Stockyard Storage Space Allocation in Dry Bulk Terminals Considering Mist Cannons and Energy Expenditure

Tang, X.; Schulte, F.

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Stockyard Storage Space Allocation in Dry Bulk Terminals Considering Mist Cannons and Energy Expenditure

Xinyu Tang(✉) and Frederik Schulte

Delft University of Technology, 2600AA Delft, The Netherlands
{X.Tang-3,F.Schulte}@tudelft.nl

Abstract. Storage space management in bulk terminals has become an important focus for research and practical operation due to the increasing demand for bulk cargo and limited storage space in stockyards. The study of storage space management in dry bulk terminals is less thorough and comprehensive, and the existing research investigates the storage space allocation problem with other operational problems like berth allocation problems, but little environmental consideration has been incorporated. We investigate the storage space allocation problem with the consideration of stacker-reclaimer assignment and mist cannon operation to deal with the dust generated during material stacking. A mixed integer programming model has been established with the aim of minimizing energy consumption to reflect the pursuit of the growing emphasis on climate-neutral operations and sustainability. We test the effectiveness of the model by conducting computational experiments. We use the commercial solver CPLEX to obtain the optimal solutions for most of the test instances. Useful managerial insights extracted from the computational results may serve as a reference for storage space management in dry bulk terminals.

Keywords: Storage space allocation · Dry bulk terminal · Mist cannon operations · Stacker-reclaimer operations · Energy consumption

1 Introduction

Stockyard in dry bulk terminal acts as a centralized storage area for bulk materials, and also functions as an essential buffer for differences between incoming and outgoing streams of bulk materials [16]. Under the influence of the increasing demand for bulk cargo and the trend towards larger vessels, storage space in the stockyard tends to become a scarce resource, leading terminal operators to focus on stockyard storage space management. Utilizing the storage space reasonably can help improve the operational efficiency of the cargo transport chain. Therefore, it is necessary to study the storage space allocation problem in dry bulk terminals.

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Apart from the operation efficiency, the port now needs to take responsibility for environmental concerns driven by the growing emphasis on a cleaner environment, neutral climate, and sustainability. A large amount of dust is generated during the operation in the dry bulk stockyard, such as stacking materials into the empty fields of stock pads. Mist cannon (also known as dust cannon, or dust suppression cannon) is a widely used facility to control dust. The fogging process involves the action of fog nozzles which nebulize water into very small micro-droplets of water under pressure. The fog drives airborne dust particles to the ground and wets the surface to prevent fugitive dust particles. When water is combined with dust in the air, due to the adhesion of the surface of water molecules, it will be combined with the dust, and the effect of gravity will drop after condensing, to achieve the purpose of dust suppression. Materials are stacked into stock pads accompanied by the water spray of the mist cannon. We consider mist cannon operation in the space allocation process, which is rarely addressed in the existing literature.

The stockyard is a complex logistics system that consists of components of different operation machines like stacker-reclaimers and mist cannons. We study Storage Space Allocation Problem (SSAP) in the stockyard of dry bulk terminals, which together considers the assignment of stacker-reclaimers and mist cannons for incoming materials. In this study, we consider import dry bulk terminals in which cargo flows from the berth area to the stockyard area. We aim to determine the specific storage locations for incoming materials with the objective of minimizing energy consumption. The contributions of the paper include the following: (1) We first model the operations of mist cannons to control the dust and study the storage space allocation, stacker-reclaimer assignment and mist cannon assignment in an integrated manner. (2) We incorporate energy consumption into the optimisation objective, corresponding to the requirements of sustainable operations.

The rest of the paper is organized as follows. Section 2 reviews relevant papers in the literature. Section 3 describes the storage space allocation problem followed by mathematical formulation in Sect. 4. Section 5 shows the preliminary results from computational experiments to test the effectiveness of the mathematical model. Finally, conclusions are drawn in Sect. 6.

2 Literature Review

Storage space management in dry bulk terminal stockyards has received far less attention than that in container terminal yards. Storage space allocation problem (SSAP) is usually investigated with other operational problems (such as berth allocation problem (BAP), train scheduling, etc.) in an integrated manner. Table 1 lists the related work on the SSAP problem in dry bulk terminals.

Ouhaman et al. [13] studied the SSAP in an export dry bulk terminal. The authors formulated the problem as a mixed-integer linear programming (MILP) problem and proposed a heuristic method to solve large-scale data sets. They limited the problem to the material flow from the production plant to storage

Table 1. Related literature on storage space allocation problem in dry bulk terminals

Literature	Publication year	Problem studied	Solution
Ouhaman et al. [13]	2020	SSAP	heuristic method
Tang et al. [17]	2016	SSAP, BAP	Benders decomposition
Sun et al. [16]	2020	SSAP	logic-based Benders decomposition
Tang et al. [18]	2022	SSAP	genetic algorithm
Ago et al. [1]	2007	SSAP, conveyor belt routing	Lagrangian decomposition
Menezes et al. [12]	2017	scheduling and planning of product flows	branch and price
De Andrade et al. [3,4]	2021,2022	BAP, SSAP, scheduling and planning of product flows	column generation, diving heuristic
Boland et al. [7]	2012	SSAP, BAP	heuristic method
Robenek et al. [14]	2014	SSAP, BAP	branch and price
Al-Hammadi and Diabat [2]	2017	SSAP, BAP	branch and price
Babu et al. [5]	2015	SSAP, ship scheduling, train scheduling	logic-based Benders decomposition
Hu and Yao [9]	2012	SRSP	genetic algorithm
Belassiria et al. [6]	2019	SRSP	branch and bound method, tabu search algorithm
Hanoun et al. [8]	2013	operational scheduling of the continuous coal handling	bi-objective Optimization
van Vianen et al. [20]	2015	SRSP	simulation
Unsal and Oguz [19]	2019	SSAP, BAP, SRSP	logic-based Benders decomposition
Our work	2023	SSAP with environmental consideration	MIP

SSAP: Storage space allocation problem, BAP: Berth allocation problem, SRSP: Stacker-reclaimer scheduling problem, MIP: Mixed integer programming.

hangars. Tang et al. [17] addressed the integrated berth scheduling and SSAP in the context of bulk raw material ports of large iron and steel companies. They developed an integer programming model to minimize total costs and solved the model using a Benders decomposition-based approach. Sun et al. [16] followed up on the work of Tang et al. [17]. They first developed a mixed-integer programming (MIP) formulation that could avoid generating scattered small fields and schedule the unloading, stacking and reclaiming operations. A logic-based Benders approach was proposed to solve the problem optimally. SSAP in large iron ore terminal stockyards was studied in the work of Tang et al. [18]. They used continuous variables to describe the specific locations of the empty fields to highlight the continuous cargo flow characteristic of dry bulk stockyard operation. A MIP model was developed and a heuristic algorithm based on genetic algorithm was proposed to solve it. Ago et al. [1] considered both the SSAP and conveyor belt routing problems, using a Lagrangian decomposition algorithm.

Menezes et al. [12] studied a production planning and scheduling problem in bulk cargo terminals. The problem considered planning and scheduling the flow of products between supply, storage, and demand nodes and a branch and price algorithm was applied to solve it. De Andrade et al. [3,4] extended this problem by integrating berth allocation and yard assignment decisions.

Boland et al. [7] studied stockyard management in coal export terminals, considering the rail system transporting coal from mines to the terminal. The decisions in this study included berth allocation, stockpile location and the start times of stockpile assembly and reclaiming decisions. Robenek et al. [14] solved the integrated berth allocation and yard assignment problem in import and export bulk ports as a single large-scale optimization problem. They constructed a MIP model and applied an exact algorithm based on a branch and price framework. Al-Hammadi and Diabat [2] added constraints on the stacking space capacity to the model of Robenek et al. [14]. Babu et al. [5] minimized the delay of ships in bulk terminals by simultaneously considering ship scheduling, stockyard planning, and train scheduling.

As an important component in the stockyard, the stacker-reclaimer is also a factor that could influence the operation in the stockyard, which is considered in the decision-making of stockyard operation. Hu and Yao [9] discussed the stacker-reclaimer scheduling problem (SRSP) with the objective of minimizing the maximum completion time. The scheduling problem is formulated as a MIP model, and a genetic algorithm is developed to solve it. Belassiria et al. [6] also studied SRSP and developed two different heuristic methods, a branch and bound method, and a tabu search algorithm. Hanoun et al. [8] addressed the operational scheduling of the continuous coal handling problem. A model of stockyard operations within a coal mine was described and the problem was formulated as a Bi-Objective Optimization Problem (BOOP). In van Vianen et al.'s work [20], simulation was applied to reschedule the stacker-reclaimers operation to increase the dry bulk terminal's performance by reducing the waiting time of cargo trains being loaded at the terminal. Unsal and Oguz [19] integrated berth allocation, yard space allocation, and SRSP and modelled the master and subproblems with MIP and constraint programming, respectively, solving the problem with a logic-based Benders decomposition algorithm.

While the climate and environmental sustainability objectives are increasingly recognized in port (operations) research [10,11,15], the existing research related to the considered problem mostly focuses on the operation efficiency of the stockyard with little consideration of environmental aspects. Dust suppression in the stockyard is paid little attention to. Our study is an attempt to incorporate environmental protection considerations and neutral climate targets into stockyard space management.

3 Problem Description

The whole stockyard consists of some long stock pads, which may be pre-occupied by existing stockpiles, leaving empty fields available for incoming materials. Figure 1 shows the layout of a typical dry bulk terminal stockyard. One stacker-reclaimer (abbreviated as "SR" below) travels on a track between two pads, and the two pads are served by the same SR. Between two stock pads is a space interval. Three intervals can be found in Fig. 2, and we label them as Int 1, 2, and 3. Like SR, mist cannon (abbreviated as "MC" below) is also mobile. The difference is that MC can move among intervals instead of moving on a fixed track. They usually move from one interval to another through the end area of the stock pad. When an SR stacks materials into the stockyard, the MC sprays water mist to control the dust generated. There are two moving routes for the SR in Fig. 2. After completion of handling material 1, if the MC continues to serve material 2, it needs to move from Int 1 to Int 2, which brings vertical transport distance. Otherwise, if the MC continues to serve material 3 planned to be allocated in pad 2, it only needs to move horizontally.

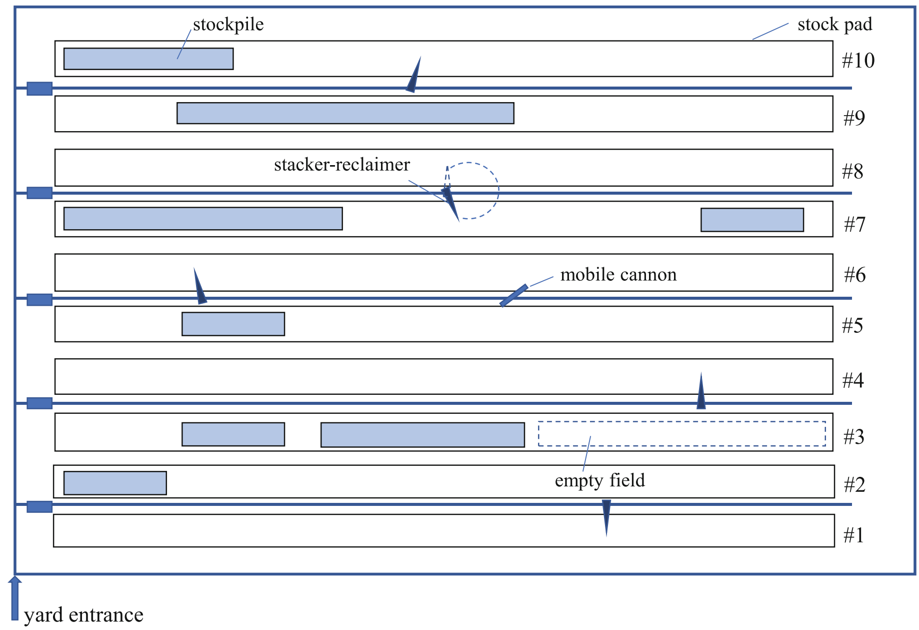

Fig. 1. Typical stockyard layout in dry bulk terminals.

We investigate the Stockyard Storage Space Allocation Problem with the MC operation to control the dust generated during stacking. We aim to find the

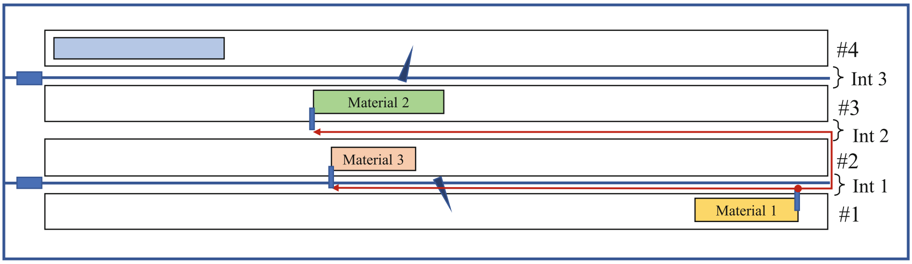

Fig. 2. Representation of mist cannon operation.

specific storage position for each incoming material with the objective of minimizing the energy consumption of operations in the stockyard. The main energy consumers in the stockyard are conveyor belts, SRs, and MCs. The energy consumption of SR and MC are further divided into two parts: energy consumption when handling materials and moving from the position of handled material to the position of material to be next served. To calculate energy consumption, we multiply the power of operating machines by the time consumed during handling or moving. Time can be obtained by dividing distance by moving speed.

When calculating the travel distance, we need to mark the position of each material and the working machine. We, therefore, introduce a virtual material 0 for each SR and MC (each SR and MC will at least serve material 0) and then set the position of the virtual material as the initial position of the machines. Hence, the moving distance can be normally calculated.

4 Mathematical Model

4.1 Assumptions

The following assumptions are made in this problem:

(1) There are plenty of empty fields to accommodate the incoming materials over the whole planning period, which means there is always enough space for stacking.
(2) One material can be stacked next to another material if a safe distance is maintained to avoid mixing. We consider a dedicated terminal for a particular cargo type. For example, in an iron ore terminal, the different types of iron ore are usually distinguished from each other by the size of the diameter of the particles and there is no strict restriction that they cannot be stacked next to each other, only that a safe distance is maintained to avoid mixing.
(3) Once the goods are stacked in the yard, the position will not change during the planning period, which is consistent with the situations in practice.
(4) The operating capability of machines in the stockyard is constant during the handling process.
(5) The moving distance is calculated from the end coordinate of the material that has just been completed handling to the start coordinate of the material to be next served.

4.2 Model Formulation

In this section, we present the mathematical model of the stockyard storage space allocation problem.

Sets and Parameters

P	set of stock pads
C	set of incoming materials
S	set of stacker-reclaimers
W	set of mist cannons
N	set of intervals
L	the horizontal length of a pad
dis	the distance between two intervals in stockyards
l_i	length of the space needed to stack the material i, $i \in C$
m_i	mass of the incoming material i, $i \in C$
ly_p	the vertical distance from the entrance of the stockyard to stock pad p, $p \in P$
α_{nw}^{st}	binary parameter which indicates whether MC w is in the interval n before planning starts, $n \in N$, $w \in W$; if $\alpha_{nw}^{st} = 1$, MC w is in the interval n
a_{sp}	binary parameter which indicates whether SR s can cover stock pad p, $s \in S$; if $a_s p = 1$, SR can cover stock pad p
b_{pn}	binary parameter which indicates whether pad p is adjacent to interval n, $n \in N$; if $b_{pn} = 1$, pad p is adjacent to interval n
xs_{s0}	the start position of SR s when the stacking operation starts
xs_{w0}	the start position of MC w when the stacking operation starts
cap_{srh}	handling capability of SR
cap_c	handling capability of conveyor belt
spe_{srm}	moving speed of SR
spe_{wcm}	moving speed of MC
spe_{cm}	moving speed of conveyor belt
P_{srh}	power of SR when handling materials
P_{srm}	power of SR when moving
P_{wch}	power of MC when spraying water mist
P_{wcm}	power of MC when moving
P_c	power of conveyor belt
sd	safe distance between two adjacent materials
M	a positive number that serves as infinity for the problem

Decision Variables

k_{ip}	0–1 variable, equal to 1 if and only if the material i is allocated to stock pad p
xs_i	start coordinate of material i
z_{ijp}	0–1 variable, equal to 1 if and only if material i and j are allocated to stock pad p and material i is allocated to the left of material j satisfying safe distance constraint
x_{is}	0–1 variable, equal to 1 if material i is handled by SR s
y_{iw}	0–1 variable, equal to 1 if material i is handled by MC w
α_{in}	0–1 variable, equal to 1 if the MC serving material i is located in the interval n
θ_{ijs}	0–1 variable, equal to 1 if and only if the material i and j are both handled by SR s, and material j is handled by SR s right after material i
μ_{ijw}	0–1 variable, equal to 1 if and only if the material i and j are both handled by MC w, and material j is handled by MC w right after material i
ρ_{ijw}	0–1 variable, equal to 1 if and only if MC w moves in the same interval when complete serving material i and then continues to serve material j
π_{ijw}	0–1 variable, equal to 1 if and only if MC w move from one interval to another when completing serving material i and then continues to serve material j
u_i, v_i	random number related to material i
δ, τ	0–1 variable

The mathematical model can be formulated as follows:

$$\begin{aligned} min \ & \sum_i P_{srh}\frac{m_i}{cap_{srh}} + \sum_i P_{wch}\frac{m_i}{cap_{srh}} + \sum_i P_c\frac{m_i}{cap_c} + \sum_i \frac{P_c\left(xs_i + \sum_p ly_p k_{ip}\right)}{spe_{cm}} \\ & + \sum_s\sum_j P_{srm}\frac{\theta_{0js}\left|xs_j - xs_{s0}\right|}{spe_{srm}} + \sum_s\sum_i\sum_j P_{srm}\frac{\theta_{ijs}\left|xs_j - xs_i - l_i\right|}{spe_{srm}} \\ & + \sum_w\sum_j P_{wcm}\frac{\mu_{0jw}dis\left|\sum_n n\alpha_{jn} - \sum_n n\alpha_{nw}^{st}\right|}{spe_{wcm}} \\ & + \sum_w\sum_i\sum_j P_{wcm}\frac{\mu_{ijw}dis\left|\sum_n n\alpha_{jn} - \sum_n n\alpha_{in}\right|}{spe_{wcm}} \\ & + \sum_w\sum_j P_{wcm}\frac{\rho_{0jw}\left|xs_j - xs_{w0}\right|}{spe_{wcm}} + \sum_w\sum_j P_{wcm}\frac{\pi_{0jw}(L - xs_{w0} + L - xs_j)}{spe_{wcm}} \\ & + \sum_w\sum_i\sum_j P_{wcm}\frac{\rho_{ijw}\left|xs_j - xs_i - l_i\right|}{spe_{wcm}} \\ & + \sum_w\sum_i\sum_j P_{wcm}\frac{\pi_{ijw}(L - xs_i - l_i + L - xs_j)}{spe_{wcm}} \end{aligned} \quad (1)$$

s.t.

$$\sum_{p\in P} k_{ip} = 1, \quad \forall\ i \in C \setminus \{0\} \tag{2}$$

$$x_{0\,s} = 1, \quad \forall\ s \in S \tag{3}$$

$$\sum_{s\in S} x_{is} = 1, \quad \forall\ i \in C \setminus \{0\} \tag{4}$$

$$\sum_{\{p\in P|a_{sp}=1\}} k_{ip} \geq 1 + M\left(1 - x_{is}\right), \quad \forall\ i \in C \setminus \{0\},\ s \in S \tag{5}$$

$$\sum_{\{p\in P|a_{sp}=1\}} k_{ip} \leq 1 - M\left(1 - x_{is}\right), \quad \forall\ i \in C \setminus \{0\},\ s \in S \tag{6}$$

$$\sum_{i} \theta_{ijs} \leq 1 + M\left(1 - x_{js}\right), \quad \forall\ j \in C \setminus \{0\},\ s \in S \tag{7}$$

$$\sum_{i} \theta_{ijs} \geq 1 - M\left(1 - x_{js}\right), \quad \forall\ j \in C \setminus \{0\},\ s \in S \tag{8}$$

$$\sum_{j\in C\setminus\{0\}} \theta_{ijs} \leq 1 + M\left(1 - x_{is}\right), \quad \forall\ i \in C \setminus \{0\},\ s \in S \tag{9}$$

$$\sum_{i} x_{is} > 1 - M\left(1 - \delta\right), \quad \forall\ s \in S \tag{10}$$

$$\sum_{j\in C\setminus\{0\}} \theta_{0js} \geq 1 - M\left(1 - \delta\right), \quad \forall\ s \in S \tag{11}$$

$$\sum_{j\in C\setminus\{0\}} \theta_{0js} \leq 1 + M\left(1 - \delta\right), \quad \forall\ s \in S \tag{12}$$

$$v_i < v_j + M\left(1 - \theta_{ijs}\right), \quad \forall i,j \in C \setminus \{0\}, s \in S \tag{13}$$

$$\theta_{ijs} + \theta_{jis} \leq 1, \quad \forall\ i,j \in C,\ s \in S \tag{14}$$

$$\theta_{ijs} \leq x_{is}, \quad \forall i,j \in C,\ i \neq j,\ s \in S \tag{15}$$

$$\theta_{ijs} \leq x_{js}, \quad \forall\ i,j \in C,\ i \neq j,\ s \in S \tag{16}$$

$$xs_j - (xs_i + l_i) - sd > M\left(z_{ijp} - 1\right), \quad \forall\ i,j \in C \setminus \{0\},\ i \neq j,\ p \in P \tag{17}$$

$$xs_j - (xs_i + l_i) - sd \leq M z_{ijp}, \quad \forall\ i,j \in C \setminus \{0\},\ i \neq j, p \in P \tag{18}$$

$$z_{ijp} + z_{jip} \geq 1 - M\left(2 - k_{ip} - k_{jp}\right), \quad \forall\ i,j \in C \setminus \{0\},\ i \neq j, p \in P \tag{19}$$

$$z_{ijp} \leq\ k_{ip}, \quad \forall\ i,j \in C \setminus \{0\}, p \in P \tag{20}$$

$$z_{ijp} \leq\ k_{jp}, \quad \forall\ i,j \in C \setminus \{0\}, p \in P \tag{21}$$

$$\sum_{n\in N} \alpha_{in} = 1, \quad \forall\ i \in C \setminus \{0\} \tag{22}$$

$$\sum_{\{n\in N|b_{pn}=1\}} \alpha_{in} \geq 1 - M\left(1 - k_{ip}\right), \quad \forall i \in C \setminus \{0\},\ p \in P \tag{23}$$

$$\sum_{\{n \in N | b_{pn}=1\}} \alpha_{in} \leq 1 + M\left(1 - k_{ip}\right), \quad \forall\, i \in C \setminus \{0\}\,,\; p \in P \tag{24}$$

$$y_{0w} = 1, \quad \forall\, w \in\; W \tag{25}$$

$$\sum_{w} y_{iw} = 1, \quad \forall\, i \in\; C \setminus \{0\} \tag{26}$$

$$\sum_{i} \mu_{ijw} \leq 1 + M\left(1 - y_{jw}\right), \quad \forall\, j \in C \setminus \{0\}\,,\; w \in W \tag{27}$$

$$\sum_{i} \mu_{ijw} \geq 1 - M\left(1 - y_{jw}\right), \quad \forall\, j \in C \setminus \{0\}\,,\; w \in W \tag{28}$$

$$\sum_{j \in C \setminus \{0\}} \mu_{ijw} \leq 1 + M\left(1 - y_{iw}\right), \quad \forall\, i \in C \setminus \{0\}\,,\; w \in W \tag{29}$$

$$\sum_{i} y_{iw} > 1 - M\left(1 - \tau\right), \quad \forall\, w \in W \tag{30}$$

$$\sum_{j \in C \setminus \{0\}} \mu_{0jw} \geq 1 - M\left(1 - \tau\right), \quad \forall\, w \in W \tag{31}$$

$$\sum_{j \in C \setminus \{0\}} \mu_{0jw} \leq 1 + M\left(1 - \tau\right), \quad \forall\, w \in W \tag{32}$$

$$u_i < u_j + M\left(1 - \mu_{ijw}\right), \quad \forall\, i, j \in C \setminus \{0\}\,, w \in W \tag{33}$$

$$\mu_{ijw} + \mu_{jiw} \leq 1, \quad \forall\, i, j \in C,\; w \in W \tag{34}$$

$$\mu_{ijw} \leq\; y_{iw}, \quad \forall\, i, j \in C,\; w \in W \tag{35}$$

$$\mu_{ijw} \leq y_{jw}, \quad \forall i, j \in C,\; w \in W \tag{36}$$

$$\sum_{n} n\alpha_{jn} \leq \sum_{n} n\alpha_{in} + M\left(1 - \rho_{ijw}\right), \quad \forall i, j \in C \setminus \{0\}\,, w \in W \tag{37}$$

$$\sum_{n} n\alpha_{jn} \geq \sum_{n} n\alpha_{in} - M\left(1 - \rho_{ijw}\right), \quad \forall\, i, j \in C \setminus \{0\}\,, w \in W \tag{38}$$

$$\sum_{n} n\alpha_{jn} \leq \sum_{n} n\alpha_{nw}^{st} + M\left(1 - \rho_{0jw}\right), \quad \forall\, j \in C \setminus \{0\}\,, w \in W \tag{39}$$

$$\sum_{n} n\alpha_{jn} \geq \sum_{n} n\alpha_{nw}^{st} - M\left(1 - \rho_{0jw}\right), \quad \forall\, j \in\; C \setminus \{0\}\,, w \in W \tag{40}$$

$$\rho_{ijw} \leq \mu_{ijw}, \quad \forall\, i, j \in C, w \in W \tag{41}$$

$$\pi_{ijw} \leq \mu_{ijw}, \quad \forall\, i, j \in C, w \in W \tag{42}$$

$$\rho_{ijw} + \pi_{ijw} \leq 1 + M\left(1 - \mu_{ijw}\right), \quad \forall\, i, j \in C, w \in W \tag{43}$$

$$\rho_{ijw} + \pi_{ijw} \geq 1 - M\left(1 - \mu_{ijw}\right), \quad \forall\, i, j \in C, w \in W \tag{44}$$

$$0 \leq xs_i \leq L, \quad \forall\, i \in C \tag{45}$$

$$0 \leq xs_i + l_i \leq L, \quad \forall\, i \in C \tag{46}$$

$$k_{ip}, x_{is}, y_{iw}, \theta_{ijs}, \mu_{ijw}, z_{ijp}, \alpha_{in} \in \{0, 1\}, \\ \forall\ i, j \in C, p \in P,\ s \in S,\ w \in W,\ n \in N \tag{47}$$

The objective (1) is to minimize the total energy consumption of operation in the stockyard. The first three terms are the energy consumption of SRs, MCs and conveyor belts, respectively of handling (SRs and MCs) and transporting (conveyor belts) materials. The fourth term is the energy consumption of the conveyor belt when moving from the stockyard entrance to the stacking position of materials in the stockyard. The next two terms represent the energy consumption of SRs when moving from the position of the material they have just handled to the position of the material they will next serve. The energy consumption of MC when moving from one material to the next one is calculated by the last six terms. The transport distance is calculated vertically and horizontally respectively. The terms with variable μ_{0jw}, ρ_{0jw}, π_{0jw} calculate the energy consumption when moving from the initial position of each MC to the position of material they first serve.

Constraint (2) guarantees that each material can be allocated to only one stock pad. Constraint (3) allocates a virtual starting material for each SR. Constraint (4) ensures that each material is served by only one SR. Constraint (5) and (6) define the relationship between variable x_{is} and k_{ip}. If material i is served by SR s, the material i will be allocated to the stock pad p which stacker-reclaimer s can cover. Constraints (7)–(13) ensure that for each SR, if it is assigned to serve material in the planning period, the served material number will form a sequence beginning with the number 0, with each number of served material appearing only once. Constraint (14) states that two materials served by one SR can not be handled simultaneously. Constraints (15) and (16) are the premise of the non-overlapping constraints in time for materials served by the same SR. Constrains (17), (18), and (19) are the non-overlapping restrictions for any two materials stacked in the same pad and they must satisfy the safe distance restriction. Constraints (20) and (21) are the premise of the non-overlapping restrictions in space.

Constraint (22) guarantees that the MC serving each material can be located to only one interval. Constraint (23) and (24) defines the relationship between variable α_{in} and k_{ip}. If material i is located in stock pad p, the MC serving material i must be located in the interval to which the stock pad p is adjacent to. Constraint (25) allocates a virtual starting material for each MC. Constraint (26) states that each material is served by only one MC. Constraints (27)–(33) ensure that for each MC, if it is assigned to serve material in the planning period, the served material number will form a sequence beginning with the number 0, with each number of served material appearing only once. Constraint (34) states that two materials served by one MC can not be handled simultaneously. Constraints (35) and (36) are the premise of the non-overlapping constraints in time for materials served by the same MC. The meaning of ρ_{ijw} is defined in constraints (37) and (38). If MC w remains in the same interval when moving from the position of material i to that of material j, the MC serving material i and j are in the same interval. Constraints (39) and (40) have the same meaning as the above two constraints, but they describe the situation of an MC moving from the initial position to its first serving material. Constraints (41) and (42) are the premise of variable ρ_{ijw} and π_{ijw}. Constraint (43) and (44) state that only one of the two variables ρ_{ijw} and π_{ijw} can be 1 if there is pair $i \rightarrow j$ in the material handling sequence of MC w. Constraint (45) and (46) show the value range of start and end coordinates. Lastly, constraint (47) determines the domains of 0–1 variables.

5 Computational Experiments

In this section, we conducted computational experiments to test the effectiveness of the proposed mathematical model using solver CPLEX 22.1 under C++ environment with a time limit of 3600 s.

5.1 Instance Generation and Computational Results

We generated 12 instances and divided them into 3 sets according to the number of stock pads, SRs, and MCs. We consider $|C|$ materials, $|P|$ stock pads, $|S|$ SRs and $|W|$ MCs in computational experiments. The configuration of each instance can be found in Table 1. Set 1 has 4 stock pads with 2 SRs and 1 MC. Set 2 has the same configuration as set 1, except for 2 MCs. Set 3 has 6 stock pads with 3 SRs and 3 MCs. Each set consists of computational instances with different material numbers. The material information (mass and length) in instances with the same material numbers is the same. (Instances 1, 5, and 9 have the same information, which is the same situation for instances 2, 6, and 10; instances 3, 7, and 11 and instances 4, 8, and 12.) The material information is generated randomly.

Table 2 shows the results obtained within the time limit. Since the first three terms in the objective (1) are fixed terms, we use “Objective value of variable parts” in the table to explicitly show the objective value dependent on decision variables, that is, the value of objective (1) excluding the first three terms. The “objective value” in the following text refers to the value of objective excluding the fixed terms. Optimal solutions can be found for 9 of the 12 instances. The increase in the number of stock pads, SRs, MCs and materials expands the scale of the model, thus making the computation time increase dramatically. It can be noticed that the results of instances 1, 5, and 9 are the same (Instances 2, 6, and 10 are in the same situation.), which means the change of some parameters like the number of stock pads, SRs and MCs have little influence on optimal solutions to some extent.

We compare the composition of objective value (of variable parts) of instance 5–8 in Fig. 3. The energy consumption of the conveyor belt moving to the specified stacking position for materials takes a larger proportion compared to the other two components (energy consumption of SR and MC) during moving. It is observed that there is a clear absolute variation of the energy consumption of the belt conveyor moving among different instances, while the change of energy

Table 2. Computational results for the test instances

Set	Ins No.	$\|C\|$	$\|P\|$	$\|S\|$	$\|W\|$	Objective value of variable parts(kW·h)	time(s)
1	1	5	4	2	1	15.25	4.64
	2	5	4	2	1	13.25	5.04
	3	6	4	2	1	19.76	68.61
	4	7	4	2	1	24.17	2480.27
2	5	5	4	2	2	15.25	9.91
	6	5	4	2	2	13.25	41.12
	7	6	4	2	2	19.76	104.54
	8	7	4	2	2	24.17	3600
3	9	5	6	3	3	15.25	226.45
	10	5	6	3	3	13.25	216.92
	11	6	6	3	3	19.76	3600
	12	7	6	3	3	23.36	3600

consumption of SR and MC moving is rather less obvious. The possible reason is that each SR and MC moves between two stock pads (in one interval), the transport distance of SR and MC is therefore relatively shorter than the distance the conveyor belt travels.

5.2 Managerial Insights

With the calculation results in Sect. 5.1, we can extract some managerial insights which may be helpful for storage space management in the stockyard.

(1) The number of stock pads open can be determined according to the number of incoming materials. Stockyards do not always need to open all the stock pads. We can find that the objective values of instances 1,5,9 are the same, which means the results obtained in the background of 4 stock pads and 6 stock pads are the same. Opening stock yards depending on the number of materials may help save operational costs of the stockyard.

(2) Materials are stacked into the adjacent stock pads which one stacker-reclaimer and mist cannon can cover, which could shorten the travel distance of SR and MC, thus saving the energy consumed. As shown in Fig. 4 and 5, all the materials are stacked in the adjacent pad 1 and 2.

(3) Materials tend to be stacked in the stock pads close to the stockyard entrance so that the conveyor belts do not need to move a long distance, which could reduce the energy consumption of the conveyor belt. Figure 4 and 5 show that materials are stacked in the pad 1 and 2 which are closest to the entrance of the stockyard.

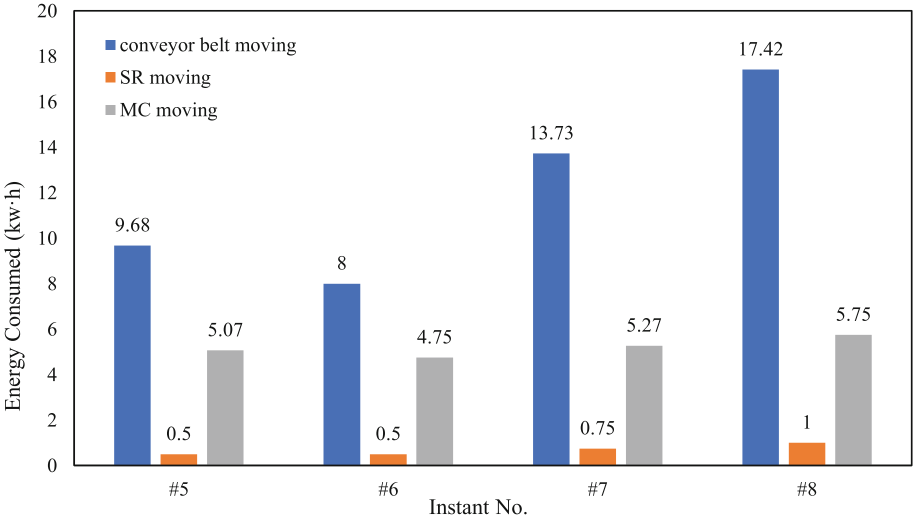

Fig. 3. Comparison of the objective value of instance 5–8.

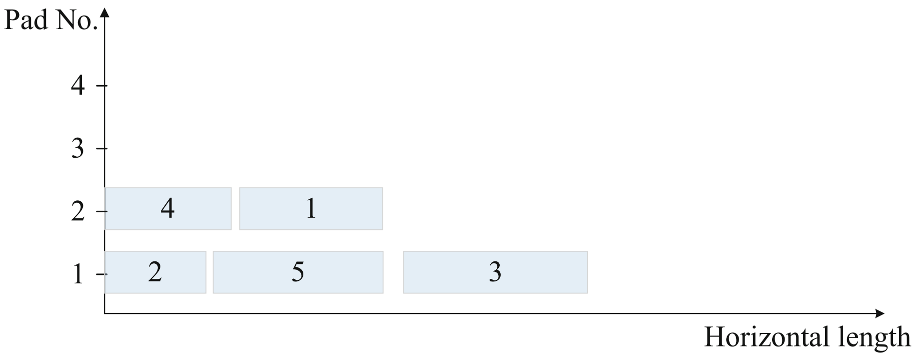

Fig. 4. Representation of solution for instance 5.

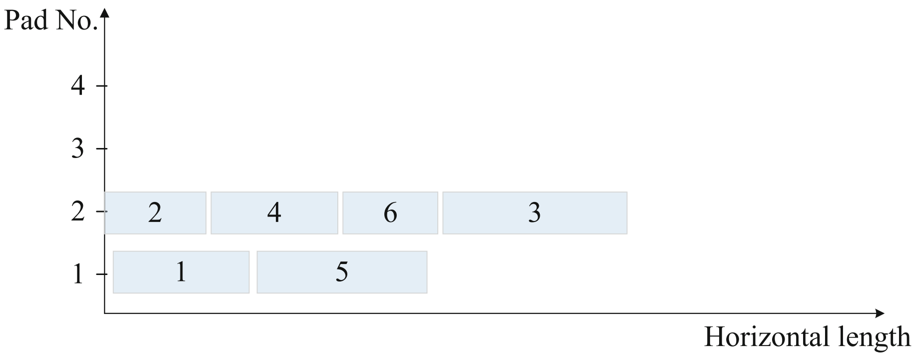

Fig. 5. Representation of solution for instance 7.

6 Conclusion

We study the Storage Space Allocation Problem with the consideration of operation machines in the stockyard. Existing studies investigate the storage space allocation problem with other operation problems such as berth allocation and stacker reclaimer scheduling. However, they pay little attention to environmental sustainability. We take the operation of mist cannon to control dust during stacking into consideration and aim to minimize the energy consumption during stacking operation. A mixed integer programming model is established, and we show the effectiveness of the proposed model by conducting computational experiments on some small-scale instances. Some managerial insights are extracted, which may help in storage space management as a reference.

Our future work will focus on the improvement of the formulation of the model and the development of an efficient algorithm to solve the model for large-scale instances. And we need to collect operational data from real-world practice as the input of computational experiments to validate the results considering practical implications.

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