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Logistics management for storing multiple cask plug and remote handling systems in ITER

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HIGHLIGHTS

- We model the logistics management problem in ITER, taking into account casks of multiple typologies.
- We propose a method to determine the best position of the casks inside a given storage area.
- Our method obtains the sequence of operations required to retrieve or store an arbitrary cask, given its storage place.
- We illustrate our method with simulation results in an example scenario.

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ABSTRACT

During operation, maintenance inside the reactor building at ITER (International Thermonuclear Experimental Reactor) has to be performed by remote handling, due to the presence of activated materials. Maintenance operations involve the transportation and storage of large, heavyweight casks from and to the tokamak building. The transportation is carried out by autonomous vehicles that lift and move beneath these casks. The storage of these casks face several challenges, since (1) the cask storage area is limited in space, and (2) all casks have to be accessible for transportation by the vehicles. In particular, casks in the storage area may block other casks, so that the former has to be moved to a temporary position to give way to the latter. This paper addresses the challenge of managing the logistics of cask storage, where casks may have different typologies. In particular, we propose an approach to (1) determine the best position of the casks inside the storage area, and to (2) obtain the sequence of operations required to retrieve and store an arbitrary cask from/to a given storage place. A combinatorial optimization approach is used to obtain solutions to both these problems. Simulation results illustrate the application of the proposed method to a simple scenario.

1. Introduction

The ITER (International Thermonuclear Experimental Reactor) is a joint international research project, aiming at the demonstration of the scientific technological feasibility of fusion power as an alternative and safe power source. The Cask and Plug Remote Handling System (CPRHS) provides the means for the remote transfer of (clean/activated/contaminated) in-vessel components and remote handling equipment between the Hot Cell Building (HCB) and the vacuum vessel in Tokamak Building (TB) through dedicated galleries, as illustrated in Fig. 1.

There are different CPRHS configurations, each defined according to the required activity. The largest CPRHS has dimensions 8.5 m × 2.62 m × 3.62 m (length, width, height) and is entrusted with the transportation of heavy (total weight up to 100 tons) and highly activated components [1]. The CPRHS comprises three subsystems: a cask envelope containing the load, a pallet that supports the cask envelope and the Cask Transfer System (CTS). The CTS acts as a mobile robot, provides the mobility for the CPRHS and can be decoupled from the entire system. The kinematic configuration, first proposed in [2], endows it with the required flexibility to navigate autonomously or remotely controlled, in the cluttered environments of the TB and the HCB.

During the reactor's operation, the in-vessel components, such as the blankets that cover the vacuum vessel, are expected to become activated. When such components have to be removed for disposal, operations are to be carried out by the CPRHS, which is required to dock in pre-defined locations, the vacuum vessel

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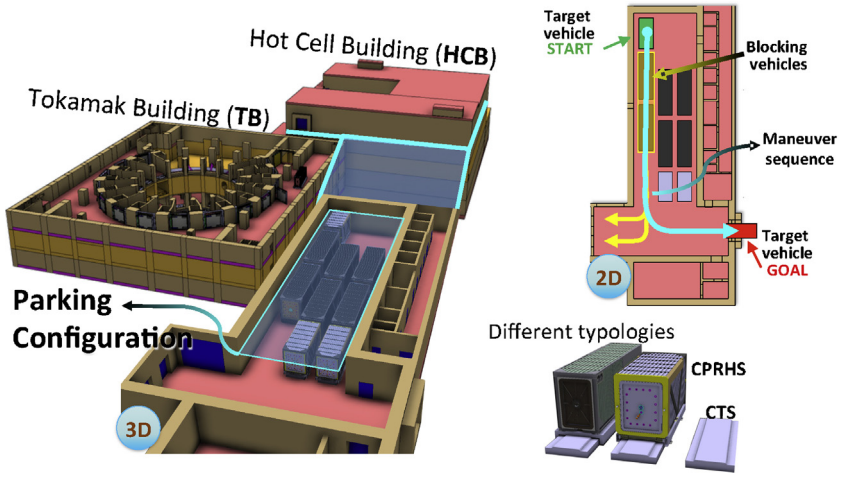

Fig. 1. Illustration of the ITER scenario: from left to right, 3D view of the environment, showing in particular the Hot Cell Building (HCB), the Tokamak Building (TB), and the parking area (PA); 2D view of the cask stored in this area; the different typologies of the Cask and Plug Remote Handling System (CPRHS), together with the Cask Transfer System (CTS).

port cells, located on the three levels of TB: divertor, equatorial and upper level. Then, the components are transported to the HCB for operations of diagnose and refurbishment or disposal of activated material. Hence, the CPRHS must dock at the docking stations through port plugs interfaces or park in parking areas (PAs) at the different levels of the HCB.

This paper addresses the problem of managing the PA for the CPRHS, hereby designated simply by *casks*. We assume the designation of specific PAs. However, given the space constraints in ITER, casks cannot be arbitrarily positioned, since when packing the casks along the available space, casks may block each other. This raises two challenges, that are addressed in this paper: first, since parked casks may block each other, how to retrieve on such blocked casks, and second, since different casks may have differing usage patterns, how to determine the location of each cask, within the PA, such that the most used ones are more easily retrieved. In other words, the first problem can be framed as a planning problem, where blocking casks are moved to temporary positions, in order for the CTS to have access to the target cask. The second problem concerns the optimal arrangement of casks within the PA.

It should be noted that the methods presented here can be applied not only to any ITER scenario (*i.e.*, not limited to the HCB), but also in different application scenarios (*e.g.*, warehouses).

Cask usage falls into two distinct patterns, depending on the type of maintenance operation they are involved: planned and unplanned. For planned operations, cask arrangement can be deterministically ordered so that blocking is minimized. Casks can be re-organized prior to commencing maintenance. However, for unplanned operations, cask usage is unpredictable by nature. Since it is critical to minimize cost losses due to ITER down time, the best one can do is minimizing expected down time, in a probabilistic sense, based on cask usage statistics. If we set the cost of moving casks to the implied ITER downtime, minimizing expected downtime amounts to minimizing expected cost. In this paper we limit our approach to unplanned operations, and thus the criterion being minimized is expected cost of moving the casks.

The problem of determining the best arrangement of items within a storage area is generically designated as *storage location assignment problem* in the Operational Research literature [3,4]. Early work has focused on the research of various assignment policies [5]. More recent research has focused on class-based storage location assignment, employing branch and bound methods [6].

This paper is organized as follows: Section 2 presents the formal problem statement, followed by the proposed solution in Section 3. Experimental results illustrating the approach are presented in Section 4, followed by the conclusions and future work in Section 5.

2. Problem statement

To formulate the problem we start by making a few simplifying assumptions about the scenario. Let us designate *operational area* the space available for both storing and moving casks around.

Our first assumption is that this operational space can be modeled by a graph $\mathcal{K} = \langle \mathcal{X}, \mathcal{E} \rangle$, where $\mathcal{X}$ is a set of nodes, representing physical locations in the environment, and $\mathcal{E}$ is a set of edges, each one denoting a feasible direct navigation path for the CTS between the corresponding pair of nodes (see Fig. 2 for an example [7,8]). Three types of nodes are considered: *stacks* are nodes that allow the storage of one or more casks in line along their length, *crossings* are transit nodes where a CTS can navigate among two arbitrary adjacent nodes, and a special node denoted *exit point*, representing the exit of the work space. Thus, the set of nodes is partitioned into a disjoint union of three subsets, $\mathcal{X} = \mathcal{S} \cup \mathcal{C} \cup \{\varepsilon\}$, where $\mathcal{S}$ and $\mathcal{C}$ are the sets of stacks and crossings, while ε is the exit point. In the example illustrated in Fig. 2, $\mathcal{S} = \{S1, S2, S3, S11, S12\}$, $\mathcal{C} = \{A, \ldots, D\}$, and $\varepsilon = EXIT$. Each stack $s \in \mathcal{S}$ is modeled as an ordered set of N_s cells of fixed size (*e.g.*, Fig. 2(c)), say $s = [1, \ldots, N_s]$. Without loss of generality, the leftmost cell 1 of a stack s is the stack exit, *i.e.*, the side where casks enter or leave the stack.

Given two arbitrary stack nodes that are connected in the graph, we assume that there is a feasible trajectory allowing a cask to navigate among these stacks. This trajectory consists in the concatenation of the edges connecting the two stack nodes.

Let $\mathcal{A}$ denote a set of casks. The length of each cask is assumed to be an integer multiple of the cell size. This multiple is denoted L_a, for $a \in \mathcal{A}$.

As its name suggests, storage to and retrieval from a stack of a cask is performed in a Last-In-First-Out (LIFO) fashion. In other words, we have that: (i) only the cask closer to the stack exit is accessible for transportation, and (ii) provided that there is enough free cells adjacent to the stack exit, a newly stored cask will occupy some of these free cells (being the amount equal to the cask size).

Given this model, together with the stated cask movement constraints, we can formulate the logistics problem in the following way:

1. the problem of storing (or retrieving) casks, corresponding to moving a single cask $a \in \mathcal{A}$ from (or to) the exit point ε to (or from) a storage position k within a stack $s \in \mathcal{S}$;

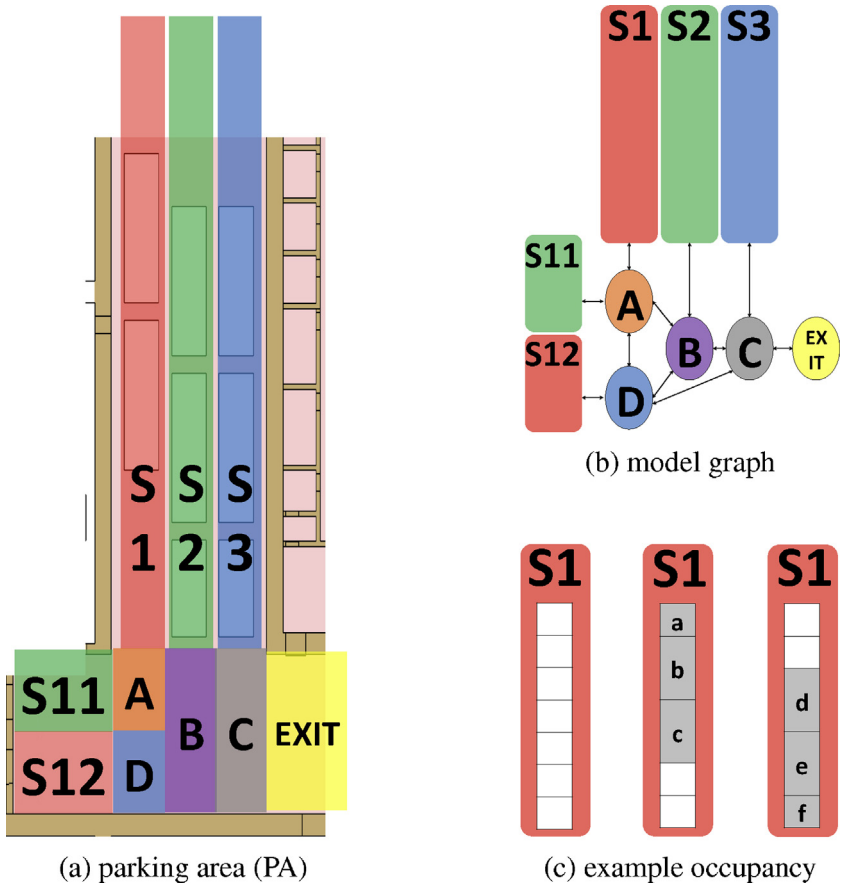

Fig. 2. Graph model of an example scenario: (a) PA divided in cells (S1–S3, S11, and S12 are stacks and A–D are transit areas; (b) corresponding model graph, where rounded rectangles denote stacks and circles denote crossing nodes; (c) examples of occupancy of a stack of 7 free slots. Casks a and f have a size of 1 slot, while casks b–e have a size of 2.

2. the problem of determining, given a cask $a \in \mathcal{A}$, the best stack s and position k within the stack, to park the cask, provided its usage rate.

The second problem arises since different locations of a given cask inside the PA imply different amounts of operations in order to retrieve it, depending on whether this cask is blocked by others.

Formulating the problem this way allows the application of standard combinatorial search methods. The followed approach is detailed in the next section.

3. Proposed solution

Having the problem stated as above, solutions can be found using standard combinatorial search methods. Let us first discuss the approach to the problem of finding the best sequence of operations to move casks from or to the PA, followed by the optimal cask storage position problem.

3.1. Cask movement planning

Given a cask a, its location l_a can be either in a stack or in a transit node. Thus, the set of possible locations is the disjoint union between crossing nodes and pairs (stack, cell), *i.e.*, $l_a \in \mathcal{C} \cup \{(s,k) \mid s \in \mathcal{S}, k \in \{1,\ldots,N_s\}\}$. The locations of all casks $\{l_a\}$ form a state where heuristic search can be used to obtain optimal solutions: given an initial and a goal state, the solution corresponds to the sequence of operations that, when applied in sequence, lead from the initial state to the goal. Given a state, the set of operators considered corresponds to all feasible actions that can be performed to a single cask. In particular, for any cask a, if it is in a stack s, it can be moved to any adjacent position, including adjacent free cells and, if it is located in cell 1, the crossing node x for which there is an edge (s, x). Otherwise, if it is in a crossing node x, it can move to either an adjacent node x' for which there is a node (x, x'), or the cell 1 in case there is an edge (x, s) to a stack s and it is free.

Note that the concept of free cell has to defined taking into account the length of each cask: a cell k in stack s is *free* with respect to a cask a if, and only if, the set of cells occupied by all other casks is disjoint to the set of cells occupied by a when $l_a = (s, k)$. Formally, this means that $\{k, \ldots, k + L_a\} \cap \{i, \ldots, i + L_b\} = \emptyset$ for all casks $b \in \mathcal{A}$ such that $l_b = (s, i)$.

To solve the problem of taking a given cask a from storage to exit ε, the proposed solution employs IDA* (Iterative Deepening A-star) to obtain the optimal solution. IDA* is a memory efficient version of the well-known A* algorithm, while maintaining the optimality property of the solution [9]. The state space comprises the locations of all casks. At each state there is a designated active cask, which is initially set to a. Search proceeds by recursively expanding successor states. These successors consist of all possible movements of the active cask to a neighbor position (either an adjacent stack cell or graph node). If a neighbor is occupied by a different cask, a subgoal is created in which the active cask is set to the blocking cask and the search tree branches over all free positions among all stacks.

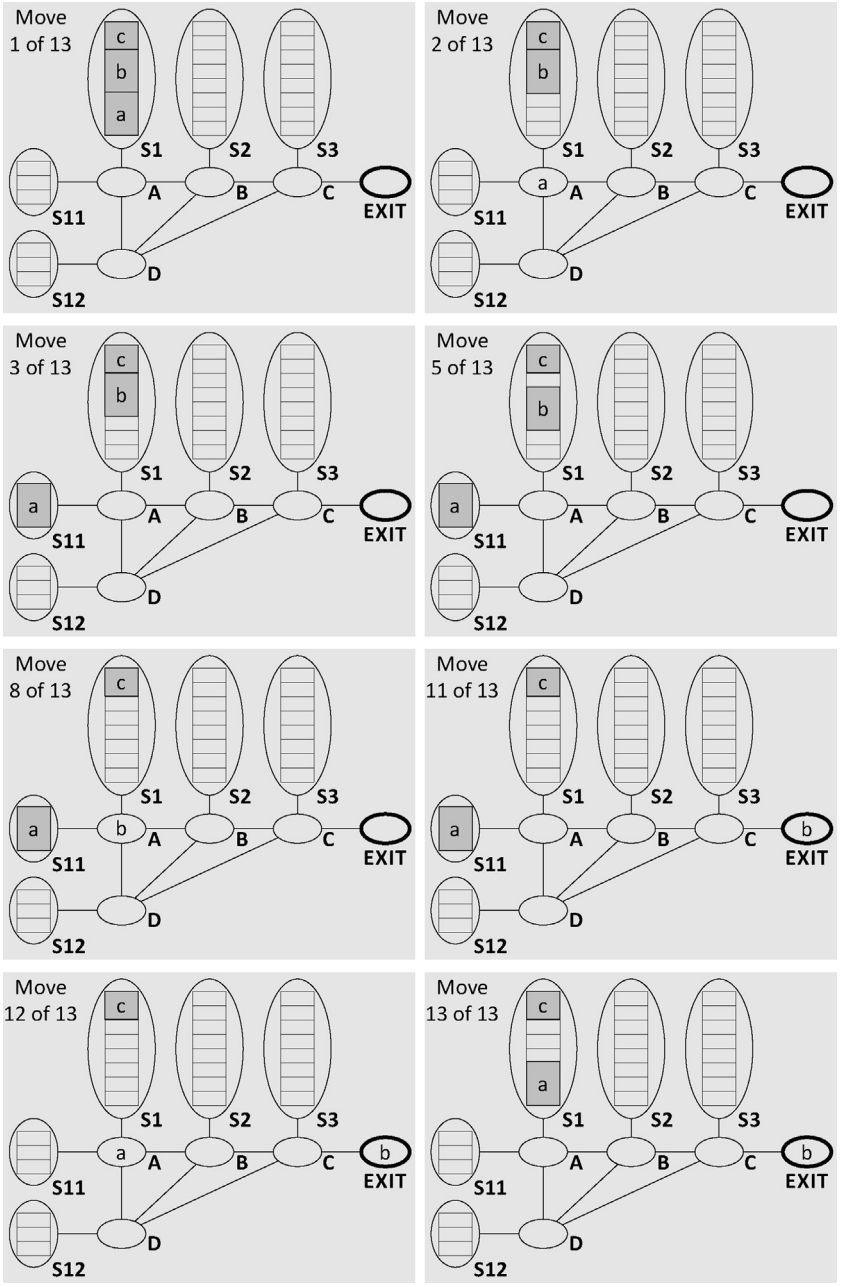

Fig. 3. Results for the cask movement planning problem, showing some intermediate steps in the sequence of operations to move cask b from stack A1 to the exit (rightmost node).

This method allows one to compute the optimal sequence of steps to get an arbitrary cask out of the PA. Thus, given one configuration of the PA, we can associate to each cask a cost, corresponding to the effort necessary to transport it to the exit. The cost reflects the total amount of steps involved in the solution, including a penalty for having to move blocking casks to temporary positions.

3.2. Cask storage location determination

Given one assignment of casks to stacks and positions, the method described above allows the computation of the cost of moving each individual cask to the exit, including the cost of moving all other blocking casks to temporary positions. All possible cask arrangements within the PA form a state space. A given state can be modeled as a function f from the casks to locations within the stacks,

$$\begin{aligned} f \quad &: \quad \mathcal{A} \to \mathcal{S} \times \mathbb{N} \\ &\quad\;\; a \mapsto (s, k) \end{aligned} \tag{1}$$

where s and k are the stack and position within the stack for a given cask a.

We model cask usage as a rate, equivalently (appart from a scale factor) to a probability of usage. This allows us to construct a global cost functional $J(f)$, set to the weighted average of the cask retrieval cost, where the weights are the usage probabilities,

$$J(f) = \sum_i p_i \, c_i(f) \tag{2}$$

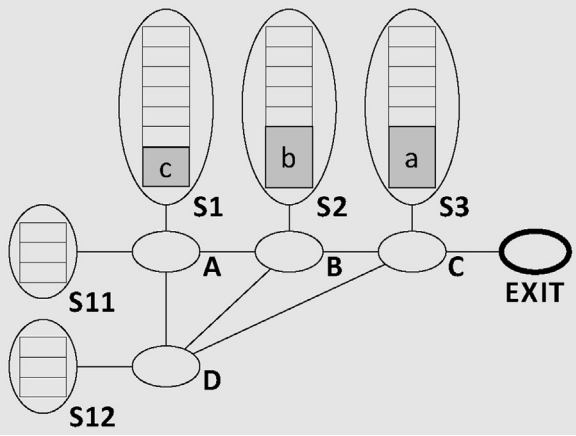

Fig. 4. Optimal solution for the cask configuration problem, given the graph shown in Fig. 2 and three casks.

where, for a cask i, $p_i \in [0\,;1]$ is the usage probability and $c_i(f)$ is the cost of moving this cask to the exit, given the arrangement defined by f. This is equivalent to the expected value of the retrieval cost.

We proceed by determining, employing combinatorial search, what is the cask arrangement within the PA, such that the global cost function is minimized. A simple branch-and-bound algorithm is used to obtain this global minimum.

4. Experimental results

To evaluate the approach, the algorithms described in the previous section were implemented. The test scenario used was the one depicted in Fig. 2, together with three casks, designated 1–3.

For an example initial configuration, Fig. 3 displays the sequence of moves necessary to take cask 2 from the stack, to the exit node. Note that, since cask 2 is blocked by cask 1, the latter has to be moved to a temporary position before the former can be retrieved from the stack.

Concerning the optimal cask placement within the PA, the optimal configuration found is shown in Fig. 4.

5. Conclusions and future work

This paper presented a method to address two problems in logistics, concerning the management of casks within the ITER: (i) determining the best sequence of operations to retrieve a single cask from the PA, possibly unblocking the path by moving other casks to temporary positions, and (ii) determining the best storage locations for casks, such that the expected cost of retrieval is minimized. This retrieval cost depends on the cask and on its cost to move it to the exit (including getting blocking casks out of the way). Expectation is computed using usage rate as probabilities of picking up casks for retrieval.

A simple proof-of-concept implementation was devised, and results for a simplified ITER-like scenario are presented. However, due to combinatorial nature of the problem, the temporal complexity grows exponentially. Future work will address this issue along two possible ways: (i) more efficient optimization methods, exploiting the structure of the problem, and (ii) approximation methods that, while not guaranteeing optimality, may provide satisfiable solutions within a reasonable execution time.

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