   | 149.00   | 0.05         | 0.39  |
| 6 × 6-6 × 6         | 40%    | 5                   | 2      | TT   | 3      | 3       | 464.33    | 590         | 8.67   | 121.33   | 0.04         | 0.09  |
| 6 × 6-6 × 6         | 40%    | 5                   | 3      | MS   | 3      | 3       | 210       | 610.33      | 8.67   | 141.67   | 0.09         | 0.28  |
| 6 × 6-6 × 6         | 40%    | 5                   | 3      | TT   | 3      | 3       | 339.33    | 573.67      | 8.67   | 105.00   | 0.06         | 0.11  |
| 6 × 6-6 × 6         | 40%    | 5                   | 4      | MS   | 3      | 3       | 172.33    | 617.00      | 8.67   | 148.33   | 0.14         | 0.35  |
| 6 × 6-6 × 6         | 40%    | 5                   | 4      | TT   | 3      | 3       | 250.33    | 566.00      | 8.67   | 97.33    | 0.07         | 0.13  |
| 6 × 6-6 × 6         | 40%    | 5                   | 5      | MS   | 3      | 3       | 148.67    | 620.67      | 8.67   | 151.33   | 0.17         | 0.44  |
| 6 × 6-6 × 6         | 40%    | 5                   | 5      | TT   | 3      | 3       | 242.00    | 556.33      | 8.67   | 87.67    | 0.09         | 0.23  |

Table 16

Step 3: Detailed Results Routing two-tier.

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |       |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|-------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best  |
| 3 × 3-2 × 2         | 40%    | 5                   | 2      | MS   | 9      | 9       | 125.67    | 208.11      | 5.11   | 16.33    | 0.01         | 0.02  |
| 3 × 3-2 × 2         | 40%    | 5                   | 2      | TT   | 9      | 9       | 133.44    | 206.33      | 5.11   | 14.56    | 0.01         | 0.01  |
| 3 × 3-2 × 2         | 40%    | 5                   | 3      | MS   | 9      | 9       | 85.11     | 212.11      | 5.11   | 17.67    | 0.01         | 0.03  |
| 3 × 3-2 × 2         | 40%    | 5                   | 3      | TT   | 9      | 9       | 131.67    | 204.22      | 5.11   | 12.44    | 0.01         | 0.02  |
| 3 × 3-2 × 2         | 40%    | 5                   | 4      | MS   | 9      | 9       | 80.89     | 215.44      | 5.11   | 18.44    | 0.02         | 0.03  |
| 3 × 3-2 × 2         | 40%    | 5                   | 4      | TT   | 9      | 9       | 116.89    | 203.56      | 5.11   | 11.78    | 0.01         | 0.02  |
| 3 × 3-2 × 2         | 40%    | 5                   | 5      | MS   | 9      | 9       | 73.56     | 213.44      | 5.11   | 16.44    | 0.02         | 0.04  |
| 3 × 3-2 × 2         | 40%    | 5                   | 5      | TT   | 9      | 9       | 108.22    | 202.33      | 5.11   | 10.56    | 0.02         | 0.04  |
| 3 × 3-2 × 2         | 40%    | 10                  | 2      | MS   | 10     | 10      | 119.80    | 215.50      | 5.40   | 16.50    | 0.01         | 0.02  |
| 3 × 3-2 × 2         | 40%    | 10                  | 2      | TT   | 10     | 10      | 127.10    | 205.60      | 5.40   | 14.20    | 0.03         | 0.03  |
| 3 × 3-2 × 2         | 40%    | 10                  | 3      | MS   | 10     | 10      | 89.90     | 209.70      | 5.40   | 16.10    | 0.01         | 0.03  |
| 3 × 3-2 × 2         | 40%    | 10                  | 3      | TT   | 10     | 10      | 125.70    | 203.50      | 5.40   | 12.10    | 0.01         | 0.02  |
| 3 × 3-2 × 2         | 40%    | 10                  | 4      | MS   | 10     | 10      | 79.70     | 214.10      | 5.40   | 17.20    | 0.02         | 0.03  |
| 3 × 3-2 × 2         | 40%    | 10                  | 4      | TT   | 10     | 10      | 111.70    | 202.80      | 5.40   | 11.40    | 0.01         | 0.02  |
| 3 × 3-2 × 2         | 40%    | 10                  | 5      | MS   | 10     | 10      | 73.30     | 211.60      | 5.40   | 15.10    | 0.02         | 0.04  |
| 3 × 3-2 × 2         | 40%    | 10                  | 5      | TT   | 10     | 10      | 98.30     | 201.50      | 5.40   | 10.10    | 0.02         | 0.04  |
| 3 × 3-2 × 2         | 60%    | 5                   | 2      | MS   | 10     | 10      | 202.20    | 377.60      | 15.00  | 23.70    | 0.03         | 0.06  |
| 3 × 3-2 × 2         | 60%    | 5                   | 2      | TT   | 10     | 10      | 290.70    | 370.80      | 15.00  | 19.80    | 0.03         | 0.05  |
| 3 × 3-2 × 2         | 60%    | 5                   | 3      | MS   | 10     | 10      | 145.80    | 380.90      | 15.00  | 24.70    | 0.05         | 0.13  |
| 3 × 3-2 × 2         | 60%    | 5                   | 3      | TT   | 10     | 10      | 224.30    | 368.00      | 15.00  | 17.00    | 0.04         | 0.06  |
| 3 × 3-2 × 2         | 60%    | 5                   | 4      | MS   | 10     | 10      | 126.40    | 395.80      | 15.00  | 30.40    | 0.07         | 0.15  |
| 3 × 3-2 × 2         | 60%    | 5                   | 4      | TT   | 10     | 10      | 203.20    | 365.60      | 15.00  | 14.60    | 0.05         | 0.08  |
| 3 × 3-2 × 2         | 60%    | 5                   | 5      | MS   | 10     | 10      | 110.60    | 410         | 15.00  | 30.30    | 0.10         | 0.19  |
| 3 × 3-2 × 2         | 60%    | 5                   | 5      | TT   | 10     | 10      | 176.20    | 364.60      | 15.00  | 13.60    | 0.06         | 0.11  |
| 3 × 3-2 × 2         | 60%    | 10                  | 2      | MS   | 10     | 10      | 227.70    | 450.20      | 19.70  | 28.80    | 0.04         | 0.16  |
| 3 × 3-2 × 2         | 60%    | 10                  | 2      | TT   | 10     | 10      | 300.20    | 439.30      | 19.70  | 23.60    | 0.03         | 0.06  |
| 3 × 3-2 × 2         | 60%    | 10                  | 3      | MS   | 10     | 10      | 160.60    | 447.20      | 19.70  | 29.00    | 0.07         | 0.17  |
| 3 × 3-2 × 2         | 60%    | 10                  | 3      | TT   | 10     | 10      | 258.90    | 435.80      | 19.70  | 20.10    | 0.04         | 0.08  |
| 3 × 3-2 × 2         | 60%    | 10                  | 4      | MS   | 10     | 10      | 138.50    | 455.90      | 19.70  | 34.00    | 0.10         | 0.20  |
| 3 × 3-2 × 2         | 60%    | 10                  | 4      | TT   | 10     | 10      | 242.60    | 434.10      | 19.70  | 18.40    | 0.06         | 0.09  |
| 3 × 3-2 × 2         | 60%    | 10                  | 5      | MS   | 10     | 10      | 127.70    | 481.00      | 19.70  | 35.50    | 0.13         | 0.26  |
| 3 × 3-2 × 2         | 60%    | 10                  | 5      | TT   | 10     | 10      | 235.70    | 432.60      | 19.70  | 16.90    | 0.08         | 0.12  |
| 3 × 3-2 × 2         | 80%    | 5                   | 2      | MS   | 10     | 3       | 414.50    | 821.70      | 52.40  | 53.20    | 0.17         | 32.70 |
| 3 × 3-2 × 2         | 80%    | 5                   | 2      | TT   | 10     | 10      | 643.90    | 805.90      | 52.40  | 39.50    | 0.12         | 0.38  |
| 3 × 3-2 × 2         | 80%    | 5                   | 3      | MS   | 10     | 3       | 292.30    | 840.60      | 52.40  | 60.10    | 0.33         | 17.44 |
| 3 × 3-2 × 2         | 80%    | 5                   | 3      | TT   | 10     | 10      | 530.50    | 802.40      | 52.40  | 36.00    | 0.19         | 0.63  |
| 3 × 3-2 × 2         | 80%    | 5                   | 4      | MS   | 10     | 5       | 224.80    | 843.40      | 52.40  | 59.10    | 0.50         | 27.99 |
| 3 × 3-2 × 2         | 80%    | 5                   | 4      | TT   | 10     | 10      | 455.40    | 800.80      | 52.40  | 34.40    | 0.28         | 0.99  |
| 3 × 3-2 × 2         | 80%    | 5                   | 5      | MS   | 10     | 7       | 183.80    | 851.80      | 52.40  | 59.50    | 0.63         | 20.32 |
| 3 × 3-2 × 2         | 80%    | 5                   | 5      | TT   | 10     | 10      | 395.40    | 799.00      | 52.40  | 32.60    | 0.36         | 1.18  |
| 3 × 3-2 × 2         | 80%    | 10                  | 2      | MS   | 10     | 1       | 482.50    | 957.40      | 70.90  | 58.50    | 0.30         | 8.17  |
| 3 × 3-2 × 2         | 80%    | 10                  | 2      | TT   | 10     | 10      | 701.90    | 947.30      | 70.90  | 48.40    | 0.24         | 1.30  |
| 3 × 3-2 × 2         | 80%    | 10                  | 3      | MS   | 10     | 1       | 331.60    | 971.00      | 70.90  | 65.20    | 0.59         | 27.82 |
| 3 × 3-2 × 2         | 80%    | 10                  | 3      | TT   | 10     | 10      | 585.70    | 943.80      | 70.90  | 44.90    | 0.33         | 1.70  |

(continued on next page)

Table 16 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 3 × 3-2 × 2         | 80%    | 10                  | 4      | MS   | 10     | 4       | 254.70    | 985.30      | 70.90  | 70.60    | 0.86         | 40.69  |
| 3 × 3-2 × 2         | 80%    | 10                  | 4      | TT   | 10     | 10      | 503.00    | 942.20      | 70.90  | 43.30    | 0.56         | 3.48   |
| 3 × 3-2 × 2         | 80%    | 10                  | 5      | MS   | 10     | 5       | 219.90    | 998.60      | 70.90  | 71.50    | 1.15         | 6.01   |
| 3 × 3-2 × 2         | 80%    | 10                  | 5      | TT   | 10     | 10      | 468.90    | 940.30      | 70.90  | 41.40    | 0.65         | 4.07   |
| 3 × 3-2 × 2         | 90%    | 5                   | 2      | MS   | 9      | 3       | 563.78    | 1117.56     | 88.56  | 87.89    | 0.42         | 48.61  |
| 3 × 3-2 × 2         | 90%    | 5                   | 2      | TT   | 9      | 9       | 944.33    | 1095.22     | 88.56  | 73.33    | 0.35         | 1.30   |
| 3 × 3-2 × 2         | 90%    | 5                   | 3      | MS   | 9      | 3       | 388.67    | 1135.33     | 88.56  | 82.78    | 0.84         | 13.35  |
| 3 × 3-2 × 2         | 90%    | 5                   | 3      | TT   | 9      | 9       | 763.78    | 1090.22     | 88.56  | 68.33    | 0.61         | 2.38   |
| 3 × 3-2 × 2         | 90%    | 5                   | 4      | MS   | 9      | 5       | 310.67    | 1183.22     | 88.56  | 90.11    | 1.50         | 6.22   |
| 3 × 3-2 × 2         | 90%    | 5                   | 4      | TT   | 9      | 8       | 738.00    | 1088.89     | 88.56  | 67.00    | 0.99         | 10.28  |
| 3 × 3-2 × 2         | 90%    | 5                   | 5      | MS   | 9      | 7       | 269.78    | 1245.22     | 88.56  | 91.78    | 1.88         | 3.82   |
| 3 × 3-2 × 2         | 90%    | 5                   | 5      | TT   | 9      | 8       | 715.44    | 1087.78     | 88.56  | 65.89    | 1.87         | 7.81   |
| 3 × 3-2 × 2         | 90%    | 10                  | 2      | MS   | 7      | 4       | 601.86    | 1186.43     | 91.29  | 94.14    | 0.45         | 6.12   |
| 3 × 3-2 × 2         | 90%    | 10                  | 2      | TT   | 7      | 7       | 1037.29   | 1168.00     | 91.29  | 82.43    | 0.34         | 1.13   |
| 3 × 3-2 × 2         | 90%    | 10                  | 3      | MS   | 7      | 2       | 421.00    | 1224.71     | 91.29  | 98.14    | 0.92         | 11.78  |
| 3 × 3-2 × 2         | 90%    | 10                  | 3      | TT   | 7      | 7       | 905.14    | 1163.43     | 91.29  | 77.86    | 0.64         | 6.03   |
| 3 × 3-2 × 2         | 90%    | 10                  | 4      | MS   | 7      | 4       | 344.29    | 1283.71     | 91.29  | 106.00   | 1.49         | 6.98   |
| 3 × 3-2 × 2         | 90%    | 10                  | 4      | TT   | 7      | 7       | 885.86    | 1161.86     | 91.29  | 76.29    | 0.97         | 12.19  |
| 3 × 3-2 × 2         | 90%    | 10                  | 5      | MS   | 7      | 6       | 301.86    | 1363.57     | 91.29  | 99.86    | 2.15         | 23.06  |
| 3 × 3-2 × 2         | 90%    | 10                  | 5      | TT   | 7      | 7       | 893.86    | 1161.00     | 91.29  | 75.43    | 1.40         | 12.88  |
| 3 × 3-3 × 3         | 40%    | 5                   | 2      | MS   | 10     | 9       | 249.30    | 479.50      | 10.90  | 48.60    | 0.05         | 0.19   |
| 3 × 3-3 × 3         | 40%    | 5                   | 2      | TT   | 10     | 10      | 313.80    | 467.40      | 10.90  | 36.50    | 0.03         | 0.09   |
| 3 × 3-3 × 3         | 40%    | 5                   | 3      | MS   | 10     | 9       | 180.50    | 482.80      | 10.90  | 51.90    | 0.07         | 0.25   |
| 3 × 3-3 × 3         | 40%    | 5                   | 3      | TT   | 10     | 10      | 291.30    | 463.80      | 10.90  | 32.90    | 0.05         | 0.10   |
| 3 × 3-3 × 3         | 40%    | 5                   | 4      | MS   | 10     | 10      | 139.30    | 478.50      | 10.90  | 44.10    | 0.12         | 0.24   |
| 3 × 3-3 × 3         | 40%    | 5                   | 4      | TT   | 10     | 10      | 238.40    | 460.30      | 10.90  | 29.40    | 0.07         | 0.12   |
| 3 × 3-3 × 3         | 40%    | 5                   | 5      | MS   | 10     | 10      | 125.00    | 488.60      | 10.90  | 48.40    | 0.15         | 0.32   |
| 3 × 3-3 × 3         | 40%    | 5                   | 5      | TT   | 10     | 10      | 211.80    | 458.10      | 10.90  | 27.20    | 0.08         | 0.16   |
| 3 × 3-3 × 3         | 40%    | 10                  | 2      | MS   | 10     | 9       | 263.00    | 517.20      | 13.20  | 48.00    | 0.05         | 1.14   |
| 3 × 3-3 × 3         | 40%    | 10                  | 2      | TT   | 10     | 10      | 393.20    | 507.70      | 13.20  | 38.50    | 0.04         | 0.10   |
| 3 × 3-3 × 3         | 40%    | 10                  | 3      | MS   | 10     | 9       | 188.10    | 520.70      | 13.20  | 50       | 0.08         | 0.26   |
| 3 × 3-3 × 3         | 40%    | 10                  | 3      | TT   | 10     | 10      | 331.20    | 504.50      | 13.20  | 35.30    | 0.06         | 0.10   |
| 3 × 3-3 × 3         | 40%    | 10                  | 4      | MS   | 10     | 10      | 146.60    | 521.30      | 13.20  | 47.70    | 0.13         | 0.35   |
| 3 × 3-3 × 3         | 40%    | 10                  | 4      | TT   | 10     | 10      | 290.40    | 500.70      | 13.20  | 31.50    | 0.08         | 0.14   |
| 3 × 3-3 × 3         | 40%    | 10                  | 5      | MS   | 10     | 10      | 126.70    | 528.40      | 13.20  | 49.80    | 0.18         | 0.38   |
| 3 × 3-3 × 3         | 40%    | 10                  | 5      | TT   | 10     | 10      | 250.70    | 498.40      | 13.20  | 29.20    | 0.10         | 0.18   |
| 3 × 3-3 × 3         | 60%    | 5                   | 2      | MS   | 10     | 1       | 461.80    | 921.70      | 34.50  | 75.90    | 0.23         | 17.91  |
| 3 × 3-3 × 3         | 60%    | 5                   | 2      | TT   | 10     | 10      | 680.20    | 896.60      | 34.50  | 52.10    | 0.14         | 0.22   |
| 3 × 3-3 × 3         | 60%    | 5                   | 3      | MS   | 10     | 1       | 317.60    | 925.00      | 34.50  | 79.70    | 0.36         | 37.68  |
| 3 × 3-3 × 3         | 60%    | 5                   | 3      | TT   | 10     | 10      | 592.40    | 893.20      | 34.50  | 48.70    | 0.21         | 0.36   |
| 3 × 3-3 × 3         | 60%    | 5                   | 4      | MS   | 10     | 3       | 245.10    | 922.40      | 34.50  | 75.60    | 0.54         | 30.07  |
| 3 × 3-3 × 3         | 60%    | 5                   | 4      | TT   | 10     | 10      | 509.20    | 890.60      | 34.50  | 46.10    | 0.31         | 0.52   |
| 3 × 3-3 × 3         | 60%    | 5                   | 5      | MS   | 10     | 7       | 200.50    | 936.80      | 34.50  | 84.00    | 0.71         | 26.83  |
| 3 × 3-3 × 3         | 60%    | 5                   | 5      | TT   | 10     | 10      | 421.50    | 888.70      | 34.50  | 44.20    | 0.40         | 0.87   |
| 3 × 3-3 × 3         | 60%    | 10                  | 2      | MS   | 10     | 0       | 551.10    | 1099.10     | 48.80  | 83.90    | 0.34         | 14.37  |
| 3 × 3-3 × 3         | 60%    | 10                  | 2      | TT   | 10     | 10      | 898.40    | 1076.10     | 48.80  | 61.30    | 0.19         | 0.58   |
| 3 × 3-3 × 3         | 60%    | 10                  | 3      | MS   | 10     | 0       | 381.90    | 1121.60     | 48.80  | 105.70   | 0.62         | 49.59  |
| 3 × 3-3 × 3         | 60%    | 10                  | 3      | TT   | 10     | 10      | 710.10    | 1072.40     | 48.80  | 57.60    | 0.32         | 0.84   |
| 3 × 3-3 × 3         | 60%    | 10                  | 4      | MS   | 10     | 0       | 291.50    | 1128.00     | 48.80  | 105.70   | 0.87         | 51.89  |
| 3 × 3-3 × 3         | 60%    | 10                  | 4      | TT   | 10     | 10      | 608.40    | 1069.00     | 48.80  | 54.20    | 0.45         | 0.90   |
| 3 × 3-3 × 3         | 60%    | 10                  | 5      | MS   | 10     | 1       | 248.50    | 1140.90     | 48.80  | 115.30   | 1.14         | 4.33   |
| 3 × 3-3 × 3         | 60%    | 10                  | 5      | TT   | 10     | 10      | 494.20    | 1066.60     | 48.80  | 51.80    | 0.61         | 1.32   |
| 3 × 3-3 × 3         | 80%    | 5                   | 2      | MS   | 8      | 0       | 902.12    | 1803.62     | 143.38 | 122.75   | 2.16         | 91.72  |
| 3 × 3-3 × 3         | 80%    | 5                   | 2      | TT   | 8      | 8       | 1476.88   | 1779.75     | 143.38 | 98.88    | 1.68         | 22.14  |
| 3 × 3-3 × 3         | 80%    | 5                   | 3      | MS   | 8      | 0       | 609.38    | 1825.38     | 143.38 | 144.50   | 4.70         | 118.34 |
| 3 × 3-3 × 3         | 80%    | 5                   | 3      | TT   | 8      | 8       | 1236.50   | 1776.12     | 143.38 | 95.25    | 2.92         | 34.05  |
| 3 × 3-3 × 3         | 80%    | 5                   | 4      | MS   | 8      | 0       | 461.62    | 1837.38     | 143.38 | 155.12   | 8.04         | 122.34 |
| 3 × 3-3 × 3         | 80%    | 5                   | 4      | TT   | 8      | 6       | 989.62    | 1772.00     | 143.38 | 91.12    | 5.06         | 56.08  |
| 3 × 3-3 × 3         | 80%    | 5                   | 5      | MS   | 8      | 0       | 379.50    | 1877.12     | 143.38 | 183.75   | 11.57        | 77.27  |
| 3 × 3-3 × 3         | 80%    | 5                   | 5      | TT   | 8      | 6       | 1024.00   | 1769.75     | 143.38 | 88.88    | 9.01         | 60.75  |
| 3 × 3-3 × 3         | 80%    | 10                  | 2      | MS   | 7      | 0       | 1037.57   | 2074.57     | 180.71 | 144.86   | 3.18         | 116.27 |
| 3 × 3-3 × 3         | 80%    | 10                  | 2      | TT   | 7      | 6       | 1697.86   | 2046.71     | 180.71 | 117.43   | 3.15         | 57.40  |
| 3 × 3-3 × 3         | 80%    | 10                  | 3      | MS   | 7      | 0       | 699.71    | 2093.00     | 180.71 | 162.43   | 7.26         | 142.63 |
| 3 × 3-3 × 3         | 80%    | 10                  | 3      | TT   | 7      | 5       | 1488.57   | 2046.43     | 180.71 | 117.14   | 6.89         | 60.07  |
| 3 × 3-3 × 3         | 80%    | 10                  | 4      | MS   | 7      | 0       | 532.71    | 2121.14     | 180.71 | 188.43   | 12.98        | 134.84 |
| 3 × 3-3 × 3         | 80%    | 10                  | 4      | TT   | 7      | 5       | 1279.00   | 2043.57     | 180.71 | 114.29   | 11.25        | 86.97  |
| 3 × 3-3 × 3         | 80%    | 10                  | 5      | MS   | 7      | 0       | 431.29    | 2140.43     | 180.71 | 204.14   | 20.76        | 138.62 |
| 3 × 3-3 × 3         | 80%    | 10                  | 5      | TT   | 7      | 4       | 1236.71   | 2039.71     | 180.71 | 110.43   | 15.03        | 124.22 |
| 3 × 3-3 × 3         | 90%    | 5                   | 2      | MS   | 3      | 0       | 1198.00   | 2396.00     | 183.33 | 189.00   | 6.16         | 122.64 |
| 3 × 3-3 × 3         | 90%    | 5                   | 2      | TT   | 3      | 1       | 2057.33   | 2355.00     | 183.33 | 151.67   | 5.42         | 97.04  |
| 3 × 3-3 × 3         | 90%    | 5                   | 3      | MS   | 3      | 0       | 810       | 2419.00     | 183.33 | 210      | 14.37        | 150.56 |
| 3 × 3-3 × 3         | 90%    | 5                   | 3      | TT   | 3      | 1       | 1942.67   | 2352.67     | 183.33 | 149.33   | 12.97        | 89.18  |
| 3 × 3-3 × 3         | 90%    | 5                   | 4      | MS   | 3      | 0       | 621.33    | 2475.67     | 183.33 | 238.33   | 24.22        | 121.25 |

(continued on next page)

Table 16 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 3 × 3-3 × 3         | 90%    | 5                   | 4      | TT   | 3      | 1       | 1729.33   | 2352.00     | 183.33 | 148.67   | 20.79        | 163.26 |
| 3 × 3-3 × 3         | 90%    | 5                   | 5      | MS   | 3      | 0       | 500.33    | 2482.33     | 183.33 | 245.33   | 35.07        | 136.81 |
| 3 × 3-3 × 3         | 90%    | 5                   | 5      | TT   | 3      | 1       | 1869.67   | 2350.33     | 183.33 | 147.00   | 31.36        | 143.37 |
| 3 × 3-3 × 3         | 90%    | 10                  | 2      | MS   | 1      | 0       | 1302.00   | 2599.00     | 244.00 | 195.00   | 6.21         | 111.08 |
| 3 × 3-3 × 3         | 90%    | 10                  | 2      | TT   | 1      | 0       | 2143.00   | 2567.00     | 244.00 | 163.00   | 4.96         | 93.45  |
| 3 × 3-3 × 3         | 90%    | 10                  | 3      | MS   | 1      | 0       | 887.00    | 2631.00     | 244.00 | 224.00   | 13.15        | 57.64  |
| 3 × 3-3 × 3         | 90%    | 10                  | 3      | TT   | 1      | 0       | 1865.00   | 2559.00     | 244.00 | 155.00   | 14.02        | 179.15 |
| 3 × 3-3 × 3         | 90%    | 10                  | 4      | MS   | 1      | 0       | 670       | 2664.00     | 244.00 | 260      | 28.37        | 191.91 |
| 3 × 3-3 × 3         | 90%    | 10                  | 4      | TT   | 1      | 0       | 1966.00   | 2570        | 244.00 | 166.00   | 27.73        | 148.41 |
| 3 × 3-3 × 3         | 90%    | 10                  | 5      | MS   | 1      | 0       | 541.00    | 2692.00     | 244.00 | 275.00   | 40.21        | 237.84 |
| 3 × 3-3 × 3         | 90%    | 10                  | 5      | TT   | 1      | 0       | 1582.00   | 2553.00     | 244.00 | 149.00   | 33.41        | 231.52 |
| 3 × 3-4 × 4         | 40%    | 5                   | 2      | MS   | 10     | 1       | 406.60    | 803.90      | 19.40  | 88.50    | 0.16         | 5.30   |
| 3 × 3-4 × 4         | 40%    | 5                   | 2      | TT   | 10     | 10      | 556.90    | 777.30      | 19.40  | 61.90    | 0.09         | 0.19   |
| 3 × 3-4 × 4         | 40%    | 5                   | 3      | MS   | 10     | 1       | 285.30    | 826.00      | 19.40  | 104.00   | 0.24         | 1.08   |
| 3 × 3-4 × 4         | 40%    | 5                   | 3      | TT   | 10     | 10      | 507.40    | 775.30      | 19.40  | 59.90    | 0.14         | 0.33   |
| 3 × 3-4 × 4         | 40%    | 5                   | 4      | MS   | 10     | 6       | 224.50    | 817.10      | 19.40  | 101.70   | 0.34         | 3.51   |
| 3 × 3-4 × 4         | 40%    | 5                   | 4      | TT   | 10     | 10      | 410.40    | 770.20      | 19.40  | 54.80    | 0.20         | 0.33   |
| 3 × 3-4 × 4         | 40%    | 5                   | 5      | MS   | 10     | 9       | 179.70    | 814.00      | 19.40  | 96.00    | 0.45         | 3.27   |
| 3 × 3-4 × 4         | 40%    | 5                   | 5      | TT   | 10     | 10      | 362.60    | 765.60      | 19.40  | 50.20    | 0.26         | 0.51   |
| 3 × 3-4 × 4         | 40%    | 10                  | 2      | MS   | 10     | 0       | 442.50    | 879.40      | 22.40  | 94.50    | 0.18         | 15.05  |
| 3 × 3-4 × 4         | 40%    | 10                  | 2      | TT   | 10     | 10      | 633.20    | 853.60      | 22.40  | 69.20    | 0.11         | 0.29   |
| 3 × 3-4 × 4         | 40%    | 10                  | 3      | MS   | 10     | 0       | 307.00    | 896.60      | 22.40  | 108.60   | 0.30         | 4.39   |
| 3 × 3-4 × 4         | 40%    | 10                  | 3      | TT   | 10     | 10      | 556.00    | 850.30      | 22.40  | 65.90    | 0.18         | 0.37   |
| 3 × 3-4 × 4         | 40%    | 10                  | 4      | MS   | 10     | 5       | 234.10    | 895.00      | 22.40  | 110.10   | 0.44         | 23.04  |
| 3 × 3-4 × 4         | 40%    | 10                  | 4      | TT   | 10     | 10      | 397.60    | 845.80      | 22.40  | 61.40    | 0.24         | 0.48   |
| 3 × 3-4 × 4         | 40%    | 10                  | 5      | MS   | 10     | 7       | 198.70    | 907.70      | 22.40  | 114.10   | 0.58         | 4.97   |
| 3 × 3-4 × 4         | 40%    | 10                  | 5      | TT   | 10     | 10      | 376.40    | 841.00      | 22.40  | 56.60    | 0.32         | 0.55   |
| 3 × 3-4 × 4         | 60%    | 5                   | 2      | MS   | 10     | 0       | 834.80    | 1667.10     | 59.40  | 131.70   | 1.57         | 46.57  |
| 3 × 3-4 × 4         | 60%    | 5                   | 2      | TT   | 10     | 10      | 1327.30   | 1635.90     | 59.40  | 100.50   | 0.77         | 4.35   |
| 3 × 3-4 × 4         | 60%    | 5                   | 3      | MS   | 10     | 0       | 571.60    | 1709.70     | 59.40  | 172.20   | 3.15         | 71.65  |
| 3 × 3-4 × 4         | 60%    | 5                   | 3      | TT   | 10     | 10      | 1112.60   | 1631.10     | 59.40  | 95.70    | 1.46         | 6.39   |
| 3 × 3-4 × 4         | 60%    | 5                   | 4      | MS   | 10     | 0       | 433.70    | 1709.50     | 59.40  | 171.90   | 4.63         | 90.23  |
| 3 × 3-4 × 4         | 60%    | 5                   | 4      | TT   | 10     | 10      | 766.70    | 1627.10     | 59.40  | 91.70    | 2.52         | 9.43   |
| 3 × 3-4 × 4         | 60%    | 5                   | 5      | MS   | 10     | 0       | 361.60    | 1759.80     | 59.40  | 216.00   | 6.03         | 127.82 |
| 3 × 3-4 × 4         | 60%    | 5                   | 5      | TT   | 10     | 10      | 672.20    | 1623.20     | 59.40  | 87.80    | 3.04         | 8.75   |
| 3 × 3-4 × 4         | 60%    | 10                  | 2      | MS   | 10     | 0       | 989.90    | 1977.50     | 80.50  | 150.90   | 2.51         | 127.50 |
| 3 × 3-4 × 4         | 60%    | 10                  | 2      | TT   | 10     | 10      | 1405.20   | 1941.70     | 80.50  | 115.20   | 1.32         | 6.55   |
| 3 × 3-4 × 4         | 60%    | 10                  | 3      | MS   | 10     | 0       | 673.10    | 2015.90     | 80.50  | 189.40   | 5.45         | 148.49 |
| 3 × 3-4 × 4         | 60%    | 10                  | 3      | TT   | 10     | 10      | 1130.20   | 1938.20     | 80.50  | 111.70   | 2.20         | 13.31  |
| 3 × 3-4 × 4         | 60%    | 10                  | 4      | MS   | 10     | 0       | 507.70    | 2019.40     | 80.50  | 192.40   | 8.49         | 113.27 |
| 3 × 3-4 × 4         | 60%    | 10                  | 4      | TT   | 10     | 10      | 935.80    | 1934.20     | 80.50  | 107.70   | 3.93         | 16.95  |
| 3 × 3-4 × 4         | 60%    | 10                  | 5      | MS   | 10     | 0       | 418.10    | 2066.60     | 80.50  | 235.30   | 12.05        | 107.67 |
| 3 × 3-4 × 4         | 60%    | 10                  | 5      | TT   | 10     | 10      | 915.50    | 1930.90     | 80.50  | 104.40   | 5.42         | 21.87  |
| 3 × 3-4 × 4         | 80%    | 5                   | 2      | MS   | 5      | 0       | 1547.80   | 3093.80     | 235.20 | 218.60   | 11.11        | 203.71 |
| 3 × 3-4 × 4         | 80%    | 5                   | 2      | TT   | 5      | 4       | 2525.20   | 3036.80     | 235.20 | 161.60   | 5.82         | 77.00  |
| 3 × 3-4 × 4         | 80%    | 5                   | 3      | MS   | 5      | 0       | 1044.40   | 3131.20     | 235.20 | 255.60   | 25.18        | 276.56 |
| 3 × 3-4 × 4         | 80%    | 5                   | 3      | TT   | 5      | 4       | 2048.40   | 3035.40     | 235.20 | 160.20   | 14.62        | 166.44 |
| 3 × 3-4 × 4         | 80%    | 5                   | 4      | MS   | 5      | 0       | 796.20    | 3178.80     | 235.20 | 302.40   | 41.80        | 213.58 |
| 3 × 3-4 × 4         | 80%    | 5                   | 4      | TT   | 5      | 3       | 1731.80   | 3033.00     | 235.20 | 157.80   | 23.47        | 116.52 |
| 3 × 3-4 × 4         | 80%    | 5                   | 5      | MS   | 5      | 0       | 651.40    | 3248.40     | 235.20 | 371.20   | 45.71        | 125.32 |
| 3 × 3-4 × 4         | 80%    | 5                   | 5      | TT   | 5      | 2       | 1572.20   | 3030.40     | 235.20 | 155.20   | 33.17        | 197.87 |
| 3 × 3-4 × 4         | 80%    | 10                  | 2      | MS   | 3      | 0       | 1769.67   | 3537.00     | 305.67 | 251.33   | 19.14        | 181.86 |
| 3 × 3-4 × 4         | 80%    | 10                  | 2      | TT   | 3      | 1       | 2482.00   | 3465.67     | 305.67 | 180      | 12.41        | 137.47 |
| 3 × 3-4 × 4         | 80%    | 10                  | 3      | MS   | 3      | 0       | 1204.33   | 3609.67     | 305.67 | 324.00   | 36.77        | 222.38 |
| 3 × 3-4 × 4         | 80%    | 10                  | 3      | TT   | 3      | 0       | 2822.33   | 3468.67     | 305.67 | 183.00   | 27.29        | 244.46 |
| 3 × 3-4 × 4         | 80%    | 10                  | 4      | MS   | 3      | 0       | 898.67    | 3585.67     | 305.67 | 300      | 50.67        | 212.19 |
| 3 × 3-4 × 4         | 80%    | 10                  | 4      | TT   | 3      | 0       | 2659.67   | 3463.67     | 305.67 | 178.00   | 39.70        | 232.33 |
| 3 × 3-4 × 4         | 80%    | 10                  | 5      | MS   | 3      | 0       | 743.33    | 3698.00     | 305.67 | 408.67   | 58.89        | 230.26 |
| 3 × 3-4 × 4         | 80%    | 10                  | 5      | TT   | 3      | 0       | 2832.33   | 3461.00     | 305.67 | 175.33   | 58.56        | 276.80 |
| 3 × 3-5 × 5         | 40%    | 5                   | 2      | MS   | 10     | 0       | 608.30    | 1211.30     | 30.70  | 130.50   | 0.45         | 34.16  |
| 3 × 3-5 × 5         | 40%    | 5                   | 2      | TT   | 10     | 10      | 945.50    | 1180.80     | 30.70  | 100.10   | 0.26         | 1.21   |
| 3 × 3-5 × 5         | 40%    | 5                   | 3      | MS   | 10     | 0       | 413.00    | 1230.30     | 30.70  | 149.60   | 0.82         | 60.28  |
| 3 × 3-5 × 5         | 40%    | 5                   | 3      | TT   | 10     | 10      | 816.40    | 1175.40     | 30.70  | 94.70    | 0.45         | 1.78   |
| 3 × 3-5 × 5         | 40%    | 5                   | 4      | MS   | 10     | 0       | 322.70    | 1252.00     | 30.70  | 165.20   | 1.12         | 38.79  |
| 3 × 3-5 × 5         | 40%    | 5                   | 4      | TT   | 10     | 10      | 609.20    | 1168.80     | 30.70  | 88.10    | 0.67         | 1.81   |
| 3 × 3-5 × 5         | 40%    | 5                   | 5      | MS   | 10     | 2       | 257.90    | 1254.20     | 30.70  | 169.50   | 1.63         | 27.94  |
| 3 × 3-5 × 5         | 40%    | 5                   | 5      | TT   | 10     | 10      | 480.30    | 1165.10     | 30.70  | 84.40    | 0.87         | 3.13   |
| 3 × 3-5 × 5         | 40%    | 10                  | 2      | MS   | 10     | 0       | 685.80    | 1369.40     | 35.80  | 139.60   | 0.66         | 133.78 |
| 3 × 3-5 × 5         | 40%    | 10                  | 2      | TT   | 10     | 10      | 1081.40   | 1337.60     | 35.80  | 107.80   | 0.37         | 2.18   |
| 3 × 3-5 × 5         | 40%    | 10                  | 3      | MS   | 10     | 0       | 463.40    | 1379.90     | 35.80  | 150.10   | 1.16         | 58.75  |
| 3 × 3-5 × 5         | 40%    | 10                  | 3      | TT   | 10     | 10      | 835.80    | 1332.40     | 35.80  | 102.60   | 0.64         | 2.24   |
| 3 × 3-5 × 5         | 40%    | 10                  | 4      | MS   | 10     | 0       | 364.90    | 1428.90     | 35.80  | 196.50   | 1.85         | 26.46  |
| 3 × 3-5 × 5         | 40%    | 10                  | 4      | TT   | 10     | 10      | 668.20    | 1326.60     | 35.80  | 96.80    | 0.93         | 3.29   |
| 3 × 3-5 × 5         | 40%    | 10                  | 5      | MS   | 10     | 0       | 295.50    | 1424.30     | 35.80  | 192.30   | 2.73         | 69.20  |

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Table 16 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 3 × 3-5 × 5         | 40%    | 10                  | 5      | TT   | 10     | 10      | 606.10    | 1322.80     | 35.80  | 93.00    | 1.34         | 4.40   |
| 3 × 3-5 × 5         | 60%    | 5                   | 2      | MS   | 8      | 0       | 1191.50   | 2382.12     | 92.50  | 204.62   | 4.95         | 137.21 |
| 3 × 3-5 × 5         | 60%    | 5                   | 2      | TT   | 8      | 8       | 1973.25   | 2329.12     | 92.50  | 151.62   | 2.18         | 19.48  |
| 3 × 3-5 × 5         | 60%    | 5                   | 3      | MS   | 8      | 0       | 806.38    | 2416.12     | 92.50  | 238.62   | 9.24         | 167.26 |
| 3 × 3-5 × 5         | 60%    | 5                   | 3      | TT   | 8      | 8       | 1579.00   | 2325.12     | 92.50  | 147.62   | 4.32         | 28.89  |
| 3 × 3-5 × 5         | 60%    | 5                   | 4      | MS   | 8      | 0       | 616.50    | 2455.62     | 92.50  | 276.62   | 16.05        | 157.24 |
| 3 × 3-5 × 5         | 60%    | 5                   | 4      | TT   | 8      | 8       | 1274.75   | 2319.25     | 92.50  | 141.75   | 7.75         | 53.43  |
| 3 × 3-5 × 5         | 60%    | 5                   | 5      | MS   | 8      | 0       | 500.50    | 2484.88     | 92.50  | 303.12   | 22.02        | 159.95 |
| 3 × 3-5 × 5         | 60%    | 5                   | 5      | TT   | 8      | 7       | 1140.88   | 2316.88     | 92.50  | 139.38   | 11.44        | 71.55  |
| 3 × 3-5 × 5         | 60%    | 10                  | 2      | MS   | 2      | 0       | 1249.00   | 2497.50     | 97.00  | 210.50   | 5.22         | 145.93 |
| 3 × 3-5 × 5         | 60%    | 10                  | 2      | TT   | 2      | 2       | 2293.00   | 2430.50     | 97.00  | 143.50   | 2.48         | 13.01  |
| 3 × 3-5 × 5         | 60%    | 10                  | 3      | MS   | 2      | 0       | 846.00    | 2532.00     | 97.00  | 245.00   | 13.08        | 246.57 |
| 3 × 3-5 × 5         | 60%    | 10                  | 3      | TT   | 2      | 2       | 2228.00   | 2428.00     | 97.00  | 141.00   | 4.08         | 25.32  |
| 3 × 3-5 × 5         | 60%    | 10                  | 4      | MS   | 2      | 0       | 644.50    | 2572.50     | 97.00  | 285.50   | 19.58        | 238.53 |
| 3 × 3-5 × 5         | 60%    | 10                  | 4      | TT   | 2      | 2       | 1722.00   | 2425.00     | 97.00  | 138.00   | 7.73         | 59.18  |
| 3 × 3-5 × 5         | 60%    | 10                  | 5      | MS   | 2      | 0       | 536.00    | 2656.00     | 97.00  | 367.00   | 31.54        | 176.95 |
| 3 × 3-5 × 5         | 60%    | 10                  | 5      | TT   | 2      | 2       | 1353.50   | 2421.50     | 97.00  | 134.50   | 12.49        | 48.59  |
| 4 × 4-2 × 2         | 40%    | 5                   | 2      | MS   | 10     | 9       | 231.30    | 446.80      | 9.60   | 35.10    | 0.05         | 0.22   |
| 4 × 4-2 × 2         | 40%    | 5                   | 2      | TT   | 10     | 10      | 343.10    | 438.70      | 9.60   | 27.10    | 0.03         | 0.07   |
| 4 × 4-2 × 2         | 40%    | 5                   | 3      | MS   | 10     | 9       | 164.60    | 453.70      | 9.60   | 35.90    | 0.07         | 0.21   |
| 4 × 4-2 × 2         | 40%    | 5                   | 3      | TT   | 10     | 10      | 287.70    | 436.10      | 9.60   | 24.50    | 0.05         | 0.09   |
| 4 × 4-2 × 2         | 40%    | 5                   | 4      | MS   | 10     | 10      | 137.20    | 461.70      | 9.60   | 40.90    | 0.09         | 0.23   |
| 4 × 4-2 × 2         | 40%    | 5                   | 4      | TT   | 10     | 10      | 203.20    | 433.90      | 9.60   | 22.30    | 0.06         | 0.13   |
| 4 × 4-2 × 2         | 40%    | 5                   | 5      | MS   | 10     | 10      | 122.10    | 454.50      | 9.60   | 35.80    | 0.13         | 0.32   |
| 4 × 4-2 × 2         | 40%    | 5                   | 5      | TT   | 10     | 10      | 193.90    | 431.10      | 9.60   | 19.50    | 0.08         | 0.13   |
| 4 × 4-2 × 2         | 40%    | 10                  | 2      | MS   | 10     | 8       | 262.90    | 506.70      | 13.50  | 42.10    | 0.06         | 0.22   |
| 4 × 4-2 × 2         | 40%    | 10                  | 2      | TT   | 10     | 10      | 390.60    | 493.90      | 13.50  | 30.40    | 0.04         | 0.10   |
| 4 × 4-2 × 2         | 40%    | 10                  | 3      | MS   | 10     | 8       | 189.80    | 513.60      | 13.50  | 49.10    | 0.09         | 0.33   |
| 4 × 4-2 × 2         | 40%    | 10                  | 3      | TT   | 10     | 10      | 301.90    | 490.80      | 13.50  | 27.30    | 0.06         | 0.11   |
| 4 × 4-2 × 2         | 40%    | 10                  | 4      | MS   | 10     | 10      | 146.10    | 508.20      | 13.50  | 41.70    | 0.13         | 0.44   |
| 4 × 4-2 × 2         | 40%    | 10                  | 4      | TT   | 10     | 10      | 240.40    | 488.10      | 13.50  | 24.60    | 0.08         | 0.14   |
| 4 × 4-2 × 2         | 40%    | 10                  | 5      | MS   | 10     | 10      | 135.00    | 510.30      | 13.50  | 40.80    | 0.19         | 0.38   |
| 4 × 4-2 × 2         | 40%    | 10                  | 5      | TT   | 10     | 10      | 214.40    | 485.20      | 13.50  | 21.70    | 0.11         | 0.17   |
| 4 × 4-2 × 2         | 60%    | 5                   | 2      | MS   | 10     | 1       | 538.40    | 1075.40     | 61.80  | 77.20    | 0.40         | 61.46  |
| 4 × 4-2 × 2         | 60%    | 5                   | 2      | TT   | 10     | 10      | 827.40    | 1053.00     | 61.80  | 55.20    | 0.24         | 1.15   |
| 4 × 4-2 × 2         | 60%    | 5                   | 3      | MS   | 10     | 1       | 372.20    | 1092.80     | 61.80  | 88.30    | 0.70         | 26.02  |
| 4 × 4-2 × 2         | 60%    | 5                   | 3      | TT   | 10     | 10      | 709.20    | 1049.90     | 61.80  | 52.10    | 0.46         | 1.57   |
| 4 × 4-2 × 2         | 60%    | 5                   | 4      | MS   | 10     | 1       | 287.90    | 1116.90     | 61.80  | 99.90    | 1.21         | 14.77  |
| 4 × 4-2 × 2         | 60%    | 5                   | 4      | TT   | 10     | 10      | 648.40    | 1046.30     | 61.80  | 48.50    | 0.77         | 1.78   |
| 4 × 4-2 × 2         | 60%    | 5                   | 5      | MS   | 10     | 4       | 236.80    | 1102.10     | 61.80  | 89.00    | 1.50         | 12.97  |
| 4 × 4-2 × 2         | 60%    | 5                   | 5      | TT   | 10     | 10      | 441.20    | 1043.40     | 61.80  | 45.60    | 0.91         | 2.14   |
| 4 × 4-2 × 2         | 60%    | 10                  | 2      | MS   | 10     | 0       | 589.70    | 1177.60     | 69.40  | 81.40    | 0.50         | 79.63  |
| 4 × 4-2 × 2         | 60%    | 10                  | 2      | TT   | 10     | 10      | 851.20    | 1153.80     | 69.40  | 58.40    | 0.34         | 1.13   |
| 4 × 4-2 × 2         | 60%    | 10                  | 3      | MS   | 10     | 0       | 401.10    | 1187.50     | 69.40  | 88.90    | 0.92         | 43.91  |
| 4 × 4-2 × 2         | 60%    | 10                  | 3      | TT   | 10     | 10      | 758.90    | 1152.10     | 69.40  | 56.70    | 0.48         | 1.35   |
| 4 × 4-2 × 2         | 60%    | 10                  | 4      | MS   | 10     | 1       | 313.80    | 1208.20     | 69.40  | 103.20   | 1.36         | 38.20  |
| 4 × 4-2 × 2         | 60%    | 10                  | 4      | TT   | 10     | 10      | 693.90    | 1148.60     | 69.40  | 53.20    | 0.75         | 2.14   |
| 4 × 4-2 × 2         | 60%    | 10                  | 5      | MS   | 10     | 2       | 260.10    | 1229.20     | 69.40  | 111.40   | 2.17         | 50.14  |
| 4 × 4-2 × 2         | 60%    | 10                  | 5      | TT   | 10     | 10      | 580.40    | 1144.90     | 69.40  | 49.50    | 1.16         | 3.09   |
| 4 × 4-2 × 2         | 80%    | 5                   | 2      | MS   | 5      | 0       | 759.40    | 1518.00     | 107.20 | 102.80   | 1.65         | 68.06  |
| 4 × 4-2 × 2         | 80%    | 5                   | 2      | TT   | 5      | 5       | 1168.60   | 1498.20     | 107.20 | 83.00    | 1.45         | 21.20  |
| 4 × 4-2 × 2         | 80%    | 5                   | 3      | MS   | 5      | 0       | 521.20    | 1541.80     | 107.20 | 119.60   | 3.75         | 54.60  |
| 4 × 4-2 × 2         | 80%    | 5                   | 3      | TT   | 5      | 4       | 992.60    | 1495.20     | 107.20 | 80       | 3.27         | 83.59  |
| 4 × 4-2 × 2         | 80%    | 5                   | 4      | MS   | 5      | 1       | 400.60    | 1560        | 107.20 | 121.80   | 6.62         | 72.41  |
| 4 × 4-2 × 2         | 80%    | 5                   | 4      | TT   | 5      | 4       | 1002.60   | 1492.40     | 107.20 | 77.20    | 5.71         | 69.78  |
| 4 × 4-2 × 2         | 80%    | 5                   | 5      | MS   | 5      | 1       | 324.60    | 1591.40     | 107.20 | 137.00   | 10.63        | 149.11 |
| 4 × 4-2 × 2         | 80%    | 5                   | 5      | TT   | 5      | 3       | 1035.60   | 1496.20     | 107.20 | 81.00    | 8.23         | 53.31  |
| 4 × 4-2 × 2         | 80%    | 10                  | 2      | MS   | 4      | 0       | 1002.50   | 2002.50     | 173.00 | 148.75   | 2.75         | 37.83  |
| 4 × 4-2 × 2         | 80%    | 10                  | 2      | TT   | 4      | 2       | 1389.50   | 1978.50     | 173.00 | 125.50   | 2.25         | 58.13  |
| 4 × 4-2 × 2         | 80%    | 10                  | 3      | MS   | 4      | 0       | 681.75    | 2027.50     | 173.00 | 158.50   | 5.96         | 58.70  |
| 4 × 4-2 × 2         | 80%    | 10                  | 3      | TT   | 4      | 2       | 1858.00   | 1977.00     | 173.00 | 124.00   | 5.19         | 83.95  |
| 4 × 4-2 × 2         | 80%    | 10                  | 4      | MS   | 4      | 0       | 530.25    | 2087.25     | 173.00 | 185.75   | 11.15        | 113.78 |
| 4 × 4-2 × 2         | 80%    | 10                  | 4      | TT   | 4      | 1       | 1703.50   | 1974.50     | 173.00 | 121.50   | 8.65         | 104.42 |
| 4 × 4-2 × 2         | 80%    | 10                  | 5      | MS   | 4      | 1       | 448.50    | 2140        | 173.00 | 194.00   | 18.66        | 141.72 |
| 4 × 4-2 × 2         | 80%    | 10                  | 5      | TT   | 4      | 0       | 1450      | 1978.00     | 173.00 | 125.00   | 15.86        | 59.73  |
| 4 × 4-2 × 2         | 90%    | 5                   | 2      | MS   | 1      | 0       | 1170      | 2336.00     | 203.00 | 213.00   | 4.02         | 51.74  |
| 4 × 4-2 × 2         | 90%    | 5                   | 2      | TT   | 1      | 0       | 1740      | 2311.00     | 203.00 | 188.00   | 3.61         | 162.32 |
| 4 × 4-2 × 2         | 90%    | 5                   | 3      | MS   | 1      | 0       | 806.00    | 2388.00     | 203.00 | 252.00   | 10.06        | 254.47 |
| 4 × 4-2 × 2         | 90%    | 5                   | 3      | TT   | 1      | 0       | 2002.00   | 2316.00     | 203.00 | 193.00   | 8.53         | 22.76  |
| 4 × 4-2 × 2         | 90%    | 5                   | 4      | MS   | 1      | 0       | 610       | 2400        | 203.00 | 246.00   | 18.69        | 257.63 |
| 4 × 4-2 × 2         | 90%    | 5                   | 4      | TT   | 1      | 0       | 1781.00   | 2312.00     | 203.00 | 189.00   | 17.66        | 64.54  |
| 4 × 4-2 × 2         | 90%    | 5                   | 5      | MS   | 1      | 0       | 501.00    | 2414.00     | 203.00 | 206.00   | 30.27        | 83.92  |
| 4 × 4-2 × 2         | 90%    | 5                   | 5      | TT   | 1      | 0       | 919.00    | 2310        | 203.00 | 187.00   | 28.00        | 158.58 |
| 4 × 4-3 × 3         | 40%    | 5                   | 2      | MS   | 10     | 0       | 515.90    | 1027.90     | 24.90  | 85.00    | 0.30         | 49.27  |

(continued on next page)

Table 16 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 4 × 4-3 × 3         | 40%    | 5                   | 2      | TT   | 10     | 10      | 740.70    | 1008.00     | 24.90  | 65.10    | 0.19         | 0.52   |
| 4 × 4-3 × 3         | 40%    | 5                   | 3      | MS   | 10     | 0       | 356.50    | 1051.90     | 24.90  | 105.50   | 0.52         | 15.50  |
| 4 × 4-3 × 3         | 40%    | 5                   | 3      | TT   | 10     | 10      | 625.20    | 1004.40     | 24.90  | 61.50    | 0.29         | 0.76   |
| 4 × 4-3 × 3         | 40%    | 5                   | 4      | MS   | 10     | 2       | 271.40    | 1044.90     | 24.90  | 101.70   | 0.80         | 36.06  |
| 4 × 4-3 × 3         | 40%    | 5                   | 4      | TT   | 10     | 10      | 528.90    | 1000.10     | 24.90  | 57.20    | 0.44         | 0.88   |
| 4 × 4-3 × 3         | 40%    | 5                   | 5      | MS   | 10     | 3       | 230.50    | 1070.10     | 24.90  | 123.70   | 1.10         | 31.03  |
| 4 × 4-3 × 3         | 40%    | 5                   | 5      | TT   | 10     | 10      | 478.70    | 998.40      | 24.90  | 55.50    | 0.59         | 1.23   |
| 4 × 4-3 × 3         | 40%    | 10                  | 2      | MS   | 10     | 0       | 580.40    | 1153.60     | 29.90  | 97.50    | 0.45         | 38.04  |
| 4 × 4-3 × 3         | 40%    | 10                  | 2      | TT   | 10     | 10      | 884.60    | 1127.20     | 29.90  | 71.30    | 0.27         | 0.63   |
| 4 × 4-3 × 3         | 40%    | 10                  | 3      | MS   | 10     | 0       | 400.70    | 1184.20     | 29.90  | 128.30   | 0.85         | 44.43  |
| 4 × 4-3 × 3         | 40%    | 10                  | 3      | TT   | 10     | 10      | 783.10    | 1124.50     | 29.90  | 68.60    | 0.45         | 1.32   |
| 4 × 4-3 × 3         | 40%    | 10                  | 4      | MS   | 10     | 0       | 297.70    | 1163.10     | 29.90  | 102.90   | 1.24         | 19.24  |
| 4 × 4-3 × 3         | 40%    | 10                  | 4      | TT   | 10     | 10      | 670.40    | 1119.50     | 29.90  | 63.60    | 0.64         | 1.36   |
| 4 × 4-3 × 3         | 40%    | 10                  | 5      | MS   | 10     | 1       | 250.10    | 1187.20     | 29.90  | 129.90   | 1.83         | 28.09  |
| 4 × 4-3 × 3         | 40%    | 10                  | 5      | TT   | 10     | 10      | 577.30    | 1116.50     | 29.90  | 60.60    | 0.88         | 2.12   |
| 4 × 4-3 × 3         | 60%    | 5                   | 2      | MS   | 10     | 0       | 1122.60   | 2244.20     | 107.70 | 162.50   | 4.54         | 131.84 |
| 4 × 4-3 × 3         | 60%    | 5                   | 2      | TT   | 10     | 10      | 1683.60   | 2201.20     | 107.70 | 119.50   | 2.61         | 14.56  |
| 4 × 4-3 × 3         | 60%    | 5                   | 3      | MS   | 10     | 0       | 760       | 2277.10     | 107.70 | 195.40   | 10.02        | 128.88 |
| 4 × 4-3 × 3         | 60%    | 5                   | 3      | TT   | 10     | 10      | 1298.80   | 2197.80     | 107.70 | 116.10   | 5.74         | 23.44  |
| 4 × 4-3 × 3         | 60%    | 5                   | 4      | MS   | 10     | 0       | 576.20    | 2296.10     | 107.70 | 210.20   | 17.58        | 152.46 |
| 4 × 4-3 × 3         | 60%    | 5                   | 4      | TT   | 10     | 10      | 1073.90   | 2193.20     | 107.70 | 111.50   | 10.33        | 35.26  |
| 4 × 4-3 × 3         | 60%    | 5                   | 5      | MS   | 10     | 0       | 471.30    | 2333.50     | 107.70 | 248.00   | 23.60        | 187.64 |
| 4 × 4-3 × 3         | 60%    | 5                   | 5      | TT   | 10     | 10      | 951.70    | 2191.00     | 107.70 | 109.30   | 13.07        | 52.00  |
| 4 × 4-3 × 3         | 60%    | 10                  | 2      | MS   | 10     | 0       | 1228.60   | 2454.70     | 124.50 | 176.20   | 5.76         | 115.21 |
| 4 × 4-3 × 3         | 60%    | 10                  | 2      | TT   | 10     | 10      | 1837.60   | 2408.50     | 124.50 | 130      | 3.48         | 30.08  |
| 4 × 4-3 × 3         | 60%    | 10                  | 3      | MS   | 10     | 0       | 826.20    | 2476.60     | 124.50 | 197.90   | 13.07        | 171.09 |
| 4 × 4-3 × 3         | 60%    | 10                  | 3      | TT   | 10     | 9       | 1520.90   | 2405.30     | 124.50 | 126.80   | 7.59         | 66.24  |
| 4 × 4-3 × 3         | 60%    | 10                  | 4      | MS   | 10     | 0       | 630.40    | 2511.10     | 124.50 | 229.40   | 21.45        | 139.61 |
| 4 × 4-3 × 3         | 60%    | 10                  | 4      | TT   | 10     | 10      | 1335.90   | 2399.80     | 124.50 | 121.30   | 11.21        | 63.05  |
| 4 × 4-3 × 3         | 60%    | 10                  | 5      | MS   | 10     | 0       | 507.60    | 2521.50     | 124.50 | 239.20   | 31.87        | 198.78 |
| 4 × 4-3 × 3         | 60%    | 10                  | 5      | TT   | 10     | 8       | 1109.40   | 2399.90     | 124.50 | 121.40   | 20.71        | 100.32 |
| 4 × 4-4 × 4         | 40%    | 5                   | 2      | MS   | 10     | 0       | 811.80    | 1620.40     | 35.60  | 150.80   | 1.22         | 69.79  |
| 4 × 4-4 × 4         | 40%    | 5                   | 2      | TT   | 10     | 10      | 1270.20   | 1581.00     | 35.60  | 111.40   | 0.70         | 3.73   |
| 4 × 4-4 × 4         | 40%    | 5                   | 3      | MS   | 10     | 0       | 553.90    | 1655.10     | 35.60  | 184.40   | 2.71         | 69.23  |
| 4 × 4-4 × 4         | 40%    | 5                   | 3      | TT   | 10     | 10      | 990       | 1575.60     | 35.60  | 106.00   | 1.20         | 5.90   |
| 4 × 4-4 × 4         | 40%    | 5                   | 4      | MS   | 10     | 0       | 425.30    | 1680        | 35.60  | 209.00   | 4.08         | 87.44  |
| 4 × 4-4 × 4         | 40%    | 5                   | 4      | TT   | 10     | 10      | 905.00    | 1571.30     | 35.60  | 101.70   | 1.97         | 8.88   |
| 4 × 4-4 × 4         | 40%    | 5                   | 5      | MS   | 10     | 0       | 343.00    | 1680        | 35.60  | 208.80   | 5.88         | 79.85  |
| 4 × 4-4 × 4         | 40%    | 5                   | 5      | TT   | 10     | 10      | 803.70    | 1568.00     | 35.60  | 98.40    | 2.99         | 13.16  |
| 4 × 4-4 × 4         | 40%    | 10                  | 2      | MS   | 9      | 0       | 909.33    | 1816.67     | 42.56  | 160.78   | 1.91         | 96.66  |
| 4 × 4-4 × 4         | 40%    | 10                  | 2      | TT   | 9      | 9       | 1264.11   | 1774.22     | 42.56  | 118.33   | 0.94         | 4.56   |
| 4 × 4-4 × 4         | 40%    | 10                  | 3      | MS   | 9      | 0       | 619.44    | 1850.67     | 42.56  | 194.78   | 3.63         | 142.00 |
| 4 × 4-4 × 4         | 40%    | 10                  | 3      | TT   | 9      | 9       | 1165.44   | 1768.56     | 42.56  | 112.67   | 1.65         | 7.86   |
| 4 × 4-4 × 4         | 40%    | 10                  | 4      | MS   | 9      | 0       | 474.22    | 1885.44     | 42.56  | 229.33   | 5.76         | 120.35 |
| 4 × 4-4 × 4         | 40%    | 10                  | 4      | TT   | 9      | 9       | 811.56    | 1763.89     | 42.56  | 108.00   | 2.58         | 9.50   |
| 4 × 4-4 × 4         | 40%    | 10                  | 5      | MS   | 9      | 0       | 382.56    | 1894.67     | 42.56  | 236.11   | 8.41         | 138.36 |
| 4 × 4-4 × 4         | 40%    | 10                  | 5      | TT   | 9      | 9       | 720.89    | 1759.89     | 42.56  | 104.00   | 3.91         | 14.35  |
| 5 × 5-2 × 2         | 40%    | 5                   | 2      | MS   | 10     | 2       | 442.80    | 875.50      | 26.60  | 74.90    | 0.20         | 8.63   |
| 5 × 5-2 × 2         | 40%    | 5                   | 2      | TT   | 10     | 10      | 625.70    | 850.20      | 26.60  | 49.60    | 0.12         | 0.38   |
| 5 × 5-2 × 2         | 40%    | 5                   | 3      | MS   | 10     | 1       | 302.20    | 871.30      | 26.60  | 68.20    | 0.34         | 49.02  |
| 5 × 5-2 × 2         | 40%    | 5                   | 3      | TT   | 10     | 10      | 588.90    | 846.10      | 26.60  | 45.50    | 0.19         | 0.70   |
| 5 × 5-2 × 2         | 40%    | 5                   | 4      | MS   | 10     | 4       | 235.80    | 886.10      | 26.60  | 80.20    | 0.53         | 16.05  |
| 5 × 5-2 × 2         | 40%    | 5                   | 4      | TT   | 10     | 10      | 515.70    | 843.10      | 26.60  | 42.50    | 0.28         | 0.95   |
| 5 × 5-2 × 2         | 40%    | 5                   | 5      | MS   | 10     | 6       | 190.80    | 882.10      | 26.60  | 73.50    | 0.68         | 22.00  |
| 5 × 5-2 × 2         | 40%    | 5                   | 5      | TT   | 10     | 10      | 423.50    | 840.60      | 26.60  | 40       | 0.38         | 1.00   |
| 5 × 5-2 × 2         | 40%    | 10                  | 2      | MS   | 10     | 1       | 494.80    | 981.10      | 31.10  | 78.80    | 0.28         | 21.81  |
| 5 × 5-2 × 2         | 40%    | 10                  | 2      | TT   | 10     | 10      | 724.70    | 954.90      | 31.10  | 53.80    | 0.16         | 0.35   |
| 5 × 5-2 × 2         | 40%    | 10                  | 3      | MS   | 10     | 1       | 340.10    | 998.00      | 31.10  | 96.30    | 0.53         | 19.39  |
| 5 × 5-2 × 2         | 40%    | 10                  | 3      | TT   | 10     | 10      | 677.40    | 950.90      | 31.10  | 49.80    | 0.27         | 0.55   |
| 5 × 5-2 × 2         | 40%    | 10                  | 4      | MS   | 10     | 2       | 260.70    | 1006.60     | 31.10  | 92.00    | 0.78         | 49.07  |
| 5 × 5-2 × 2         | 40%    | 10                  | 4      | TT   | 10     | 10      | 526.40    | 947.80      | 31.10  | 46.70    | 0.40         | 0.66   |
| 5 × 5-2 × 2         | 40%    | 10                  | 5      | MS   | 10     | 4       | 216.00    | 1009.90     | 31.10  | 93.00    | 0.94         | 15.52  |
| 5 × 5-2 × 2         | 40%    | 10                  | 5      | TT   | 10     | 10      | 464.70    | 944.90      | 31.10  | 43.80    | 0.54         | 0.86   |
| 5 × 5-2 × 2         | 60%    | 5                   | 2      | MS   | 10     | 0       | 915.40    | 1828.10     | 95.10  | 112.60   | 2.50         | 193.67 |
| 5 × 5-2 × 2         | 60%    | 5                   | 2      | TT   | 10     | 10      | 1108.90   | 1801.60     | 95.10  | 86.50    | 1.93         | 15.30  |
| 5 × 5-2 × 2         | 60%    | 5                   | 3      | MS   | 10     | 0       | 623.70    | 1865.00     | 95.10  | 147.50   | 5.54         | 117.65 |
| 5 × 5-2 × 2         | 60%    | 5                   | 3      | TT   | 10     | 10      | 1127.00   | 1797.40     | 95.10  | 82.30    | 3.38         | 22.56  |
| 5 × 5-2 × 2         | 60%    | 5                   | 4      | MS   | 10     | 0       | 475.90    | 1885.20     | 95.10  | 166.80   | 10.28        | 99.38  |
| 5 × 5-2 × 2         | 60%    | 5                   | 4      | TT   | 10     | 10      | 893.50    | 1794.10     | 95.10  | 79.00    | 7.51         | 38.03  |
| 5 × 5-2 × 2         | 60%    | 5                   | 5      | MS   | 10     | 0       | 383.10    | 1892.20     | 95.10  | 168.30   | 15.30        | 144.29 |
| 5 × 5-2 × 2         | 60%    | 5                   | 5      | TT   | 10     | 10      | 915.90    | 1790.90     | 95.10  | 75.80    | 11.39        | 62.11  |
| 5 × 5-2 × 2         | 60%    | 10                  | 2      | MS   | 10     | 0       | 1094.30   | 2186.70     | 147.60 | 137.00   | 4.12         | 109.13 |
| 5 × 5-2 × 2         | 60%    | 10                  | 2      | TT   | 10     | 10      | 1704.30   | 2155.90     | 147.60 | 106.30   | 3.63         | 41.11  |

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Table 16 (continued).

| Layout<br>(Bay-Wh.) | Fill % | Priority<br>Classes | Robots | Obj. | Number |         | Mean time |             |        |          | Mean runtime |        |
|---------------------|--------|---------------------|--------|------|--------|---------|-----------|-------------|--------|----------|--------------|--------|
|                     |        |                     |        |      | Solved | Optimal | Makespan  | Travel time | Loaded | Unloaded | First        | Best   |
| 5 × 5-2 × 2         | 60%    | 10                  | 3      | MS   | 10     | 0       | 740.30    | 2215.90     | 147.60 | 165.50   | 9.36         | 158.79 |
| 5 × 5-2 × 2         | 60%    | 10                  | 3      | TT   | 10     | 8       | 1556.70   | 2152.80     | 147.60 | 103.20   | 7.81         | 77.48  |
| 5 × 5-2 × 2         | 60%    | 10                  | 4      | MS   | 10     | 0       | 565.90    | 2245.20     | 147.60 | 191.60   | 17.16        | 135.02 |
| 5 × 5-2 × 2         | 60%    | 10                  | 4      | TT   | 10     | 8       | 1254.40   | 2149.30     | 147.60 | 99.70    | 12.86        | 100.92 |
| 5 × 5-2 × 2         | 60%    | 10                  | 5      | MS   | 10     | 0       | 456.40    | 2260        | 147.60 | 202.70   | 25.86        | 162.65 |
| 5 × 5-2 × 2         | 60%    | 10                  | 5      | TT   | 10     | 7       | 1062.70   | 2148.90     | 147.60 | 99.30    | 17.16        | 130.26 |
| 5 × 5-3 × 3         | 40%    | 5                   | 2      | MS   | 10     | 0       | 922.00    | 1842.00     | 45.80  | 152.20   | 2.22         | 72.02  |
| 5 × 5-3 × 3         | 40%    | 5                   | 2      | TT   | 10     | 10      | 1387.60   | 1796.70     | 45.80  | 106.90   | 1.21         | 4.87   |
| 5 × 5-3 × 3         | 40%    | 5                   | 3      | MS   | 10     | 0       | 618.10    | 1850.40     | 45.80  | 160.60   | 4.60         | 129.01 |
| 5 × 5-3 × 3         | 40%    | 5                   | 3      | TT   | 10     | 10      | 1104.90   | 1792.10     | 45.80  | 102.30   | 1.88         | 11.22  |
| 5 × 5-3 × 3         | 40%    | 5                   | 4      | MS   | 10     | 0       | 479.30    | 1904.10     | 45.80  | 214.20   | 7.59         | 62.76  |
| 5 × 5-3 × 3         | 40%    | 5                   | 4      | TT   | 10     | 10      | 916.70    | 1787.00     | 45.80  | 97.20    | 3.65         | 16.05  |
| 5 × 5-3 × 3         | 40%    | 5                   | 5      | MS   | 10     | 0       | 391.20    | 1926.70     | 45.80  | 230.50   | 11.37        | 87.32  |
| 5 × 5-3 × 3         | 40%    | 5                   | 5      | TT   | 10     | 10      | 856.40    | 1784.60     | 45.80  | 94.80    | 5.55         | 22.07  |
| 5 × 5-3 × 3         | 40%    | 10                  | 2      | MS   | 10     | 0       | 1048.60   | 2093.80     | 57.40  | 163.90   | 3.25         | 148.36 |
| 5 × 5-3 × 3         | 40%    | 10                  | 2      | TT   | 10     | 10      | 1509.40   | 2048.20     | 57.40  | 118.80   | 1.66         | 6.32   |
| 5 × 5-3 × 3         | 40%    | 10                  | 3      | MS   | 10     | 0       | 707.70    | 2119.40     | 57.40  | 189.90   | 7.49         | 113.75 |
| 5 × 5-3 × 3         | 40%    | 10                  | 3      | TT   | 10     | 10      | 1138.80   | 2043.00     | 57.40  | 113.60   | 3.31         | 20.36  |
| 5 × 5-3 × 3         | 40%    | 10                  | 4      | MS   | 10     | 0       | 547.30    | 2170.70     | 57.40  | 241.30   | 11.96        | 107.08 |
| 5 × 5-3 × 3         | 40%    | 10                  | 4      | TT   | 10     | 10      | 978.40    | 2038.70     | 57.40  | 109.30   | 5.57         | 32.93  |
| 5 × 5-3 × 3         | 40%    | 10                  | 5      | MS   | 10     | 0       | 445.40    | 2196.50     | 57.40  | 261.10   | 18.29        | 130.77 |
| 5 × 5-3 × 3         | 40%    | 10                  | 5      | TT   | 10     | 10      | 875.50    | 2034.80     | 57.40  | 105.40   | 9.59         | 59.78  |
| 5 × 5-3 × 3         | 60%    | 5                   | 2      | MS   | 5      | 0       | 1927.20   | 3853.40     | 199.60 | 293.40   | 25.72        | 221.45 |
| 5 × 5-3 × 3         | 60%    | 5                   | 2      | TT   | 5      | 5       | 2794.80   | 3741.40     | 199.60 | 181.80   | 19.51        | 68.65  |
| 5 × 5-3 × 3         | 60%    | 5                   | 3      | MS   | 5      | 0       | 1311.60   | 3931.80     | 199.60 | 372.20   | 46.09        | 237.74 |
| 5 × 5-3 × 3         | 60%    | 5                   | 3      | TT   | 5      | 4       | 2555.00   | 3736.80     | 199.60 | 177.20   | 35.73        | 172.45 |
| 5 × 5-3 × 3         | 60%    | 5                   | 4      | MS   | 5      | 0       | 1010      | 4030.20     | 199.60 | 467.60   | 58.82        | 200.18 |
| 5 × 5-3 × 3         | 60%    | 5                   | 4      | TT   | 5      | 5       | 1787.40   | 3729.60     | 199.60 | 170      | 50.07        | 230.94 |
| 5 × 5-3 × 3         | 60%    | 5                   | 5      | MS   | 5      | 0       | 812.40    | 4049.00     | 199.60 | 484.60   | 64.23        | 263.61 |
| 5 × 5-3 × 3         | 60%    | 5                   | 5      | TT   | 5      | 1       | 1998.60   | 3747.00     | 199.60 | 187.40   | 72.02        | 252.58 |
| 6 × 6-2 × 2         | 40%    | 5                   | 2      | MS   | 10     | 0       | 738.00    | 1473.30     | 50.50  | 96.70    | 1.29         | 66.30  |
| 6 × 6-2 × 2         | 40%    | 5                   | 2      | TT   | 10     | 10      | 1139.90   | 1448.80     | 50.50  | 72.30    | 0.82         | 4.35   |
| 6 × 6-2 × 2         | 40%    | 5                   | 3      | MS   | 10     | 0       | 508.10    | 1513.20     | 50.50  | 136.60   | 2.68         | 28.83  |
| 6 × 6-2 × 2         | 40%    | 5                   | 3      | TT   | 10     | 10      | 775.70    | 1444.10     | 50.50  | 67.60    | 1.40         | 9.67   |
| 6 × 6-2 × 2         | 40%    | 5                   | 4      | MS   | 10     | 0       | 389.40    | 1527.50     | 50.50  | 144.20   | 4.52         | 112.52 |
| 6 × 6-2 × 2         | 40%    | 5                   | 4      | TT   | 10     | 10      | 696.10    | 1439.50     | 50.50  | 63.00    | 2.38         | 7.06   |
| 6 × 6-2 × 2         | 40%    | 5                   | 5      | MS   | 10     | 1       | 315.60    | 1538.70     | 50.50  | 143.40   | 6.48         | 52.42  |
| 6 × 6-2 × 2         | 40%    | 5                   | 5      | TT   | 10     | 10      | 663.70    | 1436.70     | 50.50  | 60.20    | 4.62         | 12.43  |
| 6 × 6-2 × 2         | 40%    | 10                  | 2      | MS   | 10     | 0       | 817.60    | 1633.50     | 63.90  | 105.60   | 1.72         | 67.14  |
| 6 × 6-2 × 2         | 40%    | 10                  | 2      | TT   | 10     | 10      | 1270.90   | 1607.70     | 63.90  | 79.80    | 0.94         | 6.72   |
| 6 × 6-2 × 2         | 40%    | 10                  | 3      | MS   | 10     | 0       | 560       | 1666.90     | 63.90  | 137.90   | 3.76         | 71.20  |
| 6 × 6-2 × 2         | 40%    | 10                  | 3      | TT   | 10     | 10      | 998.60    | 1604.40     | 63.90  | 76.50    | 1.90         | 7.30   |
| 6 × 6-2 × 2         | 40%    | 10                  | 4      | MS   | 10     | 0       | 427.20    | 1693.40     | 63.90  | 159.80   | 6.27         | 152.83 |
| 6 × 6-2 × 2         | 40%    | 10                  | 4      | TT   | 10     | 10      | 859.20    | 1599.70     | 63.90  | 71.80    | 3.50         | 11.63  |
| 6 × 6-2 × 2         | 40%    | 10                  | 5      | MS   | 10     | 0       | 353.30    | 1720.20     | 63.90  | 175.40   | 9.05         | 104.48 |
| 6 × 6-2 × 2         | 40%    | 10                  | 5      | TT   | 10     | 10      | 863.80    | 1596.30     | 63.90  | 68.40    | 4.42         | 14.89  |
| 6 × 6-2 × 2         | 60%    | 5                   | 2      | MS   | 8      | 0       | 1571.38   | 3141.88     | 209.62 | 224.25   | 13.66        | 194.64 |
| 6 × 6-2 × 2         | 60%    | 5                   | 2      | TT   | 8      | 7       | 2196.88   | 3072.50     | 209.62 | 155.38   | 13.08        | 116.46 |
| 6 × 6-2 × 2         | 60%    | 5                   | 3      | MS   | 8      | 0       | 1057.62   | 3170.50     | 209.62 | 251.25   | 29.16        | 209.72 |
| 6 × 6-2 × 2         | 60%    | 5                   | 3      | TT   | 8      | 4       | 2307.38   | 3072.38     | 209.62 | 155.25   | 25.72        | 158.72 |
| 6 × 6-2 × 2         | 60%    | 5                   | 4      | MS   | 8      | 0       | 803.38    | 3205.00     | 209.62 | 285.50   | 45.81        | 213.14 |
| 6 × 6-2 × 2         | 60%    | 5                   | 4      | TT   | 8      | 3       | 2021.62   | 3073.12     | 209.62 | 156.00   | 40.01        | 196.01 |
| 6 × 6-2 × 2         | 60%    | 5                   | 5      | MS   | 8      | 0       | 650.38    | 3233.25     | 209.62 | 300.25   | 52.92        | 223.76 |
| 6 × 6-2 × 2         | 60%    | 5                   | 5      | TT   | 8      | 2       | 2240.25   | 3068.12     | 209.62 | 151.00   | 45.59        | 189.89 |
| 6 × 6-2 × 2         | 60%    | 10                  | 2      | MS   | 7      | 0       | 1786.00   | 3570.71     | 268.57 | 232.71   | 18.86        | 190.97 |
| 6 × 6-2 × 2         | 60%    | 10                  | 2      | TT   | 7      | 5       | 2854.00   | 3506.00     | 268.57 | 168.86   | 16.49        | 184.85 |
| 6 × 6-2 × 2         | 60%    | 10                  | 3      | MS   | 7      | 0       | 1212.29   | 3635.00     | 268.57 | 296.14   | 37.79        | 199.95 |
| 6 × 6-2 × 2         | 60%    | 10                  | 3      | TT   | 7      | 4       | 2662.71   | 3506.00     | 268.57 | 168.86   | 31.19        | 201.59 |
| 6 × 6-2 × 2         | 60%    | 10                  | 4      | MS   | 7      | 0       | 929.14    | 3694.71     | 268.57 | 346.29   | 49.11        | 201.91 |
| 6 × 6-2 × 2         | 60%    | 10                  | 4      | TT   | 7      | 2       | 2495.86   | 3508.43     | 268.57 | 171.29   | 46.92        | 238.42 |
| 6 × 6-2 × 2         | 60%    | 10                  | 5      | MS   | 7      | 0       | 751.57    | 3737.71     | 268.57 | 386.14   | 62.68        | 220.39 |
| 6 × 6-2 × 2         | 60%    | 10                  | 5      | TT   | 7      | 1       | 2628.00   | 3511.14     | 268.57 | 174.00   | 68.24        | 266.63 |

## A.3. Step 2: detailed results for A\*

See Tables 11 and 12.

## A.5. Step 3: Detailed results routing

See Tables 15 and 16.

## A.4. Step 2: detailed results for CP

See Tables 13 and 14.

## Data availability

The dataset can be accessed via the link in the paper.

## References

- van Asperen, E., Borgman, B., Dekker, R., 2013. Evaluating impact of truck announcements on container stacking efficiency. *Flex. Serv. Manuf. J.* 25 (4), 543–556.
- Bömer, T., Koltermann, N., Pfrommer, J., Meyer, A., 2024. Sorting multibay block stacking storage systems with multiple robots. In: Garrido, A., Paternina-Arboleda, C.D., Voß, S. (Eds.), In: *Computational Logistics*, vol. 15168, Springer, Cham, Switzerland, pp. 34–48.
- Caserta, M., Schwarze, S., Voß, S., 2011. Container rehandling at maritime container terminals. In: Böse, J. (Ed.), In: *Handbook of Terminal Planning. Operations Research/Computer Science Interfaces Series*, vol. 49, Springer, New York, pp. 247–269.
- Choe, R., Kim, T.S., Kim, T., Ryu, K.R., 2015. Crane scheduling for opportunistic remarshaling of containers in an automated stacking yard. *Flex. Serv. Manuf. J.* 27 (2), 331–349.
- Choe, R., Park, T., Oh, M.-S., Kang, J., Ryu, K.R., 2011. Generating a rehandling-free intra-block remarshaling plan for an automated container yard. *J. Intell. Manuf.* 22 (2), 201–217.
- Covic, F., 2017. Re-marshalling in automated container yards with terminal appointment systems. *Flex. Serv. Manuf. J.* 29 (3), 433–503.
- Goetschalckx, M., Ratliff, H.D., 1990. Shared storage policies based on the duration stay of unit loads. *Manag. Sci.* 36 (9), 1120–1132.
- Jiménez-Piqueras, C., Parreño-Torres, C., Alvarez-Valdes, R., Ruiz, R., 2024. The container premarshalling problem under limited crane time: A constraint programming approach. *Comput. Oper. Res.* 166, 106635.
- Jiménez-Piqueras, C., Ruiz, R., Parreño-Torres, C., Alvarez-Valdes, R., 2023. A constraint programming approach for the premarshalling problem. *European J. Oper. Res.* 306 (2), 668–678.
- Jiménez-Piqueras, C., Tierney, K., 2025. Solving the container premarshalling problem with an auxiliary bay. *Marit. Transp. Res.* 8, 100134.
- Kang, J., Oh, M.-S., Ahn, E.Y., Ryu, K.R., Kim, K.H., 2006. Planning for intra-block remarshalling in a container terminal. In: Ali, M., Dapoigny, R. (Eds.), In: *Advances in Applied Artificial Intelligence. IEA/AIE 2006*, vol. 4031, Springer, Berlin, Germany, pp. 1211–1220.
- Kemme, N., 2012. Design and Operation of Automated Container Storage Systems. Springer Science & Business Media. University of Hamburg.
- Kim, K.H., Bae, J.W., 1998. Re-marshaling export containers in port container terminals. *Comput. Ind. Eng.* 35 (3–4), 655–658.
- Maniezzo, V., Boschetti, M.A., Gutjahr, W.J., 2021. Stochastic premarshalling of block stacking warehouses. *Omega* 102, 102336.
- Park, K., Park, T., Ryu, K.R., 2009. Planning for remarshaling in an automated container terminal using cooperative coevolutionary algorithms. In: *Proceedings of the 2009 ACM Symposium on Applied Computing. SAC '09*, Association for Computing Machinery, New York, NY, USA, pp. 1098–1105.
- Parreño-Torres, C., Alvarez-Valdes, R., Parreño, F., 2022. A beam search algorithm for minimizing crane times in premarshalling problems. *European J. Oper. Res.* 302 (3), 1063–1078.
- Parreño-Torres, C., Alvarez-Valdes, R., Ruiz, R., 2019. Integer programming models for the pre-marshalling problem. *European J. Oper. Res.* 274 (1), 142–154.
- Parreño-Torres, C., Alvarez-Valdes, R., Ruiz, R., Tierney, K., 2020. Minimizing crane times in pre-marshalling problems. *Transp. Res. Part E: Logist. Transp. Rev.* 137, 101917.
- Pazour, J.A., Carlo, H.J., 2015. Warehouse reshuffling: Insights and optimization. *Transp. Res. Part E: Logist. Transp. Rev.* 73, 207–226.
- Pfrommer, J., Meyer, A., 2020. Autonomously organized block stacking warehouses: A review of decision problems and major challenges. *Logist. J.: Proc.* 16.
- Pfrommer, J., Meyer, A., Tierney, K., 2024. Solving the unit-load pre-marshalling problem in block stacking storage systems with multiple access directions. *European J. Oper. Res.* 313 (3), 1054–1071.
- Pfrommer, J., Rinciog, A., Zahid, S., Morrissey, M., Meyer, A., 2022. SLAPStack: A simulation framework and a large-scale benchmark use case for autonomous block stacking warehouses. In: de Armas, J., Ramalhinho, H., Voß, S. (Eds.), In: *Computational Logistics*, vol. 13557, Springer, Cham, Switzerland, pp. 291–305.
- Tanaka, S., Tierney, K., Parreño-Torres, C., Alvarez-Valdes, R., Ruiz, R., 2019. A branch and bound approach for large pre-marshalling problems. *European J. Oper. Res.* 278 (1), 211–225.
- Tierney, K., Pacino, D., Voß, S., 2017. Solving the pre-marshalling problem to optimality with a\* and IDA\*. *Flex. Serv. Manuf. J.* 29 (2), 223–259.