Scientia Iranica E (2017) 24(6), 3371–3393

SCIENTIA IRANICA

Sharif University of Technology
Scientia Iranica
Transactions E: Industrial Engineering
www.scientiairanica.com

Energy-conscious dynamic sequencing method for dual command cycle unit-load multiple-rack automated storage and retrieval systems

A. Roozbeh Nia[a], H. Haleh[b,*] and A. Saghaei[a]

a. *Department of Industrial Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran.*
b. *Department of Industrial Engineering, Golpayegan University of Technology, Golpayegan, Iran.*

Received 22 November 2015; received in revised form 12 June 2016; accepted 26 September 2016

KEYWORDS
Automated warehouses;
Dynamic sequencing;
Electricity tariffs;
Genetic algorithm;
Simulated annealing;
Performance analysis.

Abstract. A Dual Command (DC) cycle "dynamic sequencing" method in unit-load multiple-rack AS/RS system under Time-Of-Use (TOU) electricity tariffs is applied in this paper. To make a type of energy-efficient model, overconsumption cost of on-peak period electricity, penalty cost of overconsumption of power, bounds on the total consumed energy, and accessible times of all facilities are considered in the model. Moreover, a Genetic Algorithm (GA) is developed to achieve a near-optimum solution to the suggested energy-based mathematical model with the objective of minimizing the total cost of the AS/RS system under TOU tariffs. Considering that no benchmark is obtainable in the literature, a Simulated Annealing (SA) algorithm is developed to certify the outcome gained. For supplementary confirmation, we compare the total cost of our model with that of single-tariff model and also conduct sensitivity analysis of the allowable amount of power consumption. The system throughput, in terms of time and cost, is calculated for the model too. In the last part, sixteen numerical examples with different numbers of required storage/retrieval orders are suggested to display the function of the proposed procedure. Our outcomes verified that GA is able to obtain favorable and closer optimal solutions and the TOU tariffs model get the minimum total cost.

1. Introduction

Energy-efficient manufacturing claims of a modification made to the management of warehousing processes have been transformed from the traditional time-based perspective to the energy-based one. In Automated Storage and Retrieval Systems (AS/RS), this new policy leads to reviewing storage assignment strategies with the purpose that the least energy can be used by Storage and Retrieval (S/R) machine and conveyors for unit-load movements [1]. An AS/RS is the support for an inventory management method, and it uses an automatic S/R machine to perform tasks in a warehouse such as loading, unloading, inventory, and warehouse planning. As customer's orders vary and regularly change, the role of AS/RS is transformed from a place where items are stored for a long-term period to a temporary buffer that adjusts the balance between loading and unloading in a warehouse. Since AS/RS systems are used more frequently and the efficiency of warehouses has become essential, there is an obligation to develop the efficiency of AS/RS [2]. In an AS/RS system, in a Single Command (SC)

*. *Corresponding author. Tel.: +98 21 88534460; Fax: +98 21 88534461;*
E-mail addresses: ali.roozbehnia@gmail.com (A. Roozbeh Nia); hhaleh@gut.ac.ir (H. Haleh); a.saghaei@srbiau.ac.ir (A. Saghaei)

doi: 10.24200/sci.2017.4395

cycle, the S/R machine accomplishes a storage request or a retrieval request. Fukunari and Malmborg [3] concocted the term "interleaving", which refers to the combination of storage and retrieval operations on the same cycle to form a Dual Command (DC) cycle. In DC, the S/R machine executes a storage request and then a retrieval request.

The implementation of AS/RS system, where storage and retrieval tasks are executed by unmanned machines, has been increasing since 2010 [4]. AS/RS system is known 'to make a play for sustainability' [5] due to the improved usage of space, allowing storage of the equal quantity of units in a reduced footprint, demanding less concrete, and therefore decreasing carbon dioxide emissions. Furthermore, the capability of AS/RS systems to store inventory further densely condenses the necessity for energy to heat, cool, light, and ventilate excess square footage. However, AS/RS systems need energy similarly for their shuttle travels along the racks, and this characteristic has been abandoned in the method of optimizing such facilities. A significant body of literature is begun to develop concerning power cost which declines in warehousing systems. Most of the reported studies have been dedicated to decreasing the total electricity consumption, improving the efficiency of facilities, etc. [6-8]. In recent times, several electricity suppliers have been activated to follow the so-called Time-Of-Use (TOU) tariffs, that is, retail power pricing that changes hourly to reveal alterations in the general electricity marketplace. Such pricing suggests an enormous opportunity to shorten the costs of electricity-intensive consumers by shifting electricity usage from on-peak hours to off-peak or mid-peak hours. Under TOU electricity tariffs, the power price is based on the consumed electricity over time, and takes into account that each period has a corresponding cost per unit of energy consumed [9].

While a considerable number of studies are presented in the literature, concise criticism of the studies on the AS/RS is introduced in the next section.

2. Literature review

In the literature and in practice, there are many different types of AS/RS, which can be classified into [10]:

- *Unit-load crane-based AS/RS*: They are single-aisle or multi-aisle systems and can be either single-deep, double-deep, or even multiple-deep. The hoisted carriage of the S/R machine can be either single-shuttle or multi-shuttle;
- *Mini-load crane-based AS/RS*: They are always single-aisle systems and can be either single-deep, double-deep, or even multiple-deep. The hoisted carriage of the S/R machine can be either single-shuttle or multi-shuttle;
- *Unit-load Autonomous Vehicle Storage and Retrieval Systems (AVS/RS):* Due to the ability of accessing any storage positions in the storage racks and flexibility in changing the number of autonomous vehicles, this system has advantages compared to traditional crane-based AS/RS. They have been implemented to many facilities, primarily in Europe [11];
- *Mini-load Shuttle-Based Storage and Retrieval Systems (SBS/RS):* It is a relatively new technology in AVS/RS and is used for tote handling [12]. In the case of the SBS/RS, the vertical movement of totes is facilitated by the elevator's lifting tables mounted along the periphery of the storage racks. On the other hand, the horizontal movement of totes to their destination in the storage rack is facilitated by tire-captive shuttle carriers [10]. Some researchers, such as Carlo and Vis [12], Dukic et al. [13], Lerher et al. [14], Lerher et al. [15], Lerher [16], Lerher [10], Marchet et al. [17], and Marchet et al. [18], have studied the analytical difficulties and differences of SBS/RS.

Commonly, the storage requirements are managed by First-Come-First-Served (FCFS) approach since the sequence of goods to storage presents a physical flow where it is challenging to modify the filling (in a conveyor, for instance), while retrieval requests can be re-sequenced meanwhile they are just an information flow (list). Han et al. [19] proposed two methods for sequencing storage and retrieval requests: (1) Selecting a subset (wave) of storage and retrieval requests and sequencing the requests in the wave. Releasing the next wave when all storage and retrieval requests in the current wave have been accomplished; and (2) Re-sequencing the requests every time a new request comes in and using due dates or priorities to ensure that retrieval at the far end of the aisle is not extremely postponed. According to Van den berg and Gademan [20], these methods were mentioned as "wave sequencing" and "dynamic sequencing", respectively.

Two generally adopted shared strategies in warehouses are the random policy and the class-based one; the former is where every product can occupy every open location in the rack, while the latter is where a product can occupy every location within the zone assigned to its demand class [21]. The latest literature findings have emphasized how the performance of dedicated policies degrades when systems with Locations-To-Product Ratio (LTPR) greater than one are supposed. In its most common form ($LTPR > 1$), the problem includes finding the best storage location and the best retrieval location between the existing. In this situation, dedicated policies have to be changed by dynamic policies [21]. From the time-based approach, Gagliardi et al. [22] revealed that the best time performance is achieved by assuming the Closest Open Location (COL) rule for storage assignment and the Shortest Leg Location (SLL) rule for retrievals within each class zone. By the former, the open location that is closest to the I/O point is selected, whereas the location involving the shortest trip from the current S/R machine position is selected by the latter. This manner can be described by the fact that locations are no longer uniformly visited, as presumed by analytical models and the random movement rule.

In the past 40 years, many studies of AS/RS have been performed. The concentrated advance of AS/RS has begun with the development of the computer and informational science, which describes a significant part of the warehouse operation. The two more used methods for AS/RS design and study in the present days are analytical optimizations and simulations that are used by many authors such as Mansuri [23], Lee and Schaefer [24], Berg and Zijm [25], Kwon et al. [26], Roodbergen and Iris [27], Hachemi and Alla [28], Hua et al. [29], Atmaca and Ozturk [30], Alonso-Ayuso et al. [31], Popovic et al. [32], and Kung et al. [2].

Some recent studies are presented as follows: Hachemi et al. [33] dealt with the sequencing problem where a required product can be in several locations of a rack, and there is a set of empty locations. Therefore, the retrieval and storage locations are not recognized in advance. An optimization process working step by step is developed to determine for each DC, according to storage and retrieval requests, the location of the item to be stored and the location of the item to be retrieved in a single rack, allowing the minimum DC cycle time. The storage requests are processed in FCFS and retrieval requests are gathered by block under "wave sequencing". Brezovnik et al. [34] showed how to plan and control AS/RS system with simultaneously structural, operational, and control features using multiple-objective Ant Colony Optimizations (ACO). In order to decrease space consumption and minimize investment costs, they chose an AS/RS with no corridors and one single elevator for multiple products. Outcomes demonstrate that the expected distribution of products was reached and that ACO can be successfully used for planning automated storage systems. Yang et al. [35] examined the joint optimization of storage location assignment and storage/retrieval scheduling in multi-shuttle AS/RSs under shared storage, in which the reuse of empty location yielded by retrieval operation was permitted. A Variable Neighborhood Search (VNS) algorithm was established to solve the large-sized problems. Various numerical experiments were conducted to evaluate the performance of the proposed algorithm and examine the impact of different parameters on computational efficiency.

Boysen and Stephan [36] studied the scheduling of a single S/R machine (or crane) in AS/RSs. A novel classification scheme was offered for exactly expressing altered versions of the crane scheduling problem when changing the layout of the AS/RS, the features of the storage and retrieval requests, and the objective function. This classification scheme was then employed for giving different (known and novel) exact algorithms and complexity proofs for a variety of crane scheduling problems, reviewing the literature, and recognizing future research requirements.

Khojasteh and Son [37] dealt with an order picking problem in a multi-aisle AS/RS where a single S/R machine makes storage and retrieval operations. When retrieval requests involve multiple items and the items are in multiple stock locations, the S/R machine must travel to several storage locations to fulfill a customer order. The objective is to minimize the total time traveled by the S/R machine to complete the retrieval process of customer orders. The problem was formulated as a nonlinear programming model and a heuristic was suggested called the Shortest Travel Distance (STD) heuristic to solve it. In addition, Wenrui et al. [38] designed a modified mini-load AS/RS to fit the new features of e-commerce in logistics. Meanwhile, a matching problem, involving the improvement of picking efficiency in a new system, was considered. The problem was how to decrease the travelling distance of totes among aisles and picking stations. A multi-stage heuristic algorithm was suggested with some heuristic approaches based on similarity coefficients, minimizing the transportations of items which cannot get to the endpoint picking stations just through direct conveyors. Qiang and Xiwen [39] investigated an on-line scheduling and routing problem concerning the AS/RS from tobacco industry. In their problem, stacker cranes run on one common rail among two racks. Multiple input/output-points are positioned at the bottom of the racks. The stacker cranes conveying the bins among the input/output points and cells on the racks to complete requests are created over time. Each request has to be done within its response time. The objective is to minimize the time by which all the generated requests are accomplished. Under a given physical layout, the authors analyze the complexity of the problem and design on-line algorithms for both one-stacker-crane and two-stacker-crane models.

To the best of the author's knowledge, there exist only a few research studies which have considered energy issue in the AS/RS system. The energy-based approach to the sequencing problem under a static approach (block/wave sequencing) was firstly introduced by Meneghetti and Monti [40], who proposed a greedy heuristic for the Energy-Based Full Turnover (EBFT) dedicated policy. Factors involving energy consumption and round trip times, such as the storage allocation strategy, the re-sequencing time-based or energy-based policies, the demand distribution, and the shape of the rack, are examined by a 2^4 factorial design of experiments. Their model has $O(N^2 \log_2 N)$ complexity and a relative error of 8%, with respect to the optimum solution, similar to the heuristic by Lee and Schaefer [24] for the Time-Based Full Turnover (TBFT) policy and the time minimization objective. Similarly, the EBFT policy introduced by Meneghetti and Monti [41] assigned the locations, which required the minimum energy consumption for crane movements, to the products sorted by their turnover frequency in a decreasing order.

Lerher et al. [42] developed the energy efficiency model for the mini-load AS/RS for the support of the design process of warehouses. They performed some analysis of energy efficiency model based on the achievement of the required throughput capacity (application of travel time model), mechanical model of the S/R machine with the hoisted carriage (engine power and velocity), and energy consumption with CO_2 emission. Meneghetti and Monti [43] presented an optimization model for the sustainable design of refrigerated AS/RS, which takes into account specific characteristics of the food supply chain, such as temperature control. Rack configuration along with surfaces and volumes of the cold cell was conjointly optimized to minimize the total annual cost of the AS/RS facility, presenting energy requirements both for refrigeration and picking operations explicitly, other than investment costs. The design problem was modeled and solved by Constraint Programming with the purpose of easily managing non-linear functions. After that, Meneghetti and Monti [1] analyzed the role of weight, showing how heavy items tend to occupy lower positions in multiple-weight unit-load racks, while light items increase their gravitational energy by occupying upper locations. As a consequence, by changing the weight of a given item, the step-wise profile of its dedicated zone was modified accordingly. Lately, Meneghetti et al. [21] have proposed a classification of racks based on system height with the purpose of deciding on the appropriate crane specifications required to compute the torque to be overcome by motors to serve a specified place within a rack. They developed an overall optimization model based on constraint programming hybridized with large neighborhood search, permitting the joint application of the best control strategies. These strategies were used for sequencing and storage assignment both to time- and energy-based optimizations, along with the outline of multiple-weight unit loads and energy recovery. Also, analysis of simulations was performed so that the effect of the rack shape on energy saving could be assessed.

As seen, these research studies only focus on energy-based design specifications of AS/RS such as rack shape, rack stratification from floor, and mechanical model of the S/R machine and its motors. This study was motivated by the research work of Hachemi et al. [33]; a DC cycle "dynamic sequencing" method was developed in a unit-load multiple-rack AS/RS. As the prevailing (time-based or energy-based) models of AS/RS are concerned with already well-known objectives (minimum cost, maximum throughput, minimum travel time, and minimum energy), for the first time in the literature, the energy-based model under time-of-use electricity tariffs (on-peak hours, mid-peak hours, or off-peak hours) for the unit-load AS/RS is proposed and discussed. To generate a type of energy-efficient AS/RS, over the cost of on-peak period electricity consumption, penalty cost of power overconsumption, limitations on the allowable amount of energy consumption, and available time of all facilities are applied in the model. Moreover, a Genetic Algorithm (GA) is utilized to obtain a near-optimum solution to the recommended mathematical model with the objective of minimizing the total cost of the energy-conscious AS/RS. While no benchmark is obtainable in the literature, a Simulated Annealing (SA) algorithm is employed additionally to certify the fallouts achieved. Furthermore, the total cost of our model is compared with the single tariff model, and a sensitivity analysis of the allowable amount of power consumption is done. In addition, system throughput, in terms of time and cost, is calculated for the model. In summary, emphases of the differences of this study with the above-revealed research studies are as follows:

- Proposing time-of-use tariffs (on-peak hours, mid-peak hours or off-peak hours) and limitation on the total electricity consumption to make an energy-conscious AS/RS model;
- Considering the dynamic sequencing for sequencing storage and retrieval requests and employing the due dates to avoid the excessive postponement of retrieval requests of costumers;
- Adding loading/unloading time and energy consumption by conveyor and S/R machine to make the model more applicable;
- Considering a Genetic Algorithm (GA) and Simulation Annealing (SA) to solve the new model better and comparing the results.

The paper is structured as follows. In Section 3, the concept of energy-conscious model is introduced and the assumptions are made. In Section 4, the problem is mathematically expressed. A GA and SA are suggested to solve the model in Section 5. To show the function of the recommended methodology, numerical test problems are solved in Section 6. As a final point, conclusions and future research issues are presented in Section 7.

3. The problem and assumptions

An industrial unit desires to use automation technology for its warehouse; so, a unit-load AS/RS is installed in a part of it at the beginning. This new system consists of one aisle with two racks in front of each other served by a conveyor and an S/R machine. Items are stored on storage modules, such as pallets, constituting the unit-loads. All the storage racks are of the same size and have the same number of locations while each rack location holds only one unit-load item. The items purchased from different suppliers should be stored, and thus a forklift should take them to the Input/Output (I/O) station and put them on the conveyor. After that, conveyor moves the items to the S/R machine to load them in a rack location (see Figure 1). So, storage requests of all items from all suppliers are known and processed according to First-Come, First-Served (FCFS). Retrieval requests of all customers are known and the "dynamic sequencing" approach is applied. Therefore, re-sequence the requests every time a new request comes in and employ the due dates to ensure that retrieval at the far end of the aisle is not excessively delayed. To avoid the complexity of model, the S/R machine can move simultaneously both vertically and horizontally at constant speeds; that is, acceleration and deceleration are ignored [33,35,44]. Thus, the travel time required to reach any location in the rack is calculated by the Tchebyshev metric. It is assumed that for each retrieval request, there is a storage request available in order to form a DC cycle. The sequencing problem consists of determining order priority of customers and then storage and retrieval locations, satisfying the retrieval and storage requests for each DC cycle.

It must be emphasized that the European Union legalized guidelines, such as Directive of the European Parliament and of the Council 2006/32/WE from 5th April, 2006, on energy endues efficiency and energy services and repealed Council Directive 93/76/EEC. Based on universal trends and the latest progress in the green technologies, there is a requirement to take into consideration the energy consumption and CO_2 emission in a company with the typically applied objectives (minimum travel time, maximum throughput and minimum cost). Hence, in the present study, the energy efficiency model based on TOU electricity tariffs for the unit-load AS/RS is proposed and evaluated. With respect to ($LTPR > 1$), the objective involves finding which rack has the required item and subsequently an empty location (opening) among the available and retrieval locations out of all those that contain the requested items. These operations are done so as to give the minimum total cost in all DC cycles at the unit-load AS/RS system so that all restrictions will be fulfilled. The algorithm of the research is made cycle by cycle until all the retrieval and storage requests of all customers are completely fulfilled. We will make the following assumptions that are very common in AS/RS models cited in the literature review; see Ashayeri et al. [44].

3.1. *Assumptions*

The succeeding assumptions are employed for the mathematical formulation:

(a) Incoming and outgoing items are transferred at

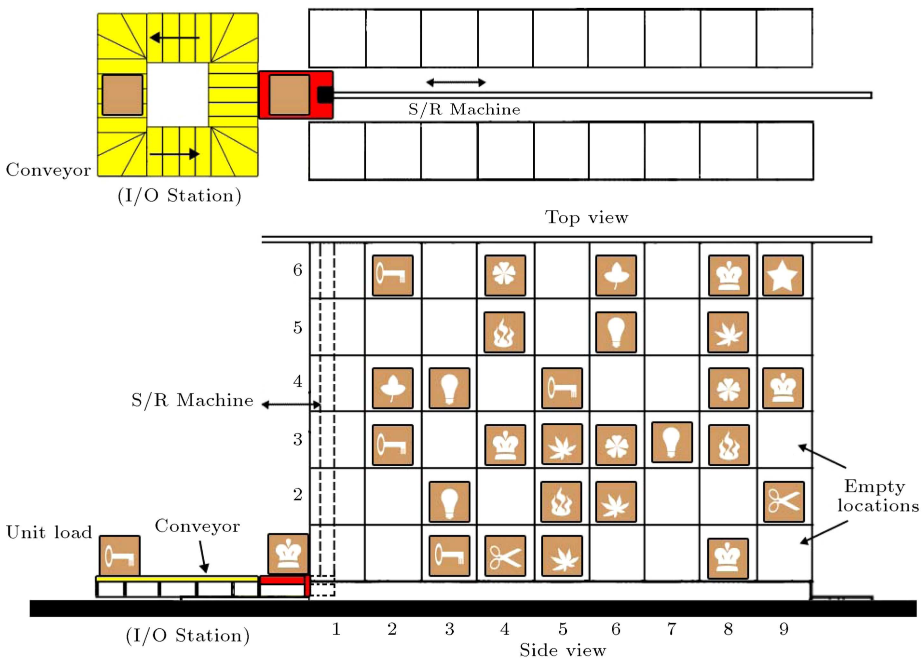

Figure 1. Unit-load AS/RS warehouse.

the same point designated as the I/O station. This I/O station is situated at lower left-hand corner of the rack face on the both sides of the aisle, at (0,0) coordinates;

(b) There is enough buffer space for loading/unloading items in I/O station;

(c) The S/R machine operated on DC cycle and can carry only one unit-load. Therefore, at the same time, it just performs one DC cycle;

(d) At the beginning of a working shift, the S/R machine is at the I/O station. Moreover, the S/R machine stays in I/O station after the completion of each DC cycle (storage and retrieval) and waits for the next operation request. The S/R machine cannot stop while doing a DC cycle;

(e) The specifications of the S/R machine and the conveyor such as velocities in the horizontal and vertical directions, loading/unloading times, and amount of consumed power are known, respectively;

(f) The initial state of each location in each rack, either empty or occupied by a specific item, is known;

(g) The orders' due date of all customers are known;

(h) There is no inventory shortage in this AS/RS warehouse. In order to be able to carry out a DC, it is necessary that the total number of items stored be at least equal to the total number of all requested items;

(i) Customer orders and supplied items are independent. The number of items in a customer's order is known and can be zero (customer did not order some types of items). Moreover, the required quantity of item can be more than 1, i.e. an item type common to several retrieval requests;

(j) The items' locations for storage or retrieval are unknown in the racks;

(k) For a retrieval request, an item can be in multiple racks or multiple locations of a rack. Therefore, $LTPR > 1$ and there exists a set of locations associated with this item as well as one predetermined rack or rack's location (randomized storage assignment);

(l) The distance between I/O station and storage/retrieval locations is known;

(m) The travel time is dependent on the retrieval sequencing, unknown before;

(n) Over-utilized and under-utilized (idleness) times of all facilities are allowable. Similarly, costs of over-utilized and under-utilized times of all facilities are known;

(o) Available working time and the total allowable power consumption are known;

(p) The amount of energy consumption by each facility and unit cost (tariff) of kW power used by a facility in mid-peak hours and on-peak hours are known. The mid-peak hours start from 7:00 to 17:00 (10 h), the on-peak hours start from 17:00 to 20:00 (3 h), and the off-peak hours start from 20:00 to 7:00 (11 h).

4. Mathematical model

Note that considering the former mathematical formulations of the model at hand, the notations are primarily presented.

4.1. Notations

Let us define the parameters and variables of the model as follows:

R_r	Vector of item type quantities requested by customer, $r \in [1, R]$
R_s	Vector of item type quantities supplied by supplier, $s \in [1, S]$
i	Item type index, $i \in [1, n]$
m	The number of R/S machines in warehouse, $m \in [1, M]$
S_q	Rack q in warehouse, $q \in [1, Q]$
k	The horizontal location index, $k \in [1, K]$
j	The vertical location index, $j \in [1, J]$
S_h	The horizontal speed of the S/R machine (m/s)
S_v	The vertical speed of the S/R machine (m/s)
$Rack_{q,(k,j)}$	State matrix of rack q. The elements of this matrix represent the item types stored in their corresponding locations (k, j),

$$Rack_{q,(k,j)} = \begin{cases} i, & \text{if an item } i \text{ is in location } (k, j) \\ 0, & \text{if this location is empty} \end{cases}$$

X, which is a decision multi-dimensional array, is defined as follows:

$$X_{(R_r,i),S_q,(k_1k_2j_1j_2)} = 0 \text{ or } 1,$$

$$k_1, k_2 \in [1, K] \text{ and } j_1, j_2 \in [1, J].$$

That is:

- $X_{(R_r,i),S_q,(k_1k_2j_1j_2)} = 1$, if the request of customer r for item i be in rack q with the location of coordinates k_1, j_1 (storage) and the location of coordinates k_2, j_2 (retrieval) used for DC cycle;
- $X_{(R_r,i),S_q,(k_1k_2j_1j_2)} = 0$, otherwise.

4.1.1. Time notations

$t_{(k,j)}$ The Tchebyshev travel time to a location of coordinates (k, j) is equal to $\max\left\{\frac{k}{s_h}, \frac{j}{s_v}\right\}$

t_{ls} The required time for storing an item on the rack location by S/R machine (s)

t_{us} The required time for retrieval of an item from the rack location by S/R machine (s)

t_{lc} The required time for loading an item on S/R machine by conveyor (s)

t_{uc} The required time for unloading an item from S/R machine by conveyor (s)

T Regular working time in a normal shift before on-peak hours for electricity in warehouse (s)

O_t Over working time of all facilities, more than regular T (s)

U_t Under working time or idleness time of all facilities, less than regular T (s)

$tdc_{(R_r,i),S_q,(k_1k_2j_1j_2)}$ The travel time of a DC cycle for the request of customer r for item i in rack q.

4.1.2. Cost notations

C_{ot} Overtime unit cost of a facility in AS/RS warehouse

C'_{ut} Undertime (idleness) unit cost of a facility in AS/RS warehouse

C_{mp} Unit cost (tariff) of kW power used by a facility in mid-peak hours

C'_{op} Difference unit cost of kW power used by a facility in mid-peak hours with on-peak hours

C'_{fp} Difference unit cost of kW power used by a facility in off-peak hours with mid-peak hours

C_{pp} Penalty unit cost for over kW power used by all facilities in a day (24 h)

$TC(I)$ Total cost of underworking time (idleness) of all facilities

$TC(O)$ Total cost of overworking time of all facilities

$TC(P)$ Total cost of the consumed power for all facilities (mid-peak, on-peak and off-peak hours)

$TC(mid-peak)$ Normal cost of the consumed power for all facilities with mid-peak tariff

$TC(on-peak)$ Extra cost of the consumed power for all facilities in on-peak hours

$TC(off-peak)$ Discount of the consumed power cost for all facilities in off-peak hours

$TC(penalty)$ Penalty cost for overconsumption of kW power used by all facilities in a day (24 h)

4.1.3. Power notations

P_{sh} Amount of kW power used by an S/R machine per second

P_{co} Amount of kW power used by a conveyor per second

P Allowable amount of kW power (upper limit) used by all facilities in a day (24 h)

O_p Overconsumption of kW power used by all facilities (more than P); client will be a high-power consumer

U_p Under consumption of kW power used by all facilities (less than P); client will be a low power consumer

PC Total amount of consumed power by all facilities (kWs)

PC' Total amount of consumed power by all facilities in on-peak hours (kWs)

PC'' Total amount of consumed power by all facilities in off-peak hours (kWs)

PC_{sh} Total amount of power consumption by all R/S machines (kWs)

PC_{co} Total amount of power consumption by all conveyors in I/O stations (kWs)

With respect to the above descriptions, the mathematical model of the problem is denoted in the next subsections.

4.2. The DC travel time

Let k_1 and k_2, as well as j_1 and j_2 be the horizontal and vertical coordinate, respectively of two distinct rack q locations. According to Tchebyshev, travel time to a location of coordinate (k, j) is equal to $\max\left\{\frac{k}{s_h}, \frac{j}{s_v}\right\}$, we can easily calculate the DC travel time (tdc) combining the two locations [33]. So, we find:

$$tdc_{(R_r,i),S_q,(k_1k_2j_1j_2)} = \max\left\{\frac{k_1}{s_h}, \frac{j_1}{s_v}\right\} + t_{ls} + \max\left\{\frac{|k_1-k_2|}{s_h}, \frac{|j_1-j_2|}{s_v}\right\} + t_{us} + \max\left\{\frac{k_2}{s_h}, \frac{j_2}{s_v}\right\}, \tag{1}$$

where, t_{ls} and t_{us} are the times required for storage/retrieval of an item into/from a rack location by S/R machine.

4.3. The total cost of facilities performance

In a regular working shift, under-utilized time (U_t) of a machine is treated as the unused capacity of that machine (when any operation has not been assigned to a facility), whereas over-utilized time (O_t) is considered as the overload on a machine [45]. The total cost of all S/R machines performance includes overconsumption and underconsumption times (idleness) as follows:

$$TC(I) + TC(O) = (U_t.C'_{ut}) + (O_t.C_{ot}). \qquad (2)$$

4.4. The total cost of consumed power

The total cost of consumed power by all facilities in a day (24 h) is calculated as:

$$TC(P) = TC(mid-peak) + TC(on-peak) - TC(off-peak) + TC(penalty), \qquad (3)$$

where, the negative sign in $TC(off-peak)$ is related to a discount for power cost in off-peak hours. We assumed that the mid-peak hours for electricity tariff start from 7:00 to 17:00 (10 h), the on-peak hours start from 17:00 to 20:00 (3 h), and the off-peak hours start from 20:00 to 7:00 (11 h) in a day. The normal cost of consumed power for all facilities with mid-peak tariff is:

$$TC(mid-peak) = PC \times C_{mp} = (PC_{sh} + PC_{co}) \times C_{mp}, \qquad (4)$$

where the consumed power by S/R machines and conveyors is as follows:

$$PC_{sh} = P_{sh}.\left[\sum_{r=1}^{R}\sum_{i=1}^{n}\sum_{q=1}^{Q}\sum_{k_1=1}^{K}\sum_{k_2=1}^{K}\sum_{j_1=1}^{J}\sum_{j_2=1}^{J} X_{(R_r,i),S_q,k_1k_2j_1j_2)}.tdc_{(R_r,i),S_q,(k_1k_2j_1j_2)}\right], \qquad (5)$$

$$PC_{co} = P_{co}.\left[\left(t_{lc}.\sum_{s=1}^{S} R_s\right) + \left(t_{uc}.\sum_{r=1}^{R} R_r\right)\right]. \qquad (6)$$

As mentioned in subsection 4.2, the required time for the S/R machine to load or unload an item at a storage location is considered in the DC travel time. Therefore, for calculating the consumed power, we similarly consider the required time for loading/unloading an item on/from the S/R machine by conveyor (t_{lc}, t_{uc}) in I/O station. Also, extra cost of consumed power for all facilities in on-peak hours is as follows:

$$TC(on-peak) = PC' \times C'_{op} = [\min\{O_t, 3\} \times (P_{sh} + P_{co})].C'_{op}, \qquad (7)$$

where, number "3" in Eq. (7) is the duration of on-peak hours in a day (24 h). Finally, discount on the cost of consumed power of all facilities in off-peak hours is:

$$TC(off-peak) = PC'' \times C'_{fp} = [\max\{(O_t - 3), 0\} \times (P_{sh} + P_{co})].C'_{fp}. \qquad (8)$$

In addition, if we consume more than the allowable amount of kW power (P) that power provider has determined, we should pay penalty cost for it that is:

$$TC(penalty) = O_P \times C_{PP}. \qquad (9)$$

4.5. The constraints

We must ensure that only one DC cycle will be selected [33]. It is an SOS constraint (Special Ordered Set of variables):

$$\sum_{r=1}^{R}\sum_{i=1}^{n}\sum_{q=1}^{Q}\sum_{k_1=1}^{K}\sum_{k_2=1}^{K}\sum_{j_1=1}^{J}\sum_{j_2=1}^{J} X_{(R_r,i),S_q,(k_1k_2j_1j_2)} = 1. \qquad (10)$$

As mentioned before, there is an energy-conscious condition in this model that makes the constraints; therefore, we assume the TOU electricity tariffs in a day. Consequently, the total available time before starting on-peak hours (T) for all S/R machine is limited and will be as follows:

$$\left(\sum_{r=1}^{R}\sum_{i=1}^{n}\sum_{q=1}^{Q}\sum_{k_1=1}^{K}\sum_{k_2=1}^{K}\sum_{j_1=1}^{J}\sum_{j_2=1}^{J} X_{(R_r,i),S_q,(k_1k_2j_1j_2)}.tdc_{(R_r,i),S_q,(k_1k_2j_1j_2)}\right) + U_t - O_t = T.m. \qquad (11)$$

With respect to Eq. (11), if working time becomes more than T, two events might take place. First, we should pay extra cost for consumed power because the on-peak hours will start. Second, we should pay less cost for consumed power because the operations time will be long enough and the off-peak hours will start. In addition, there exists a capacity constraint on the total amount of consumed electricity in each period due to infrastructure and provider's limitations. Therefore, the total allowable amount of power consumption by all facilities in a day (24 h) is limited to P, that is:

$$PC + U_p - O_p = P. \qquad (12)$$

If $O_P > 0$, then a client or company will be a high power consumer and it should pay penalty cost. Then, with replacing the related equations, we have Eq. (13) as shown in Box I.

$$\left[\begin{array}{l} P_{sh}.\left[\sum_{r=1}^{R}\sum_{i=1}^{n}\sum_{q=1}^{Q}\sum_{k_1=1}^{K}\sum_{k_2=1}^{K}\sum_{j_1=1}^{J}\sum_{j_2=1}^{J} X_{(R_r,i),S_q,(k_1k_2j_1j_2)}.tdc_{(R_r,i),S_q,(k_1k_2j_1j_2)}\right] \\ +P_{co}.\left[\left(t_{lc}.\sum_{s=1}^{S}R_s\right)+\left(t_{uc}.\sum_{r=1}^{R}R_r\right)\right] \end{array}\right]+U_p-O_p=P. \quad (13)$$

Box I

$$MinTC=[(U_t.C'_{ut})+(O_t.C_{ot})]+C_{mp}.\left[\begin{array}{l} P_{sh}.\left[\sum_{r=1}^{R}\sum_{i=1}^{n}\sum_{q=1}^{Q}\sum_{k_1=1}^{K}\sum_{k_2=1}^{K}\sum_{j_1=1}^{J}\sum_{j_2=1}^{J} X_{(R_r,i),S_q,(k_1k_2j_1j_2)}.tdc_{(R_r,i),S_q,(k_1k_2j_1j_2)}\right] \\ +P_{co}.\left[\left(t_{lc}.\sum_{s=1}^{S}R_s\right)+\left(t_{uc}.\sum_{r=1}^{R}R_r\right)\right] \end{array}\right]$$

$$+C'_{op}.\left[\min\{O_t,3\}\times(P_{sh}+P_{co})\right]-C'_{fp}.\left[\max\{(O_t-3),0\}\times(P_{sh}+P_{co})\right]+(C_{PP}\times O_P)$$

$$\text{s.t} \sum_{r=1}^{R}\sum_{i=1}^{n}\sum_{q=1}^{Q}\sum_{k_1=1}^{K}\sum_{k_2=1}^{K}\sum_{j_1=1}^{J}\sum_{j_2=1}^{J} X_{(R_r,i),S_q,(k_1k_2j_1j_2)}=1$$

$$\left[\sum_{r=1}^{R}\sum_{i=1}^{n}\sum_{q=1}^{Q}\sum_{k_1=1}^{K}\sum_{k_2=1}^{K}\sum_{j_1=1}^{J}\sum_{j_2=1}^{J} X_{(R_r,i),S_q,(k_1k_2j_1j_2)}.tdc_{(R_r,i),S_q,(k_1k_2j_1j_2)}\right]+U_t-O_t=T.m$$

$$\left[\begin{array}{l} P_{sh}.\left[\sum_{r=1}^{R}\sum_{i=1}^{n}\sum_{q=1}^{Q}\sum_{k_1=1}^{K}\sum_{k_2=1}^{K}\sum_{j_1=1}^{J}\sum_{j_2=1}^{J} X_{(R_r,i),S_q,(k_1k_2j_1j_2)}.tdc_{(R_r,i),S_q,(k_1k_2j_1j_2)}\right] \\ +P_{co}.\left[\left(t_{lc}.\sum_{s=1}^{S}R_s\right)+\left(t_{uc}.\sum_{r=1}^{R}R_r\right)\right] \end{array}\right]+U_p-O_p=P$$

$$X_{(R_r,i)(k_1k_2j_1j_2)}=\begin{cases}1\\0\end{cases}$$

$$U_t,O_t,U_p,O_p\geq 0. \quad (14)$$

Box II

4.6. The final model

Based on Eqs. (1)-(13), the multi-rack multi-constraint DC cycle AS/RS model under TOU tariffs strategy can be easily obtained as shown in Box II.

The objective is to find a storage rack with the requested item and then an empty location (opening) from all empty locations and a retrieval location from all locations comprising the requested items so that the total cost of AS/RS model under energy-conscious strategy given in Eq. (14) is minimized and all limitations are satisfied.

In the succeeding section, a meta-heuristic solution procedure is recommended to efficiently solve the model.

5. The solution algorithm

To better understand the complexity of the problem, let us consider 20 types of goods in an AS/RS unit-load warehouse and four customer's requests for them. With respect to "dynamic sequencing", first, customers' requests should be arranged by due dates and then by sequencing each retrieval request. Hence, the number of possible solutions in this problem can be calculated by:

$$\text{Number of possible solutions} = 4!\times 20!$$

$$=58,389,648,196,239,360,000. \quad (15)$$

The "dynamic sequencing" shown above makes optimization of this model difficult. It is outstanding that some of these solutions may not be feasible regarding the limitations of AS/RS system such as available working time and upper limit on energy consumption. Enumerating all these outcomes to find out the optimum solution is computationally intractable for medium- to large-sized problems. In addition, some researchers, such as Meneghetti and Monti [40] and Meneghetti et al. [21], indicate that considering $(LTPR > 1)$ in the model makes it NP-hard. As a consequence of this fact, meta-heuristic algorithms are proposed in this research for solving the problem. Several investigators have successfully employed meta-heuristic approaches to solve complex optimization problems in various subjects of engineering and scientific fields. Some of these meta-heuristic procedures are: genetic algorithm [46-48], simulated annealing [49-51], ant colony optimization [52,53], imperialist competitive algorithm [54], particle swarm optimization [55-57], threshold accepting [58], Tabu search [59,60], neural networks [61], evolutionary algorithm [62], Harmony search [63,64], and differential evolution [65-67,47]. Among these procedures, the population-based ones are regularly desired to others and in some situations illustration superior performances [54]. Therefore, a genetic algorithm is utilized in this research in order to solve the formulated model in Eq. (14). Moreover, another meta-heuristic algorithm of simulated annealing is applied additionally to qualify and certify the solutions achieved.

In the following subsection, brief explanations are provided for genetic algorithm and simulated annealing.

5.1. Genetic Algorithm (GA)

The basic factors of a GA are population size, N_{GA}, crossover probability, P_c, and mutation probability, P_m. In this paper, setting of GA parameters is based on pilot study. Additionally, the steps involved in the proposed real coded GA algorithm are:

1. Set parameters P_c, P_m, and N_{GA};
2. Initialize the population randomly;
3. Calculate the objective function (total cost) of all chromosomes;
4. Select individuals for mating pool;
5. Apply the crossover operation for each pair of chromosomes with probability P_c;
6. Apply the mutation operation for each chromosome with probability P_m;
7. Replace the current population by the resulting mating pool;
8. Evaluate the objective function;

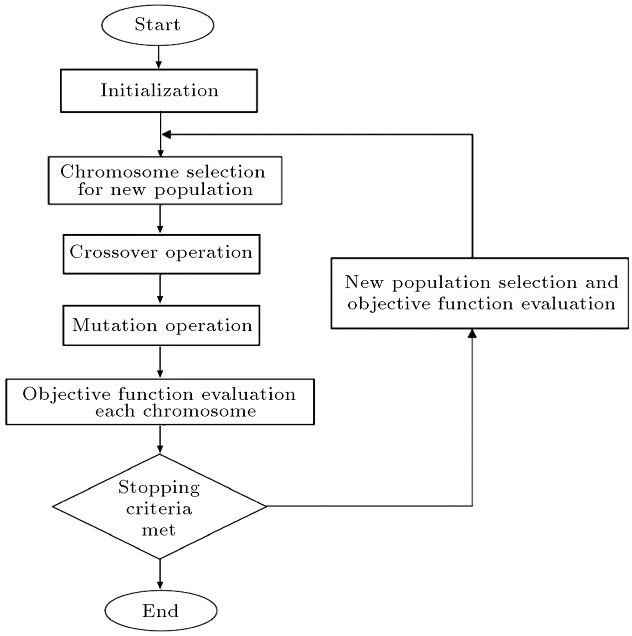

Figure 2. The flowchart of the GA [68].

9. If stopping criterion is met, stop. Otherwise, go to Step 5.

Figure 2 displays the flowchart of the GA algorithm [68].

5.2. Simulated Annealing (SA)

Consider a collection of molecules at a high temperature, moving around freely. Since physical systems have a tendency to lower energy states, the molecules are likely to move to positions that lower the energy of the ensemble as a whole as the system cools down. However, molecules really move to positions, which rise the energy of the system with a probability $e^{-\left(\frac{\Delta E}{T}\right)}$, where ΔE is the rise in the energy of the system and T is the current temperature. If the ensemble is allowed to cool down slowly, it will finally promote a regular crystal, which is the optimal state rather than flawed solid, and would be the poor local minima. In the function optimization, a parallel procedure can be defined. This procedure can be expressed as the problem of finding a solution, among a potentially very large number of solutions, with minimum cost. By considering the cost function of the proposed system as the free energy and the possible solutions as the physical states, a solution process is presented (e.g., see [69-72]) in optimization based on a simulation of the physical annealing process. This technique is called "Simulated Annealing". The SA algorithm is given below to solve such problems:

1. Start with some state, S
2. $T = T_0$
3. Repeat {

```
While (not at equilibrium){
    Perturb S to get a new state S_n
    ΔE = E(S_n) − E(S)
    if ΔE < 0
        Replace S with S_n
    Else with probability e^{−(ΔE/T)}
        Replace S with S_n
    }
    T = C * T,    0 < C < 1
    } until (frozen)
```

In this algorithm, the state (S) becomes the state (the estimated solution) of the problem in question instead of the ensemble of molecules. Energy (E) corresponds to the quality of (S) and is determined by a cost function used to assign a value to the state, and temperature (T) is a control parameter used to guide the process of finding a low-cost state where T_0 is the initial value of T and C ($0 < C < 1$) is a constant used to decrease the value of T [73]. The advantages of SA are:

i. It optimizes continuous or discrete parameters;
ii. It does not need derivative information;
iii. It deals with many parameters;
iv. It is well suited for parallel computers;
v. It optimizes parameters with complex surfaces; they can jump out of a local minimum;
vi. It works with numerically produced data, experimental data, or analytical functions.

To implement SA on a particular problem, we must describe a cooling or annealing timetable for the algorithm, a perturbation function, and an energy function. Any annealing schedule should include the initial temperature, the rate at which the temperature should be reduced, and good ending conditions for both the loops of the algorithms [73].

5.3. The steps concerned with the solution method

Step 1: In a given test problem, determine the total cost of all required S/R orders using Eq. (14) by GA and SA;
Step 2: Find a better algorithm for each test problem;
Step 3: Determine the system throughput rate;
Step 4: Do the sensitivity analysis of allowable amount of power consumption (P);
Step 5: Compare the model's results with those of the used single-electricity tariff.

The flowchart of the solving procedure and a depiction of the solution to a test problem with 20-item types are presented in Figures 3 and 4, respectively.

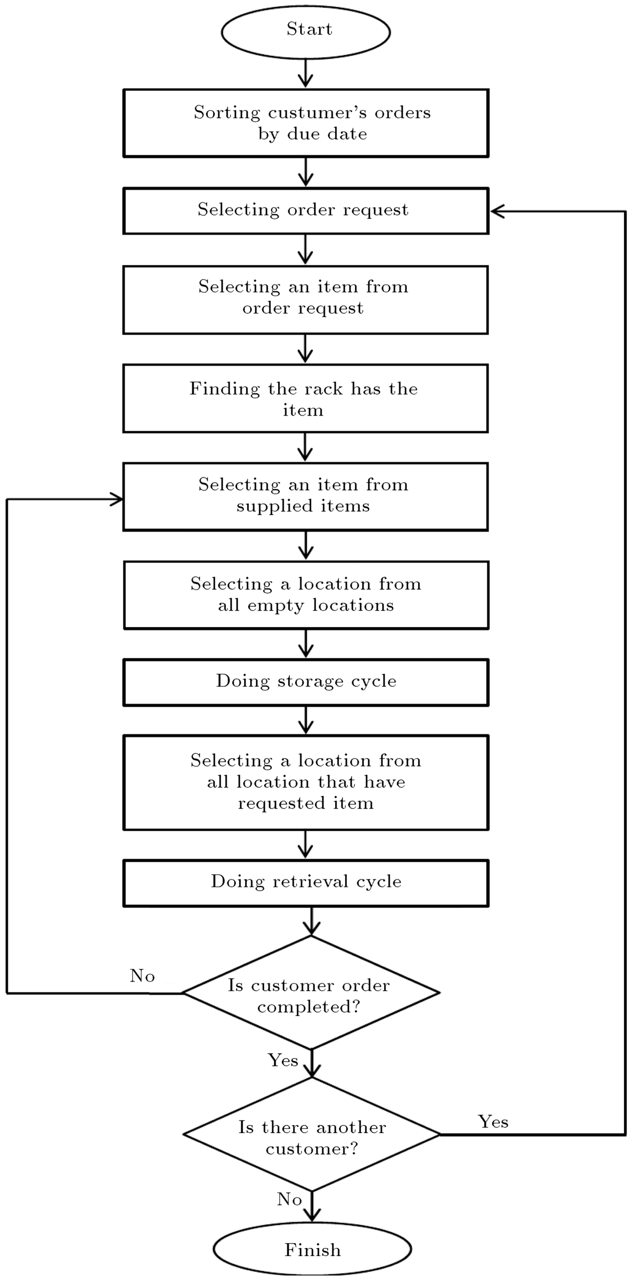

Figure 3. Flowchart of the solving procedure.

6. Numerical examples

In this section, the proposed procedure presented in section 5.3 is investigated by some numerical test problems to evaluate their performance. As pointed out in Section 3, for energy-efficient AS/RS, we considered the warehouse of an industrial unit where its working shift starts at 7:00 AM. With respect to the dimensions of building, in a part of the warehouse, two AS/RS racks with 10 locations per line and 20 locations per column together with one S/R machine are installed. The racks could contain 20 types of items (thus, multi-item), and the size of each rack location is considered 1×1 (m^2) as a unit-load. The horizontal

r1:	2	13	17	3	9	6	18	10	19	16	12	1	11	14	20	4	7	8	5	15
r2:	4	15	19	3	8	7	12	10	14	6	17	2	11	9	13	16	18	20	5	1

Figure 4. The representation of the chromosome (sequencing) for two customer orders with 20-item type.

and vertical speeds of S/R machine are $s_h = 4$ and $s_v = 0.9$ (m/s), respectively. The required times for loading/unloading by S/R machine are $t_{ls} = 10$ and $t_{us} = 10$ (s), respectively. In addition, the required times for loading/unloading by conveyor are $t_{lc} = 13$ and $t_{uc} = 13$ (s), respectively. The power consumptions by S/R machine and conveyor are $P_{sh} = 1172$ and $P_{co} = 5.4$ (kWs), respectively. Furthermore, the time performance costs of equipment include overtime and under time (idleness) are $C_{ot} = 0.002$ and $C'_{ut} = 0.001$, respectively. The power performance costs ($/kWs) include $C_{mp} = 2.08 \times 10^{-5}$, $C'_{op} = 1.6 \times 10^{-5}$, $C'_{fp} = 0.91 \times 10^{-5}$, and $C_{pp} = 1 \times 10^{-5}$. Finally, that total allowable consumed power per day is $P = 5000000$ (kWs) and the total allowable working time per day is $T = 36000$ (s). The suggested AS/RS initial data of all test problems are approximately definite according to some related papers, such as (e.g. [9,21,42,45]), equipment catalogs, and our knowledge in material handling and mechanical engineering. It might be vary from the actual systems installed in practice.

The order requests of four customers (R_r) and purchased items from four suppliers (R_s) are given in the form of a matrix in Table A.1, in the Appendix. In these matrixes, each row related to a customer/supplier and the elements of them represent the quantities required for each type of item (1-20, respectively). In addition, in Table A.2, in the Appendix, matrix $Rack_{q,(k,j)}$ represents the racks state as the numbers inside the locations are the item types (zero number is an empty location). The due dates used for incoming customer's orders are 6, 4, 5, and 8 days, respectively.

Additionally, the preliminary parameter values for employment of GA and SA are as follows:

For GA:

Probability of crossover $(P_c) = 0.8$,
Probability of mutation $(P_M) = 0.05$,
Probability of reproduction $(P_E) = 0.15$,
Population $(N_{GA}) = 40$,
Stopping criterion = 100 iterations.

For SA:

$T_0 = 110$,
$T_{\text{final}} = 2$,
Number of steps = 100,
Stopping criterion = 100 iteration.

It is noticeable from the literature that the parameters used in GA and SA have a robust effect on both result quality and result time [74,75]. Hence, The GA and SA parameters used are based on a pilot study. Moreover, sixteen numerical test problems with 20 types of items and different numbers of required S/R orders (small: 80-, 180-, 280-, and 380-S/R; medium: 480-, 580-, 680- and 780-S/R; large: 880-, 980-, 1080- and 1180-S/R; extra-large: 1280-, 1380-, 1480-, and 1580-S/R) are used. All the numerical examples are solved on a PC with Intel corei5-4460 processor having 3.20 GHz CPU and 8 Gig RAM. Furthermore, all algorithms are coded using the MATLAB R2014a software.

The phases encompassed in the proposed method to solve the test problems are presented as follows:

- **Step 1:** In an assigned test problem, settle the total cost of all required S/R orders using Eq. (14) by GA, and SA. In this stage, each algorithm is executed 20 times for each test problem, where their minimum total costs, the least CPU times (s), and consumed power are presented in Table 1.
- **Step 2:** Obtain the superior algorithm for each test problem. The superior algorithm is determined by finding the percentage difference between their outcomes. With regard to the outcomes given in Table 1, GA is the better algorithm for the total cost of the energy-conscious TOU tariffs of AS/RS system. However, SA is obviously the superior algorithm in terms of the least CPU time (s). Also, in terms of the total cost of the consumed power in the model, GA again is the better algorithm. Figures 5-7 demonstrate this superiority well. All improvement trends by algorithms are shown in Figure 8. As a result, GA, in terms of the total cost improvement, starts with a gradual downward

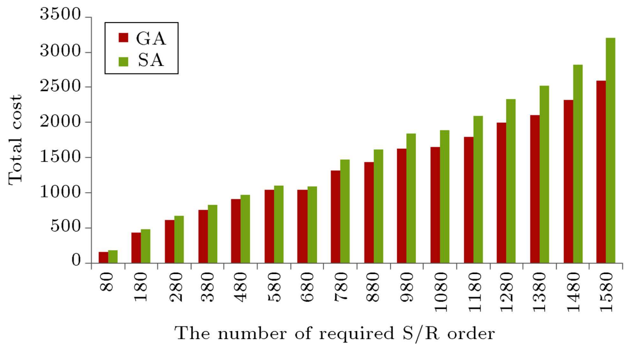

Figure 5. The total cost comparison of meta-heuristic algorithms (Step 2).

Table 1. The results of energy-based model obtained by the algorithms (Steps 1 to 3).

Problem size	No	Required S/R orders	Total cost ($)		CPU time (s)		Power cost ($)		Detailed results for GA			Percentage results for GA	
			GA	SA	GA	SA	GA	SA	Total travel time	Perf. cost	Power cost	Perf.[a] cost (%)	Power cost (%)
Small	1	80	157.62	184.42	65.76	17.87	126.72	142.66	4886.06	30.90	126.72	19.60	80.40
	2	180	434.66	486.82	145.52	37.53	412.02	458.31	12777.72	22.64	412.02	5.21	94.79
	3	280	612.11	679.44	223.92	41.16	594.68	654.88	17825.86	17.43	594.68	2.85	9 7.15
	4	380	759.04	834.94	306.48	72.57	745.90	820.67	22002.92	13.14	745.90	1.73	98.27
Medium	5	480	913.13	977.05	385.48	94.48	904.62	969.27	26388.03	8.51	904.62	0.93	99.07
	6	580	1049.37	1101.84	464.51	119.70	1044.27	1076.39	30244.75	5.10	1044.27	0.49	99.51
	7	680	1044.67	1086.46	545.61	144.70	1039.27	1055.59	30094.22	5.40	1039.27	0.52	99.48
	8	780	1316.53	1467.93	636.1	173.15	1311.89	1368.63	38321.00	4.64	1311.89	0.35	99.65
Large	9	880	1433.05	1616.48	709.3	192.93	1419.93	1453.36	42560.33	13.12	1419.93	0.92	99.08
	10	980	1627.24	1845.29	808.04	229.73	1599.96	1621.16	49635.92	27.27	1599.96	1.68	98.32
	11	1080	1654.88	1891.53	894.88	278.72	1625.62	1678.58	50629.72	29.26	1625.62	1.77	98.23
	12	1180	1793.6	2094.92	964.09	341.78	1754.24	1847.21	55679.72	39.36	1754.24	2.19	97.81
Extra large	13	1280	2001.66	2335.94	1039.77	400.06	1947.14	2080.42	63262.00	54.52	1947.14	2.72	97.28
	14	1380	2103.02	2523.62	1121.6	482.01	2041.13	2192.43	66947.78	61.90	2041.13	2.94	97.06
	15	1480	2319.06	2817.66	1201.24	569.22	2241.41	2432.21	74821.33	77.64	2241.41	3.35	96.65
	16	1580	2590.74	3199.56	1286.31	662.13	2493.29	2737.28	84727.17	97.45	2493.29	3.76	96.24

[a]Perf.: Performance

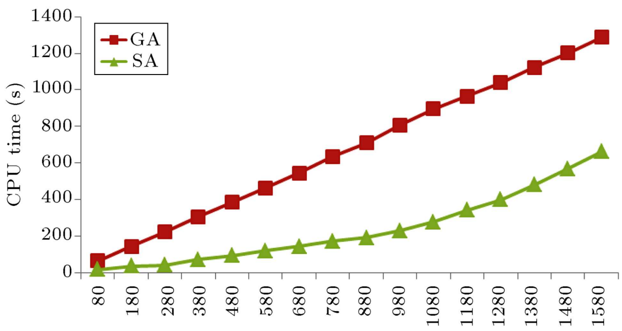

Figure 6. The CPU time comparison of meta-heuristic algorithms (Step 2).

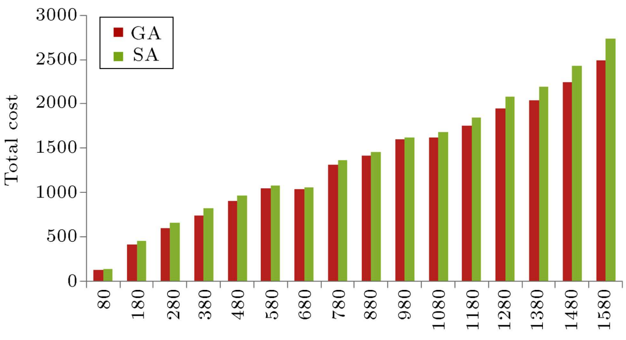

Figure 7. The total cost of consumed power comparison of meta-heuristic algorithms (Step 2).

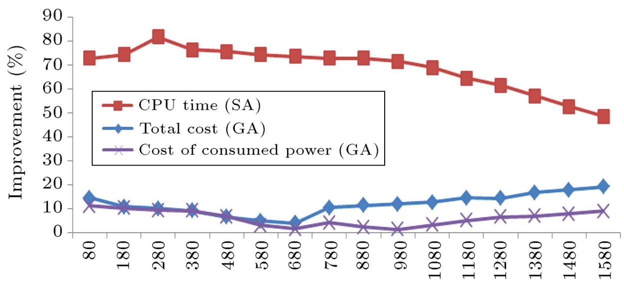

Figure 8. SA and GA improvement trends for CPU time, total cost, and cost of consumed power (Step 2).

trend to hit the lowest point of 3.85% in medium-sized (680-S/R) test problem, and then displays a slow upward trend to hit the highest point of 19.03% in extra-large (1580-S/R) test problem. Likewise, GA, in terms of consumed power cost, has a similar trend with the total cost improvement. Finally, CPU time improvement trend by SA has a surge to reach a peak of 81.62% in 280-S/R, and then a regularly descending trend to hit the lowest point of 48.52% in 1580-S/R test problem.

It is noticeable that with regard to growth in the number of S/R orders, the performance cost and the consumed power cost will increase; also, difference cost between them becomes more (see Figure 9). The percentage of consumed power cost

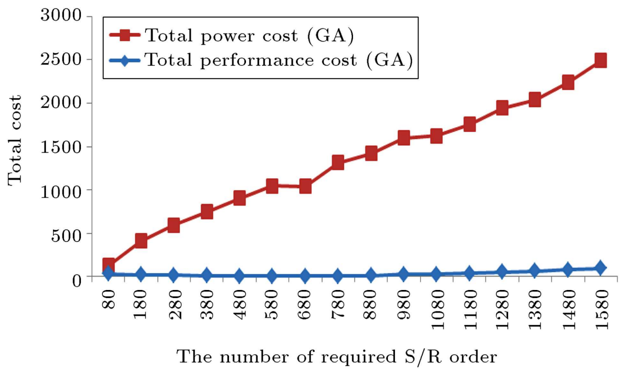

Figure 9. The performance cost and the power cost trends by GA (Step 2).

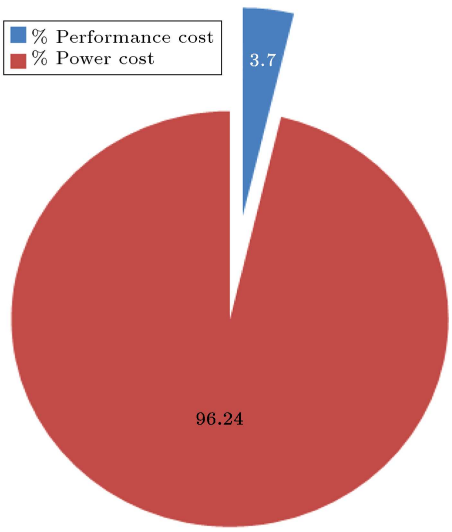

Figure 10. The pie chart of detailed cost percentage for performance and power costs of GA for 1580-S/R order problem (Step 2).

in all test problems is greater than performance cost. For example, in 1580-R/S test problem, the percents of performance cost and power cost are 3.67% and 96.24%, respectively. The pie chart of detailed cost percentage for 1580-S/R example by GA is demonstrated in Figure 10.

- **Step 3:** Determine the system throughput rate. Now, one can determine the AS/RS system throughput rate in terms of time and cost. With respect to Hachemi et al. [33], the time throughput in AS/RS system is calculated as follows:

$$\rho_{time} \frac{\text{number of stored and delivered items}}{\text{total travel time}} \text{ (items/s)}. \quad (16)$$

In addition, with respect to DC cycle AS/RS, throughput capacity per hour can be determined as follows [10]:

$$\lambda_{time} = \frac{3600}{\text{mean travel time}} \times 2\text{(item/h)}. \quad (17)$$

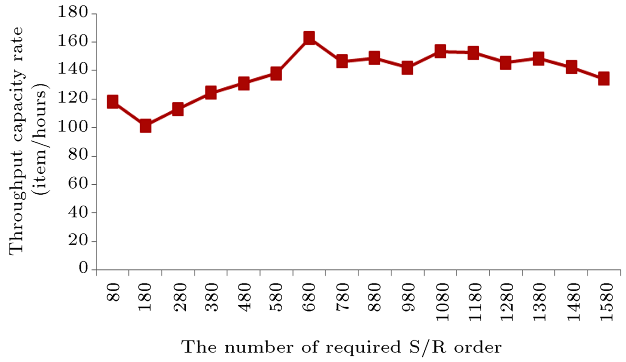

Figure 11. Throughput capacity rate (item/hour) trends by GA for all test problems (Step 3).

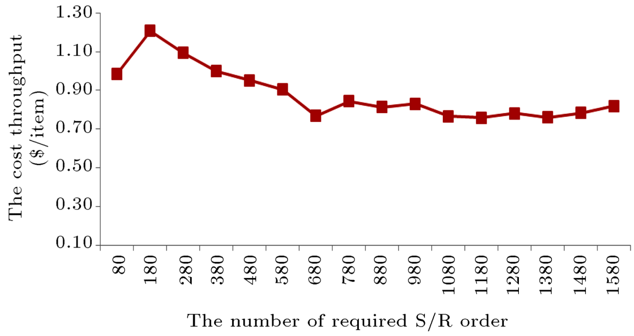

Figure 12. The cost throughput trends by GA for all test problems (Step 3).

Correspondingly, the cost throughput is estimated as follows:

$$\rho_{\text{cost}} = \frac{\text{total cost}}{\text{number of stored and delivered items}} (\$/\text{item}). \quad (18)$$

For example, $\rho_{time} = 0.1300$ means 1300 items stored/delivered per 10000 units of time (s), $\lambda_{time} = 117$ means 117 items stored/delivered per hour, and $\rho_{\text{cost}} = 0.99$ means 0.99 units of money paid for a stored/delivered item. With respect to Eqs. (16)-(18), the results of system throughput are detailed in Table 1. The throughput capacity rate and the cost throughput trends over GA for all test problems are presented in Figures 11 and 12, respectively. Consequently, GA, in terms of the throughput capacity per hour, starts with a downward trend in small-sized (180-S/R) test problem, and then a regularly ascending trend to hit the highest point of 162.69 (item/h) in 680-S/R order test problem; after that, a fluctuation starts in a downward trend until extra-large-sized (1580-S/R) test problem. Similarly, in terms of the time throughput, GA has a parallel trend with the throughput capacity improvement. Furthermore, in terms of the cost throughput, GA starts with an upward trend in small-sized (180-S/R) test problem and then a gradually downhill trend to extra-large-sized (1580-S/R) test problem;

- **Step 4:** Do the sensitivity analysis of the allowable amount of power consumption (P). A possible approach that helps decline the effect of operating at the maximal capacity is related to power providers who pursue to smooth the peak-to-average ratio of load demand by a TOU tariffs plan. With field-proven samples around the world, these pricing plans direct consumers to shift their usage of electricity over time periods, leading to a lower electricity bill, provided that the consumer is able to correctly schedule her electricity-consuming operations [76]. As mentioned before as well as considering TOU tariffs in our model, there exists a capacity limitation on the total electricity amount consumed in each day (P) due to infrastructure and provider's restrictions. In the power market, different power providers present various amounts of P for all customer types such as residential, commercial, etc. Hence, in this step, we make sensitivity analysis of P from 2500000 to 40000000 (kWs) with three test problems (80-, 480- and 880-S/R orders). With respect to Table 2, with an increase in the amount of P, at first, the total cost of the model will decrease, and finally it will be stabilized. As a result, the total cost of test problems with 80-, 480-, and 480-S/R orders will be stabilized after about 10000000, 30000000, and 50000000 (kWs). These trends are presented in Figures 13 and 14. This issue could be useful for decision-makers to choose an appropriate power provider with the proper offer type of that satisfies their power needs with the minimum cost;

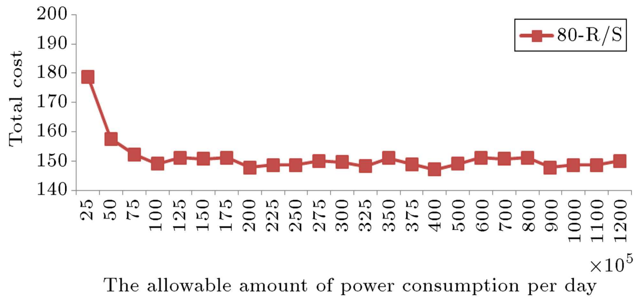

Figure 13. The sensitivity analysis of (P) in 80-S/R orders test problem (Step 4).

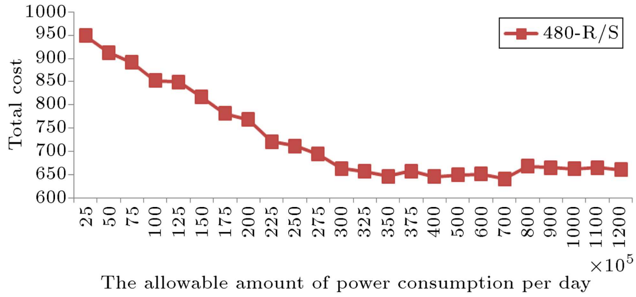

Figure 14. The sensitivity analysis for (P) in 80-S/R orders test problem (Step 4).

- **Step 5:** Compare the results of the model with those of the used single-electricity tariff.

  In this step, we investigate the proposed TOU AS/RS model with a single-electricity tariff model in terms of the total cost. With considering single-electricity tariff, the cost of consumed power in on-peak and off-peak hours will be ignored and the total cost of the AS/RS model in a day will be calculated by only mid-peak hours tariff. With respect to Table 3, the TOU AS/RS model achieved the lower amount of the total cost toward single-electricity tariff in all test problems. Until the medium-sized test problem, both models get similar results, but with growth in the number of required S/R orders, the TOU AS/RS is realized as a dramatic improvement trend for the total cost to hit the highest point of 23.06% in 1580-S/R order test problem (see Figure 15). It means that with an increase in the number of required S/R orders, the decision-makers of distribution centers should chose an energy provider that offers TOU electricity tariffs rather than single tariff for minimizing their the total cost.

Table 2. Sensitivity analysis for the allowable amount of power consumption per day (P) and related total cost ($) (Step 4).

P* (kWs)	**2.5**	**5**	**7.5**	**10**	**12.5**	**15**	**17.5**	**20**	**22.5**	**25**	**27.5**	**30**
80 S/R	178.68	157.62	152.36	149.15	151.20	150.78	151.22	147.77	148.73	148.68	150 .05	149.63
480 S/R	949.33	913.13	890.92	852.15	849.71	817.05	781.10	768.69	721.43	711.56	69 4.21	662.94
880 S/R	1467.58	1433.05	1423.66	1390.30	1367.76	1333.05	1316.36	1266.62	1249.49	1247.10	1223.51	1183.90
P* (kWs)	**32.5**	**35**	**37.5**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
80 S/R	148.20	151.04	148.94	147.07	149.15	151.20	150.78	151.22	147.77	148.73	148 .68	150.05
480 S/R	656.69	646.89	658.18	645.75	649.45	650.88	640.76	668.39	665.28	662.86	66 5.56	661.06
880 S/R	1142.46	1139.46	1112.44	1081.38	1008.64	992.45	987.13	972.51	993.44	987. 81	991.27	982.96

*P (kWs)= $P \times 1000000$

Table 3. The total cost comparison of TOU tariff model with single tariff model (Step 5).

Problem size	No.	Required S/R order	Total cost ($) TOU tariff	Total cost ($) Single tariff	The better method	Difference with single	Improvement (%)*
Small	1	80	157.62	157.52	Single	-0.1	-0.06
	2	180	434.66	438.88	TOU	4.22	0.97
	3	280	612.11	614.51	TOU	2.4	0.39
	4	380	759.04	788.45	TOU	29.41	3.87
Medium	5	480	913.13	915.18	TOU	2.05	0.22
	6	580	1049.37	1063.67	TOU	14.3	1.36
	7	680	1044.67	1054.02	TOU	9.35	0.90
	8	780	1316.53	1366.51	TOU	49.98	3.80
Large	9	880	1433.05	1500.59	TOU	67.54	4.71
	10	980	1627.24	1799.25	TOU	172.01	10.57
	11	1080	1654.88	1833.05	TOU	178.17	10.77
	12	1180	1793.6	2106.58	TOU	312.98	17.45
Extra large	13	1280	2001.66	2316.85	TOU	315.19	15.75
	14	1380	2103.02	2432.32	TOU	329.3	15.66
	15	1480	2319.06	2738.14	TOU	419.08	18.07
	16	1580	2590.74	3188.05	TOU	597.31	23.06

*Improvement (%): Min. = −0.06, Max. = 23.06, Ave. = 7.97.

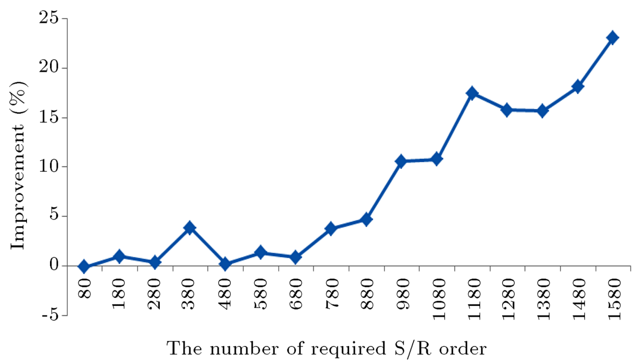

Figure 15. The total cost improvement trend by TOU AS/RS model over single tariff for all test problems (Step 5).

7. Conclusions and recommendation for future research

The dynamic sequencing in dual command cycle unit-load automated storage and retrieval systems under energy-conscious policy is presented in this paper. The sequencing is done by taking into account the fact that each retrieval request and storage item is associated with multiple racks and multiple rack locations, and not one known location. In contrast to the method proposed by Hachemi et al. [33], our model studies dynamic sequencing, multiple racks, multiple customer/supplier requests, and it comprises extra restrictions based on the energy-conscious strategies such as time-of-use tariffs (on-peak hours, mid-peak hours or off-peak hours) for electricity, penalty cost for overconsumption of power and limitations on the total amount of consumed power by all facilities. We propose an optimal approach of energy-conscious unit-load AS/RS system in terms of integer programming, combined with some meta-heuristic algorithms. Therefore, a Genetic Algorithm (GA) is employed to find a near-optimum solution to the proposed mathematical model. The optimization process is found for each DC cycle, and in accordance with storage and retrieval requests of all customers and suppliers, the location of the item can be stored and retrieved. This process recognizes the minimum total cost of the AS/RS with regard to limitations of facilities' time performance and consumed power. Meanwhile, no benchmark is accessible in the literature, and Simulated Annealing (SA) algorithm is developed as well to validate the results achieved. The sixteen test problems with different numbers of required storage/retrieval orders in four classes (small, medium, large, and extra-large sizes) are offered to indicate the application of the proposed approach. Moreover, AS/RS system throughput is computed in terms of time and cost. The AS/RS model under TOU tariffs is compared with single tariff model, and a sensitivity analysis is done on the allowable amount of the consumed power. The fallouts indicate that GA has superior performances in terms of the total cost, facilities performance cost, and power consumption cost, but SA is obtained in a lesser time in terms of CPU time (s). Besides, the consumed power percentage of facilities in all test problems is greater than another cost and the TOU tariffs model has minimum total cost rather than the single tariff model.

This work can be extended by considering the followings:

(a) Greenhouse gas (GHG) emissions can be added to energy-efficient model;
(b) Multiple-aisle warehouse with multiple-shuttle and robots can be considered;
(c) Shortage in AS/RS system can occur;
(d) Other meta-heuristic algorithms, such as Ant Colony Optimization (ACO), Differential Evolution (DE), Imperialist Competitive Algorithm (ICA), and Particle Swarm Optimization (PSO) may also be applied to solve the model;
(e) Some parameters can be considered fuzzy or random. In this case, the model has either fuzzy or stochastic nature;
(f) Setting up meta-heuristic algorithms and employing an automatic tuning method for parameters can be considered;
(g) Some new AS/RS models, such as shuttle-based AS/RS can be considered;
(h) Acceleration and deceleration of S/R machine movement can be considered.

Abbreviations

DC	Dual Command
TOU	Time-Of-Use
GA	Genetic Algorithm
SA	Simulated Annealing
AS/RS	Automated Storage and Retrieval Systems
S/R	Storage and Retrieval
SC	Single Command
AVS/RS	Autonomous Vehicle Storage and Retrieval Systems
SBS/RS	Shuttle-Based Storage and Retrieval Systems
FCFS	First-Come-First-Served
LTPR	Location-To-Product Ratio
COL	The Closest Open Location
SLL	The Shortest Leg Location Rule
I/O	Input/Output
ACO	Ant Colony Optimizations
VNS	Variable Neighborhood Search
STD	The Shortest Travel Distance
EBFT	Energy-Based Full Turnover
TBFT	Time-Based Full Turnover
SOS	Special Ordered Set of variables

References

1. Meneghetti, A. and Monti, L. "Multiple-weight unit load storage assignment strategies for energy-efficient automated warehouses", *Int. J. log. Res. Appl.*, **17**(4), pp. 304-322 (2014a).

2. Kung, Y., Kobayashi, Y., Higashi, T., Sugi, M. and Ota, J. "Order scheduling of multiple stacker cranes on common rails in an automated storage/retrieval system", *Int. J. Prod. Res.*, **52**(4), pp. 1171-1187 (2014).

3. Fukunari, M. and Malmborg, C.J. "A network queuing approach for evaluation of performance measures in autonomous vehicle storage and retrieval systems", *Eur. J. Oper. Res.*, **193**(1), pp. 152-167 (2009).

4. MHIA. *AS/RS: An Investment in the Future*, Quarterly Report (Spring 2011). http://www.mhia.org/ news/mhia/10657/as-rs-industry-group-releases-sprin g-2011-quarterly-report.

5. MHIA. *Automated Storage Systems Make a Play for Sustainability,* Quarterly Report (Fall 2009). http://www.mhia.org/news/industry/9141/as-rs-industry-group-releases-fall-2009-quarterly-report.

6. Fang, K., Uhan, N., Zhao, F. and Sutherland, J.W. "A new shop scheduling approach in support of sustainable manufacturing", *Proceedings of the 18th CIRP Int. Conf. Life Cycle Eng.*, pp. 305-310 (2011).

7. Herring, H. "Does energy efficiency save energy? The debate and its consequences", *Appl. Energ.*, **63**, pp. 209-226 (1999).

8. Abdelaziz, E., Saidur, R. and Mekhilef, S. "A review on energy saving strategies in industrial sector", *Renew. Sust. Energ. Rev.* **15**, pp. 150-168 (2011).

9. Zhang, H., Zhao, F., Fang, K. and Sutherland, J.W. "Energy-conscious flow shop scheduling under time-of-use electricity tariffs", *CIRP Annals - Manuf. Technol.*, **63**, pp. 37-40 (2014).

10. Lerher, T. *Throughput and Energy Related Performance Calculations for Shuttle based Storage and Retrieval Systems, (Energy Science, Engineering and Technology)*, New York: Nova Science Publishers, Inc., cop. ISBN 978-1-63483-431-5 (2016).

11. Malmborg, C.J. "Conceptualizing tools for autonomous vehicle storage and retrieval systems", *Int. J. Prod. Res.*, **40**(8), pp. 1807-1822 (2002).

12. Carlo, H.J., and Vis, I.F.A. "Sequencing dynamic storage systems with multiple lifts and shuttles", *Int. J. Prod. Econ.*, **140**(2), pp. 844-853 (2012).

13. Dukic, G., Opetuk, T. and Lerher, T. "A throughput model for a dual-tray vertical lift module with a human order-picker", *Int. J. Prod. Econ.*, pp. 1-8 (2015). DOI: 10.1016/j.ijpe.2015.04.009.

14. Lerher, T., Ekren, B.Y., Dukic, G., and Rosi, B. "Travel time model for shuttle-based storage and retrieval systems", *Int. J. Adv. Manuf. Technol.*, **78**(9-12), pp. 1705-1725 (2015a). DOI: 10.1007/s00170-014-6726-2.

15. Lerher, T., Ekren, B.Y., Sari, Z. and Rosi, B. "Simulation analysis of shuttle based storage and retrieval systems", *Int. J. Simu. Model.*, **14**(1), pp. 48-59 (2015b). DOI: 10.2507/IJSIMM14(1)5.281.

16. Lerher, T. "Travel time model for double-deep shuttle-based storage and retrieval systems", *Int. J. Prod. Res.*, pp. 1-22 (2015). DOI: 10.1080/00207543.2015.1061717.

17. Marchet, G., Melacini, M., Perotti, S., and Tappia, E. "Analytical model to estimate performances of autonomous vehicle storage and retrieval systems for product totes", *Int. J. Prod. Res,* **51**(14), pp. 4365-4387 (2012).

18. Marchet, G., Melacini, M., Perotti, S. and Tappia, E. "Development of a framework for the design of autonomous vehicle storage and retrieval systems", *Int. J. Prod. Res*, **50**(24), pp. 7134-7148 (2013).

19. Han, M.H., McGinnis, L.F., Shieh, J.S. and White, J.A. "On sequencing retrievals in an automated storage/retrieval system", *IIE Trans.*, **19**, pp. 56-66 (1987).

20. Van den berg, J.P. and Gademan, A.J.R.M. "Simulation study of an automated storage/retrieval system", *Int. J. Prod. Res.*, **38**, pp. 1339-1356 (2000).

21. Meneghetti, A., Dal Borgo, E. and Monti, L. "Rack shape and energy efficient operations in automated storage and retrieval systems", *Int. J. Prod. Res., Special Issue: Energy-Aware Manufacturing Operations*, pp. 7090-7103 (2015).

22. Gagliardi, J-P., Renaud, J. and Ruiz, A. "On storage assignment policies for unit-load automated storage and retrieval systems." *Int. J. Prod. Res.* **50** (3), pp. 879-892 (2012).

23. Mansuri, M. "Cycle time computation, and dedicated storage assignment, for AS/RS systems", *Eur. J. Oper. Res.*, **33**(1-2), pp. 307-310 (1997).

24. Lee, F.H., and Schaefer, K.S. "Sequencing methods for automated storage and retrieval systems with dedicated storage", *Comput. Ind. Eng.*, **32**(2), pp. 351-362 (1997).

25. Berg, J.P., and Zijm, W.H.M. "Models for warehouse management: classification and examples", *Int. J. Prod. Econ.*, **59**(1-3), pp. 519-528 (1999).

26. Kwon, H.M., Kim, Y.J. and Koh, S.G. "An analysis of the end of aisle order picking system: multi-aisle served by a single order picker", *Int. J. Prod. Econ.*, **98**(2), pp. 162-171 (2005).

27. Roodbergen, K.J. and Iris, F.A. "A survey of literature on automated storage and retrieval systems", *Eur. J. Oper. Res.*, **194**(2), pp. 343-362 (2008).

28. Hachemi, K. and Alla, H. "Pilotage dynamique d'un systeme automatise de stockage/destockage a convoyeur gravitationnel", *J. Eur. Syst. Autom.* (In French), **42**(5), pp. 487-508 (2008).

29. Hua, H.Y., Zhu, Z.D. and Hsu, W.J. "Load shuffling algorithms for split-platform AS/RS", *Robot. Comput.-Int. Manuf.*, **26**, pp. 677-685 (2010).

30. Atmaca, E. and Ozturk, A. "Defining order picking policy: A storage assignment model and a simulated annealing solution in AS/RS systems", *Appl. Math. Model.*, **37**, pp. 5069-5079 (2013).

31. Alonso-Ayuso, A., Tirado, G. and Udias, A. "On a selection and scheduling problem in automatic storage and retrieval warehouses", *Int. J. Prod. Res.*, **51**(17), pp. 5337-5353 (2014).

32. Popovic, D., Vidovic, M., and Bjelic, N. "Application of genetic algorithms for sequencing of AS/RS with a triple-shuttle module in class-based storage", *Flex. Serv. Manuf. J.*, **26**, pp. 432-453 (2014).

33. Hachemi, K., Sari, Z. and Ghouali, N. "A step-by-step dual cycle sequencing method for unit-load automated storage and retrieval systems", *Comput. Ind. Eng.*, **63**, pp. 980-984 (2012).

34. Brezovnik, S., Gotlih, J., Balič, J., Gotlih, K. and Brezočnik, M. "Optimization of an automated storage and retrieval systems by swarm intelligence", *Procedia Eng.*, **100**, pp. 1309-1318 (2015).

35. Yang, P., Miao, L., Xue, Z. and Ye, B. "Variable neighborhood search heuristic for storage location assignment and storage/retrieval scheduling under shared storage in multi-shuttle automated storage/retrieval systems", *Transp. Res. Part E*, **79**, pp. 164-177 (2015).

36. Boysen, N. and Stephan, K. "A survey on single crane scheduling in automated storage/retrieval systems", *Eur. J. Oper. Res*, **254**(3), pp. 691-704 (2016).

37. Khojasteh, Y. and Son, J. "A travel time model for order picking systems in automated warehouses", *Int. J. Adv. Manuf. Technol*, **86**(5-8), pp. 2219-2229 (2016).

38. Wenrui, W., Yaohua W. and Yingying W. "A multi-stage heuristic algorithm for matching problem in the modified miniload automated storage and retrieval system of e-commerce", *Chinese J. Mech. Eng.*, **29**(3), pp. 641-648 (2016).

39. Qiang, G. and Xiwen, L. "The complexity and on-line algorithm for automated storage and retrieval system with stacker cranes on one rail", *J. Syst. Sci. Complex,* **29**(5), pp. 1302-1319 (2016). DOI: 10.1007/s11424-015-4197-7.

40. Meneghetti, A. and Monti, L. "Energy efficient dual command cycles in automated storage and retrieval systems." *In Proceedings of the World Renewable Energy Congress,* Vol. **7**, May 8-13, 2011, edited by Bahram Moshfegh, pp. 1668-1675. Linköping, Sweden:

Linköping University Electronic Press. ISBN 978-91-7393-070-3 (2011).

41. Meneghetti, A. and Monti, L. "Sustainable storage assignment and dwell-point policies for automated storage and retrieval systems", *Prod. Plan. Cont.* **24**(6) pp. 511-520 (2013b).

42. Lerher, T., Edl, M. and Rosi, B. "Energy efficiency model for the mini-load automated storage and retrieval systems", *Int. J. Adv. Manuf. Technol.*, **70**, pp. 97-115 (2014).

43. Meneghetti, A. and Monti, L. "Greening the food supply chain: an optimisation model for sustainable design of refrigerated automated warehouses", *Int. J. Prod. Res.* (2014b). DOI: 10.1080/00207543.2014.985449.

44. Ashayeri, J., Heuts, R.M., Valkenburg, M.W.T., Veraart, H.C. and Wilhelm, M.R. "A geometrical approach to computing expected cycle times for zone based storage layouts in AS/RS", *Int. J. Prod. Res.*, **40**, pp. 4467-4483 (2002).

45. Abazari, A.M., Solimanpur, M. and Sattari, H. "Optimum loading of machines in a flexible manufacturing system using a mixed-integer linear mathematical programming model and genetic algorithm", *Comput. Ind. Eng.*, **62**, pp. 469-478 (2012).

46. Pasandideh, S.H.R., Niaki, S.T.A. and Roozbeh nia, A. "A genetic algorithm for vendor managed inventory control system of multi-product multi-constraint economic order quantity model", *Expert Syst. Appl.*, **38**(3), pp. 2708-2716 (2011).

47. Roozbeh Nia, A., Hemmati Far, M. and Niaki, S.T.A. "A fuzzy vendor managed inventory of multi-item economic order quantity model under shortage: An ant colony optimization algorithm", *Int. J. Prod. Econ.*, 155, pp. 259-271 (2014).

48. Popovic, D., Vidovic, M. and Bjelic, N. "Application of genetic algorithms for sequencing of AS/RS with a triple-shuttle module in class-based storage", *Flex. Serv. Manuf. J.*, **26**, pp. 432-453 (2014).

49. Aarts, E.H.L. and Korst, J.H.M. "Simulated annealing and Boltzmann machine; a stochastic approach to computing", 1st Edn., Chichester, John Wiley and Sons, UK (1989).

50. Muppani, V.R. and Adil, G.K. "Efficient formation of storage classes for warehouse storage location assignment: a simulated annealing approach", *Omega*, **36**(4), pp. 609-618 (2007).

51. Atmaca, E. and Ozturk, A. "Defining order picking policy: A storage assignment model and a simulated annealing solution in AS/RS systems", *Appl. Math. Model.*, **37**, pp. 5069-5079 (2013).

52. Colorni, A., Dorigo, M. and Maniezzo, V. "Ant system for job-shop scheduling", Belgian Journal of Operations Research, Stat. Comput. Sci., **34**(1), pp. 39-53 (1994).

53. Dorigo, M. and Stutzle, T. "Ant colony optimization", Cambridge, MA, MIT Press, USA (2004).

54. Roozbeh Nia, A., Hemmati Far, M. and Niaki, S.T.A. "A hybrid genetic and imperialist competitive algorithm for green vendor managed inventory of multi-item multi-constraint EOQ model under shortage", *Appl. Soft Comput. J.*, **30**, pp. 353-364 (2015).

55. Alfi, A. and Fateh, M.M. "Intelligent identification and control using improved fuzzy particle swarm optimization", *Expert Syst. Appl.*, **38**(10), pp. 12312-12317 (2011).

56. Kaveh, A. and Laknejadi, K. "A novel hybrid charge system search and particle swarm optimization method for multi-objective optimization", *Expert Syst. Appl.*, **38**(12), pp. 15475-15488 (2011).

57. Öztürkoglu, Ö., Gue, K.R. and Meller, R.D. "A constructive aisle design model for unit-load warehouses with multiple pickup and deposit points", *Eur. J. Oper. Res.*, **236**(1), pp. 382-394 (2014)

58. Dueck, G. and Scheuer, T. "Threshold accepting: A general purpose algorithm appearing superior to simulated annealing", *J. Comput. Phys.*, **90**(1), pp. 161-175 (1990).

59. Joo, S.J. and Bong, J.Y. "Construction of exact D-optimal designs by Tabu search", *Comput. Stat. Data Anal.*, **21**(2), pp. 181-191 (1996).

60. Chen, L., Langevin, A. and Riopel, B. "A tabu search algorithm for the relocation problem in a warehousing system", *Int. J. Prod. Econ.*, **129**, pp. 147-156 (2011).

61. Abbasi, B. and Mahlooji, H. "Improving response surface methodology by using artificial neural network and simulated annealing", *Expert Syst. Appl.*, **39**(3), pp. 3461-3468 (2012).

62. Laumanns, M., Thiele, L., Deb, K. and Zitzler, E. "Combining convergence and diversity in evolutionary multi-objective optimization", *Evol. Comput.*, **10**(3), pp. 263-282 (2002).

63. Jaberipour, M. and Khorram, E. "A new harmony search algorithm for solving mixed-discrete engineering optimization problems", *Eng. Optim.*, **43**(5), pp. 507-523 (2011).

64. Kaveh, A. and Ahangaran, M. "Discrete cost optimization of composite floor system using social harmony search model", *Appl. Soft Comput. J.*, **12**(1), pp. 372-381 (2012).

65. Liu, H., Cai, Z., Wang, Y. "Hybridizing particle swarm optimization with differential evolution for constrained numerical and engineering optimization", *Appl. Soft Comput. J.*, **10**(2), pp. 629-640 (2010).

66. Liao, T.W. "Two hybrid differential evolution algorithms for engineering design optimization", *Appl. Soft Comput. J.*, **10**(4), pp. 1188-1199 (2010).

67. Lee, K.M., Hsu, M.R., Chou, J.H. and Guo, C.Y. "Improved differential evolution approach for optimization of surface grinding process", *Expert Syst. Appl.*, **38**(5), pp. 5680-5686 (2011).

68. Taleizadeh, A.A., Niaki, S.T.A. and Makui, A. "Multiproduct multiple-buyer single-vendor supply chain problem with stochastic demand, variable lead-time, and multi-chance constraint", *Expert Syst. Appl.*, **39**, pp. 5338-5348 (2012).

69. Kirkpatrick, S., Gelatt, C.D.J.r. and Vecchi, M.P. "Optimization by simulated annealing", IBM Research Report RC, 9355 (1982).

70. Kirkpatrick, S., Gelatt, C.D. and Vecchi, M.P. "Optimization by simulated annealing", *Sci.*, **220**, pp. 671-680 (1983).

71. Vecchi, M.P. and Kirkpatrick, S. "Global wiring by simulated annealing", *IEEE Trans. Comput. Aid. D.*, **2**, pp. 215-222 (1983).

72. Cerny, V. "Thermodynamic approach to the traveling salesman problem-an efficient simulation algorithm", *J. Optim. Theory. Appl.*, **45**, pp. 41-51 (1985).

73. Maiti, M.K. and Maiti, M. "Inventory of damageable items with variable replenishment and unit production cost via simulated annealing method", *Comput. Ind. Eng.*, **49**, pp. 432-448 (2005).

74. Yang, J., Xu, M. and Gao, Z. "Sensitivity analysis of simulated annealing for continuous network design problems", *J. Transp. Syst. Eng. Info. Technol.,* **9**(3), pp. 64-70 (2009).

75. Kao, Y.T. and Zahara, E. "A hybrid genetic algorithm and particle swarm optimization for multimodal functions", *Appl. Soft. Comput. J.*, **8**(2), pp. 849-857 (2008).

76. Mikhaylidi, Y., Naseraldin, H. and Yedidsion L. "Operations scheduling under electricity time-varying prices", *Int. J. Prod. Res.* (2015). DOI: 10.1080/00207543.2015.1058981.

Appendix

In this section, we present the initial data of orders request and supplied items and the initial data of rack state for all test problems.

Table A.1. The initial data of orders request and supplied items for all test problems (20 types of items).

Required S/R orders	Orders request and supplied items
80	$R_r = \begin{bmatrix} 2&0&2&1&0&1&0&1&1&0&2&0&1&1&0&2&0&2&1&0 \\ 0&1&0&2&2&0&2&0&2&2&0&1&0&2&2&0&1&0&2&1 \\ 0&1&1&1&1&0&1&2&0&2&1&2&2&0&1&0&2&1&1&1 \\ 1&1&2&0&2&2&2&0&1&0&1&2&2&2&0&1&2&1&1&0 \end{bmatrix}$
	$R_s = \begin{bmatrix} 0&2&2&2&0&0&1&2&2&0&0&1&1&1&0&0&2&2&1&0 \\ 2&1&0&0&2&2&2&0&0&2&1&2&0&2&2&1&0&0&2&1 \\ 0&2&2&0&1&0&1&1&1&0&2&0&2&0&1&1&0&1&0&2 \\ 1&0&1&1&2&2&1&2&0&1&2&0&1&1&1&2&1&2&0&1 \end{bmatrix}$
180	$R_r = \begin{bmatrix} 4&0&4&3&0&2&0&3&3&0&2&0&3&3&0&5&0&3&3&0 \\ 0&3&0&2&2&0&4&0&2&5&0&5&0&3&3&0&3&0&4&5 \\ 0&4&5&4&2&0&2&4&0&5&2&5&2&0&4&0&5&5&2&4 \\ 6&1&4&0&4&6&2&0&4&0&3&2&2&3&0&3&2&1&3&0 \end{bmatrix}$
	$R_s = \begin{bmatrix} 0&3&3&3&0&0&1&3&3&0&0&5&3&1&0&0&3&4&1&0 \\ 4&2&0&4&3&3&2&0&4&6&1&6&0&2&2&4&2&0&6&2 \\ 3&4&4&0&1&2&4&1&2&0&4&0&2&4&1&2&0&3&4&2 \\ 1&0&6&2&2&4&1&4&0&4&2&2&4&1&4&2&4&4&0&4 \end{bmatrix}$
280	$R_r = \begin{bmatrix} 6&0&6&6&0&4&0&6&6&0&6&0&4&3&3&5&0&3&5&6 \\ 0&5&0&2&5&0&4&1&2&6&0&6&0&6&6&0&6&0&4&5 \\ 0&6&5&6&6&0&6&6&0&8&3&5&6&0&4&0&5&8&6&6 \\ 8&4&4&0&4&8&4&0&4&0&6&2&2&4&0&8&4&2&3&0 \end{bmatrix}$
	$R_s = \begin{bmatrix} 0&6&4&4&0&0&1&6&6&0&0&5&3&6&0&0&8&4&4&0 \\ 4&2&0&8&6&3&2&0&4&6&1&8&0&2&4&4&3&0&8&5 \\ 6&8&4&0&4&2&8&1&2&0&8&0&2&4&3&6&0&6&5&8 \\ 2&0&6&2&2&8&2&8&0&8&6&2&8&1&6&3&4&4&0&4 \end{bmatrix}$
380	$R_r = \begin{bmatrix} 8&0&8&6&0&8&0&10&8&0&4&0&4&6&8&10&0&6&2&6 \\ 0&6&0&2&6&0&4&2&4&8&0&8&0&8&8&0&6&0&4&4 \\ 0&8&6&10&8&0&10&6&0&10&6&6&10&0&4&0&6&10&8&10 \\ 10&4&6&0&4&10&4&0&6&0&10&6&6&4&0&10&8&4&6&0 \end{bmatrix}$
	$R_s = \begin{bmatrix} 0&6&4&4&0&0&2&6&8&0&0&4&4&6&0&0&8&4&4&0 \\ 6&4&0&10&6&6&2&0&4&8&2&10&0&6&8&4&6&0&10&6 \\ 8&10&6&0&8&2&10&4&8&0&10&0&6&4&4&6&0&6&6&10 \\ 6&0&8&6&6&10&6&10&0&10&6&4&10&2&6&8&4&8&0&4 \end{bmatrix}$

Table A.1. The initial data of orders request and supplied items for all test problems (20 types of items) (continued).

Required S/R orders	Orders request and supplied items																				
480	$R_r =$	10	0	8	6	0	12	0	8	8	0	8	0	6	8	8	12	0	8	4	6
		0	6	0	10	6	0	6	10	10	10	0	8	0	10	8	0	8	0	6	10
		0	10	6	8	10	0	10	6	0	12	10	10	10	0	8	0	6	10	8	8
		12	8	10	0	8	12	8	0	6	0	8	6	8	6	0	12	10	8	6	0
	$R_s =$	0	6	10	6	0	0	6	6	8	0	0	8	8	6	0	0	8	8	6	0
		6	6	0	10	6	6	10	0	10	12	8	10	0	6	10	8	10	0	10	6
		10	10	6	0	10	8	0	8	8	0	10	0	10	10	8	10	0	10	8	10
		6	0	8	6	6	10	8	10	0	10	6	6	8	2	6	8	8	8	0	8
580	$R_r =$	12	0	12	8	0	12	0	12	12	0	10	0	12	8	8	12	0	8	8	8
		0	12	0	10	8	0	8	10	10	12	0	12	0	10	12	0	12	0	6	12
		0	10	10	12	10	0	12	8	0	14	10	10	10	0	10	0	8	10	10	10
		14	8	8	0	12	14	10	0	8	0	8	6	8	12	0	14	10	12	6	0
	$R_s =$	0	8	10	8	0	0	8	10	8	0	0	12	12	8	0	0	12	10	12	0
		8	12	0	10	8	12	10	0	10	14	12	10	0	6	10	10	10	0	10	8
		10	10	12	0	10	8	0	8	12	0	10	0	10	10	12	10	0	10	8	10
		12	0	8	10	12	10	12	10	0	10	6	8	8	6	6	8	8	8	0	10
680	$R_r =$	12	0	12	14	0	12	0	12	12	0	14	0	12	14	14	12	0	14	10	14
		0	12	0	10	10	0	10	10	10	12	0	12	0	10	12	0	12	0	8	12
		0	14	10	12	14	0	12	14	0	14	10	14	10	0	14	0	14	10	14	10
		14	10	14	0	12	14	10	0	10	0	14	10	10	12	0	14	10	12	10	0
	$R_s =$	0	14	10	12	0	0	14	10	14	0	0	12	12	10	0	0	12	10	12	0
		14	12	0	10	12	12	10	0	10	14	10	10	0	12	10	10	10	0	10	12
		10	10	12	0	14	14	0	12	10	0	10	0	10	0	12	10	0	10	14	10
		12	0	14	10	12	10	12	10	0	14	12	10	12	14	14	14	10	12	0	10
780	$R_r =$	18	0	14	14	0	16	0	12	12	0	14	0	12	14	14	16	0	14	10	14
		0	14	0	12	12	0	16	14	14	18	0	12	0	16	12	0	12	0	10	12
		0	14	12	14	14	0	12	14	0	14	12	14	12	0	14	0	14	14	14	16
		18	12	14	0	14	18	14	0	12	0	14	12	14	12	0	18	14	12	10	0
	$R_s =$	0	14	14	12	0	0	14	14	14	0	0	12	12	16	0	0	12	12	16	0
		14	12	0	16	12	12	10	0	10	18	10	14	0	12	10	14	14	0	10	16
		10	14	12	0	14	14	0	12	14	0	14	0	14	0	16	16	0	16	14	10
		14	0	14	12	14	12	12	14	0	14	12	10	12	14	14	14	16	12	0	14
880	$R_r =$	18	0	14	14	0	16	0	12	20	0	14	0	12	14	14	16	0	20	10	14
		0	14	0	12	20	0	20	14	14	20	0	20	0	20	20	0	20	0	12	12
		0	20	20	14	14	0	12	20	0	14	18	14	20	0	14	0	14	14	14	16
		20	12	14	0	14	20	16	0	12	0	14	12	14	12	0	20	14	12	10	0
	$R_s =$	0	14	14	12	0	0	16	14	14	0	0	16	12	18	0	0	16	14	18	0
		12	12	0	18	18	12	18	0	12	18	18	14	0	12	14	14	14	0	12	18
		18	18	18	0	14	14	0	18	18	0	14	0	18	0	18	12	0	18	14	12
		14	0	14	12	14	18	14	14	0	14	12	14	14	14	16	14	18	12	0	14
980	$R_r =$	22	0	18	18	0	18	0	12	20	0	18	0	18	14	18	18	0	20	10	18
		0	18	0	16	20	0	20	18	18	24	0	20	0	20	20	0	20	0	12	12
		0	20	20	14	14	0	18	20	0	18	18	14	20	0	14	0	18	14	18	18
		20	16	14	0	14	20	16	0	16	0	14	16	14	16	0	24	14	18	10	0
	$R_s =$	0	22	22	22	0	0	20	14	14	0	0	16	22	18	0	0	16	14	18	0
		20	18	0	18	22	20	18	0	20	24	22	22	0	16	14	20	14	0	16	20
		18	24	18	0	20	14	0	22	18	0	14	0	22	0	20	12	0	20	22	16
		14	0	22	20	14	16	22	18	0	22	18	14	14	14	16	14	22	16	0	22

Table A.1. The initial data of orders request and supplied items for all test problems (20 types of items) (continued).

Required S/R orders		Orders request and supplied items																			
1080	$R_s =$	24	0	18	18	0	24	0	20	22	0	18	0	18	14	18	22	0	22	10	18
		0	24	0	16	22	0	22	18	18	24	0	22	0	22	22	0	22	0	12	20
		0	22	24	24	24	0	18	22	0	22	18	14	22	0	14	0	18	14	18	18
		26	16	14	0	14	22	16	0	16	0	22	16	14	16	0	24	14	18	10	0
	$R_s =$	0	22	22	22	0	0	20	14	14	0	0	16	22	18	0	0	16	14	18	0
		20	18	0	18	22	20	18	0	20	24	22	22	0	16	14	20	14	0	16	20
		18	24	18	0	20	14	0	22	18	0	14	0	22	0	20	12	0	20	22	16
		14	0	22	20	14	16	22	18	0	22	18	14	14	14	16	14	22	16	0	22
1180	$R_s =$	26	0	18	18	0	24	0	20	22	0	18	0	18	14	18	28	0	22	10	18
		0	24	0	16	22	0	26	22	20	26	0	22	0	22	22	0	22	0	12	22
		0	22	24	24	24	0	18	24	0	28	18	14	22	0	16	0	18	20	18	20
		28	16	20	0	14	28	24	0	18	0	22	20	24	20	0	26	20	18	20	0
	$R_s =$	0	22	22	22	0	0	24	24	14	0	0	16	24	18	0	0	16	18	20	0
		20	18	0	18	22	20	20	0	24	24	22	22	0	16	14	20	20	0	16	20
		18	24	18	0	20	14	0	22	20	0	14	0	22	0	24	18	0	20	24	18
		14	0	22	20	14	16	22	18	0	28	24	24	20	22	18	16	24	24	0	22
1280	$R_s =$	26	0	18	20	0	28	0	28	22	0	18	0	18	20	18	28	0	22	10	18
		0	24	0	22	22	0	26	22	24	28	0	22	0	22	22	0	22	0	16	22
		0	22	24	24	26	0	20	20	0	32	24	16	22	0	24	0	24	24	18	20
		34	16	20	0	22	32	22	0	18	0	22	24	24	28	0	32	20	18	20	0
	$R_s =$	0	22	22	22	0	0	24	24	14	0	0	16	24	22	0	0	20	22	22	0
		20	18	0	18	22	20	20	0	24	24	22	22	0	20	24	22	22	0	20	22
		18	24	18	0	20	18	0	28	28	0	16	0	22	0	22	24	0	20	24	18
		24	0	22	20	24	24	22	18	0	32	24	24	20	28	18	16	24	24	0	22
1380	$R_s =$	30	0	18	20	0	30	0	28	28	0	20	0	28	20	18	32	0	28	10	18
		0	28	0	28	22	0	28	22	24	30	0	22	0	28	22	0	28	0	20	28
		0	22	28	24	28	0	24	20	0	34	28	18	22	0	28	0	24	24	18	24
		34	16	20	0	22	34	22	0	18	0	22	24	24	28	0	34	20	18	20	0
	$R_s =$	0	20	22	28	0	0	24	24	14	0	0	16	24	22	0	0	26	22	20	0
		18	26	0	24	22	20	26	0	26	30	22	24	0	26	24	22	22	0	28	22
		22	24	24	0	24	18	0	28	28	0	26	0	28	0	26	26	0	26	22	28
		24	0	22	22	24	24	22	18	0	32	22	24	20	28	18	16	24	24	0	22
1480	$R_s =$	36	0	18	24	0	38	0	28	28	0	20	0	28	20	18	36	0	28	10	18
		0	28	0	28	26	0	28	22	24	34	0	22	0	28	22	0	28	0	20	28
		0	22	28	24	28	0	24	24	0	38	28	24	28	0	34	0	24	26	24	26
		34	26	26	0	22	34	26	0	22	0	24	28	24	28	0	38	20	18	20	0
	$R_s =$	0	28	22	28	0	0	24	24	22	0	0	16	24	22	0	0	26	22	20	0
		18	26	0	24	32	20	26	0	26	40	22	24	0	26	24	32	22	0	28	22
		22	24	24	0	24	28	0	28	28	0	26	0	28	0	26	26	0	26	30	28
		24	0	22	22	20	24	32	18	0	32	22	34	30	28	28	16	24	24	0	22
1580	$R_s =$	36	0	28	24	0	48	0	28	28	0	20	0	28	20	18	36	0	28	10	18
		0	28	0	28	26	0	28	32	34	34	0	22	0	28	22	0	28	0	20	28
		0	32	28	34	28	0	34	24	0	38	38	24	28	0	34	0	24	26	24	26
		44	26	26	0	32	34	26	0	22	0	24	28	24	28	0	38	20	18	20	0
	$R_s =$	0	28	32	38	0	0	24	34	32	0	0	16	24	22	0	0	26	22	20	0
		28	36	0	24	32	30	30	0	26	40	32	24	0	26	24	32	22	0	28	22
		22	24	26	0	24	28	0	28	28	0	26	0	28	0	26	26	0	26	30	28
		26	0	22	22	30	24	32	20	0	32	22	34	30	28	28	16	24	24	0	22

Table A.2. The initial data of rack state for all test problems (20 types of items).

$Rack_{1,(k,j)}$										$Rack_{2,(k,j)}$									
0	1	0	5	8	19	0	9	12	16	18	10	2	12	0	0	13	17	5	1
20	7	11	14	4	3	13	6	0	18	14	3	16	9	0	0	7	19	0	8
17	15	10	2	1	9	0	4	13	0	15	0	4	11	20	6	12	4	6	0
19	16	0	12	11	0	0	20	15	18	3	18	2	16	17	11	7	9	0	0
6	3	5	17	8	14	7	10	2	5	1	10	5	19	8	20	14	15	13	0
0	16	0	4	13	19	0	7	10	11	1	6	16	3	0	0	5	18	15	20
18	20	9	17	6	3	12	2	0	15	14	19	10	8	0	0	4	9	0	7
8	1	14	3	9	4	0	13	20	0	12	0	17	2	11	13	5	17	11	0
1	11	0	19	14	0	0	15	18	17	3	18	12	8	13	2	16	9	0	0
5	6	8	2	7	12	16	10	5	1	6	10	14	19	20	15	7	1	4	0
12	9	19	0	5	8	0	16	0	1	10	0	18	12	2	13	0	5	1	17
13	0	6	18	14	3	4	7	11	20	0	14	16	0	3	9	0	19	8	7
0	13	4	2	0	1	9	15	10	17	4	15	0	20	11	12	6	0	4	6
0	15	20	0	18	11	0	12	16	19	2	3	18	17	0	16	11	9	0	7
3	5	6	8	14	17	2	10	5	7	5	1	10	20	19	0	8	13	14	15
13	0	19	0	4	16	11	10	0	7	0	16	1	6	3	18	5	15	20	0
19	9	0	3	6	20	18	15	2	12	19	0	14	0	10	8	0	4	7	9
1	0	8	20	13	0	4	9	3	14	0	12	2	17	0	11	5	13	17	11
0	1	11	0	14	19	0	17	15	18	18	3	0	12	8	0	13	2	16	9
8	5	6	12	7	2	1	5	10	16	10	6	19	14	15	20	1	0	7	4

Biographies

Ali Roozbeh Nia is a PhD student of Industrial Engineering at Science and Research Branch, Islamic Azad University, Iran. He has published in the areas of green supply chain, vendor managed inventory and fuzzy inventory control.

Hassan Haleh, PhD, is an Assistant Professor of Industrial Engineering at Golpayegan University of Technology, Iran. He presently focuses his study on the areas of automated warehouses, supply chain, FMS and CAD/CAM.

Abbas Saghaei, PhD, is an Associate Professor of Industrial Engineering at Science and Research Branch, Islamic Azad University, Iran. He currently focuses his research on the areas of statistical process control, design of experiments, and Six Sigma.