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نظام شاحنة جديد مبني على اختيار النظام الآلي للتخزين والاسترجاع (AS/RS)

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الخـلاصـة

تدرس هذه الورقة مستودع ذات اتجاه واحد، عالي الكثافة، ممر عميق، وتطور شاحنة مقرها، نظام دورة واحدة اختيار نظام التخزين الآلي واسترجاع (AS / RS) التي تقلل من وقت السفر أو استهلاك الطاقة. ويعتبر المستودع كاملا تماما في بداية مهمة الانتقاء، ومحاذاة الشاحنات في محطة الانتاج هو معروف قبل وصولهم. الوقت والخوارزمية القائمة على الطاقة يعين أفضل عنوان الخلية من البليت المنتج والروبوت الأمثل المكوك وفقا لتعليمات اختيار النظام شاحنة. خلافا للدراسات السابقة، تركز هذه الدراسة على جزء تخزين محفوظة في المستودع لأوامر من الشاحنات وتعرف الممر العام ومكونات الروبوت المكوك. وباختلاف معظم الخوارزميات، فإن الخوارزمية المستخدمة في هذه الدراسة لا تحدد فقط الطريق الأدنى لوقت السفر ولكن أيضا الطريق الأقل استهلاكا للطاقة كحالتين مختلفتين. يتم ترتيب مهمة اختيار أمر مع منطقة التخزين محفوظة كوجهة كمشكلة تحليلية. تتم مقارنة نتائج المحاكاة الزمنية لوقت انتقاء الطاقة والوقت ويتم مناقشة التطبيقات الحقيقية في مستودع الشركة الشريكة للمشروع.

A new truck based order picking model for automated storage and retrieval system (AS/RS)

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ABSTRACT

This paper examines a single-direction, high density, deep-lane warehouse and develops a truck based, one-cycle order picking automated storage and retrieval system (AS/RS) that minimizes either travel time or energy consumption. The warehouse is considered completely full at the beginning of the picking task, and the alignment of the trucks at the output station is known before they arrive. The time and energy based algorithm assigns the best cell address of the product pallet and optimum shuttle robot according to the truck order picking instructions. Unlike previous studies, this study focuses on a reserved storage part in the warehouse for orders of trucks and defines overall aisle and shuttle robot components. Different from most algorithms, the algorithm used in this study identifies not only the minimum travel time route, but also the least energy consuming route as two different cases. The order picking task with the reserved storage area as the destination is formulated as an analytical problem. Energy and time based order picking period simulation results are compared, and real applications in the warehouse of the project partner firm are discussed.

Keywords: AS/RS; energy and time optimization; order picking; warehouse automation.

INTRODUCTION

AS/RS is a system that reduces complexity in product picking operations and offers appropriate solutions to companies in today's competitive environment. There are many types of warehouse configurations that vary according to product size, variety, weight, quantity of firm orders, picking techniques, and loading and unloading points. The picking process from these configurations has brought about different approaches, and various picking techniques have been presented by researchers. Some of these techniques are mathematical modeling, simulation, metaheuristic methods, mixed integer programming, dynamic programming, simulation methods, discrete time methods, and so on.

In this study, the products are picked from their appropriate shelf positions and moved to reserved truck areas with the help of analytical and mathematical modeling in the warehouse system. Unlike other studies, the automation components of the system and operation templates are described in detail. Time based and energy based optimization processes are applied separately in this study. The first section is an introduction, and the second section is about relevant literature as well as comparisons between previous studies and this study. Features of the system, rack configuration, and the robots that are used are described in section 3. The truck based order picking policy, method, and optimization algorithms are discussed in section 4. Results of time and energy based order picking optimization processes are given in section 5, and the concluding ideas are discussed in section 6.

Time optimization and stock management issues are common research topics about warehouse systems. Since energy and time parameters dictate cost effectiveness of systems, it is important to optimize the parameters. There are two base processes that are considered separately in warehouse systems, namely, loading and picking up. Products are loaded or picked up one by one or in multiple numbers by aisle robots (AR) and shuttle robots (SR). Methods of loading and picking up differ according to the type of warehouse. For instance, there is no direct access to each product in deep-lane shelf systems, and vice versa in back-to-back shelf systems. Process algorithms such as the first in first out (FIFO) storage/retrieval process are also altered according to the different shelf types. In deep-lane shelf systems discussed in the study, products are loaded to the input side and are then unloaded from the output side. Thus, loading of products is considered as order picking.

LITERATURE REVIEW

Results of the extensive literature survey carried out for warehouse management and optimization systems relevant to this study such as decreasing time, energy consumption, or costs are examined. Wang and Chan (2014) developed a mathematical model in the form of a multi-objective integer programming model to obtain the optimal number of vehicles. These vehicles were following the most effective routes for the pick-up and delivery of multiple products along the production flow, which would minimize energy consumption and operational costs. Unlike Wang and Chan, this study focuses on outputs of AS/RS for shipment since orders affect the production flow. Ko *et al.* (2006) proposed a hybrid optimization/simulation approach for determining the dynamic distribution network structures and simulation model to capture the uncertain clients' demands, order picking time, and travel time for the capacity plan of warehouses that may be used in the preliminary design. The interests of this study with regard to storage and retrieval processes differ from Ko's approach. Shiau and Lee (2010) implemented a warehouse management system to demonstrate the elimination of storage buffers and reduction of operation time for a tea factory. This study's order picking approach uses an analytical solving method and differs from all of the genetic algorithms. Chen *et al.* (2013) proposed a new routing algorithm based on Ant Colony Optimization (ACO) for two-order pickers. Their simulation study showed that ACO for two-order pickers gave the shortest total picking time for most examples and can be performed at different warehouses. It can be applied to high density deep-lane structures such as the one used in this study but only for a wide variety of products and a large number of racks.

Yu Y. and Koster (2009) carried out a study on compact, multi-deep AS/RS including the storage and retrieval (S/R) machines that operate in the horizontal and vertical directions of the rack and an orthogonal gravity conveying mechanism that operates in the third dimension of depth. It is suitable for standard masses of loads to control velocities of gravity conveyors since mass affects the friction force. In this study, masses of product pallets vary as a result of the different densities of products. Makris *et al.* (2006) presented an energy-saving approach to the order picking problem in a warehouse, which is directly related to the traveling salesman problem (TSP). In contrast to most heuristic algorithms, their study identified the least energy consuming route instead of searching for the minimum travel time route. They determined at the end of the study that a small service time loss in many cases may save significant energy without any additional costs. Even though their study is related to this study from the point of energy consumption, the application of the TSP problem is suitable for only multi-load S/R systems, but in this study both AR and SR carry only one product pallet.

Meneghetti *et al.* (2015) proposed a new decision support tool for the design of AS/RS and introduced the topic of energy consumption for crane movements with related impacts on costs and carbon dioxide emissions. It appears that non-electrical cranes and carbon emissions are discussed, and hence this work differs from this study due to the type of energy discussed. Park *et al.* (2006) analyzed pick time distributions for deterministic and exponential throughput and investigated how the size of the high turnover region vs. low turnover region affects throughput in mini-load systems. While their work is helpful for this study with regard to two class storages, which are high and low turnover regions, mini-load rack systems, which are discussed in this study, are quite different from unit load rack systems. Berg and Gademann (2000) put forth a simulation study of an AS/RS and compared several storage location assignment policies. They also focused on the relationship between efficient travel of the response time performance and S/R machines. Although they deal with important problems, their relationship approach may be developed for deep-lane structures. Barenji *et al.* (2014) proposed an architecture for the structural modeling of an intelligent distributed control system for a manufacturing facility, by utilizing RFID technology. In most of these systems, the communication units are wireless or RFID based. In the system used in this study, the communication between the barcode reader, SR, AR, and the server PC was also done via wireless access points and adaptors. Wu *et al.* (2014) aimed at determining the optimal rotation production cycle time, which minimizes the long-run average system cost per unit time. In this study, minimizing the cycle times of picking product pallets is attempted, and not only the minimum travel time route but also the least energy consuming route is determined as a result.

Le-Duc and Koster (2007) considered the order batching problem for a two-block rectangular warehouse. They first examined the first and second moments of the order picker's travel time and then used these travel times to estimate the average throughput time of a random order. Schleyer and Gue (2012) developed discrete time models for the throughput time distribution of orders arriving at a one-block warehouse. They presented the means for using single- or multi-line orders for determining the optimal batch size, and the experimental results showed that the optimal batch size was slightly larger in comparison with the batch size produced when minimizing average throughput time is chosen. Pan and Wu (2012) also presented an approximation method using the self-correcting technique algorithm for evaluating the throughput time of an order picking system with multiple pickers. Le-Duc and Koster's or Schleyer and Gue's S-shape route applications and Pan and Wu's method are useful for back-to-back shelf systems but are not suited for the high density shelves used in this study.

De Koster *et al.* (2007) carried out a wide range of studies for typical decision problems in design and control of manual order picking processes and focused on optimal layout design, routing, storage assignment, order batching, and zoning methods. A wide variety of approaches and studies have been discussed in this quite good literature review study, but for some reason there is a very limited focus on the types of warehouse structures, and this study has a specific warehouse structure. Onut *et al.* (2008) considered a distribution-type warehouse and intended to design a multiple-level warehouse configuration that minimizes the annual carrying costs. They developed a particle swarm optimization algorithm as a novel heuristic approach for determining the optimal layout. However, in this study, annual as well as daily operational costs are discussed. Chang *et al.* (2007) proposed a new mathematical model for the warehouse order picking optimization problem (W-OPP) in an automated warehouse with capacity constraints and multiple objectives. They used a genetic algorithm (GA) to solve some combination optimum problems and NP-hard problems with an improved initializing population. Their proposed GA approaches are not reasonable for this study since the order picking scenarios in this study are predictable or determinable.

Chuang *et al.* (2012) proposed a two-stage clustering assignment problem model (CAPM) for the customized multi-item-small-quantity orders picking problem. In the first stage, they developed a mathematical programming model to search for the maximum total item support. In the second stage, they used assignment techniques to store the item group with minimum picking distances. Even though their CAPM approach matches the truck based approach used in this study, it differs with regard to the variety and quantity of focused orders. Van Nieuwenhuyse and De Koster (2009) carried out analytical studies on some control methods such as the capacity of picking and sorting operations, order batching policy, and the picking policy as well as the impact of these methods on the average customer order throughput time. Since energy consumption is required for optimizing the order picking, it is discussed in this study together with energy optimization and time.

Parikh and Meller (2008) focused on the problem of choosing between a batch picking and a zone picking strategy, and they proposed a cost model to estimate the cost for each picking strategy. Changing zones of the treated system in this study do not affect the picking throughput. Pan and Shih (2008) investigated an order picking system involving multiple pickers in a warehouse and proposed a throughput model for the determination of the picking operation performance. This model was useful for coincidental multiple order pickers, but the structure in this study does not allow for the coincidence of order pickers, for example, SRs. Chan and Hing (2011) presented a simulation study of a real storage assignment problem for a multi-level rack and manual-pick warehouse system. The study results suggest that the most important issue for a storage assignment system is to match the customer order variety with the warehouse storage type. In their warehouse systems, they focused on the most traditional classification ABC system that results in a restriction used in the storage type in this study.

As seen in previous studies, automated warehouse systems have a range of diversities. The warehouse may be structured in different ways including back-to-back, deep-lane, and two blocks. Order picker types differ in loading methods, for example, multi-load, unit load, and mini-load. Products vary in size measurements such as mass and volume, and the target customers are different, for example, children, women, or men. Costs differ in time periods such as establishment (initial), annual, and daily. The decision-making process is made into a problem type and solution approach such as P, NP-hard, TSP and GA, and ACO. Order picking policies differ in target of efficiency, for example, customer based, production based, area based, route based, energy based, time based, and cost based. In this study, a unique system according to objectives like truck based batch processing, energy or time based order picking, and deep-lane AS/RS is discussed. Original research results contributing to applications that include optimization methods of a real company application, control structures, and robot designs are presented. While most of literature studies focus on theoretical optimization methods, this study examines a real application study for a beverage company in the city of Tokat in Turkey. This is the first study to discuss the whole structure of a warehouse storage system and its components, and it is the first study that offers a reserved area in a deep-lane warehouse for orders of trucks.

ESTABLISHED WAREHOUSE SYSTEM AND ROBOTS

The constructed system is a one-direction high density deep-lane warehouse. There is no possibility of direct access to any product pallet. The deep-lane storage warehouse model is selected for maximum efficiency of the storage area due to limited product variety. The remaining product pallets are carried to the endpoints of tubes after order picking for implementation of the FIFO rule. AS/RS is a Cartesian robot that includes AR and SR. SR moves along the x-axis, whereas AR moves along the y- and z-axes. An area for thirty pallets is reserved in all first floor tubes for truck based order picking. Storage area, aisle and shuttle robots, and shelf notations of input and output stations are shown in Figure 1.

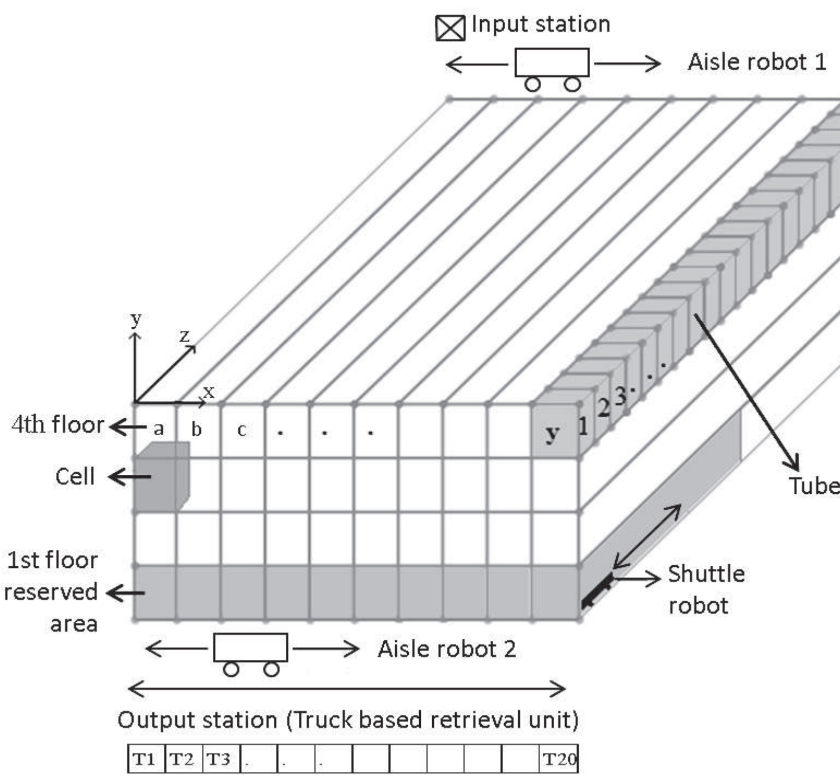


Figure 1. Configuration of the deep-lane AS/RS.

Pallets are brought to the input station wrapped with stretch film after coming off the production line. The starting point of the storage process, the input station, is a conveyor line that is the connection point of AS/RS and the palletizing robot. Groups of packaged products stacked on wooden pallets are sorted on the rail at the end of the conveyor line. Product data of sorted pallets defined on barcodes are transferred to the database during the palletizing process. Pallets are taken and carried to AR1 by SR. AR1 carries the pallet to the input of the selected tube according to product type, and pallets are carried to the intra-end point of the tube via SR. An empty SR, which gets on to AR2, passes to the rack area at the input of the suitable tube, lifts the product pallet, and returns to AR2 in the order picking process. In this way, product pallets loaded from the input station to the warehouse are pulled from the output station according to the FIFO rule.

There are 20 horizontal rows, 4 vertical floors, and a depth of 56 cells in the warehouse system, which is designed as a storage structure. If the warehouse is full, the number of pallets can be 4480, meaning that there is approximately 4480 tons of products' weight, which could not be reached at conventional warehouses. The upper view of the warehouse rack system is shown in Figure 2. The 'X' signs in Figure 2 depict the cross links that increase the strength of the warehouse. The notations used in this article are shown in Table 1.

The warehouse rack system is shown in Figure 3, whereas Figure 4 shows a product pallet to be stored in the system. There is an SR under the product pallet. The SR carries the product to the desired location by lifting it via lift motors. The location where product pallets are positioned is known as the cell, and pallet cells are designated according to a code system shown in Figure 5. As an example, code *4f12* represents the *12*th cell of block *f* on the 4th floor. SR carries the product to the deepest location in the tube. Thus, the warehouse area is used most efficiently when all cells in the tubes are used.

Table 1. The notations used in this article.

AS/RS	Automatic storage and retrieval system
AR	Aisle robot
SR	Shuttle robot
T	Truck
IS	Input station
OS	Output station
FIFO	First in first out
4f12	12th cell (z value) of block f (x value) on the 4th floor (y value)
Nm	Newton meter (unit of torque)
PLC	Programmable logic controller
PC	Personnel computer
AC	Alternative current
DC	Direct current
WAP	Wireless access point
3D	3 dimensional
a	Apricot juice
b	Peach juice
c	Mixed juice
d	Milk
e	Cherry juice
f	Apple juice
T_x	Truck output station
X_p	Product pallet's x coordinate
Y_p	Product pallet's y coordinate
Z_p	Product pallet's z coordinate
X_t	Truck x coordinate
X_{te}	Time period that elapses for 1 unit to be carried along the ***x***-axis
Y_{te}	Time period that elapses for 1 unit to be carried along the ***y***-axis
Z_{te}	Time period that elapses for 1 unit to be carried along the ***z***-axis
SR_l	Lifting and lowering speed of SR
SR_{ell}	The lifting and lowering energy consumption of SR
$T_{x,z}$	The moving time periods for only ***x***- and ***z***-axes
$T_{y,z}$	The moving time periods for only ***y***- and ***z***-axes
X_{ec}	Energy consumption in ***x***-axis
Y_{ec}	Energy consumption in ***y***-axis
Z_{ec}	Energy consumption in ***z***-axis
$E_{x,y,z}$	Total energy consumption in ***x***-, ***y***-, and ***z***-axes
m/s	Meter/second
Rpm	Revolutions per minute
kWh	Kilowatt hour

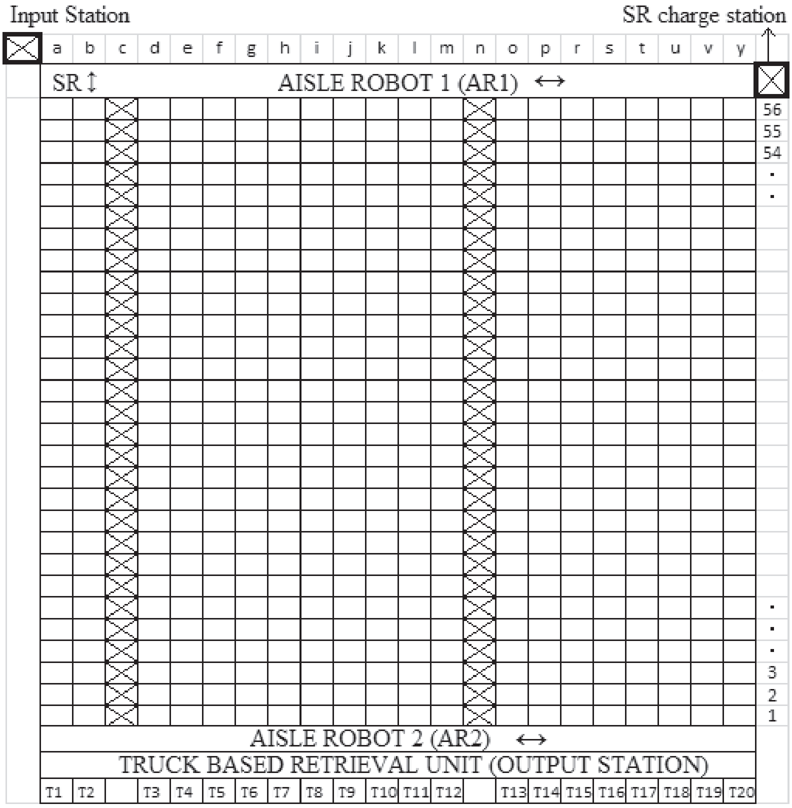


Figure 2. Storage area, input and output station layout.

Figure 3. Projected warehouse construction.

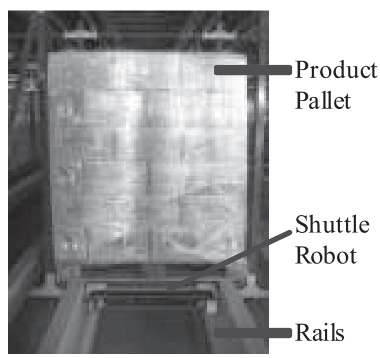


Figure 4. Product pallet, rails, and shuttle robot.

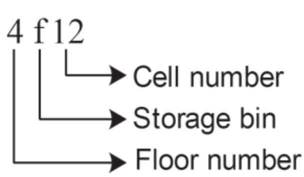


Figure 5. Product pallet address' coding.

Aisle robots and shuttle robots

One of the components of AS/RS is AR. There are two ARs in the performing AS/RS. One loads pallets from the input station to the stock zone, whereas the other sorts pallets from the stock zone to the bottom roof, that is, the truck based retrieval zone, according to order picking data. AR and its solid model are shown in Figure 6. There are 11 sensors on the AR. While a portion of the sensors work synchronously with SR, others conduct the motions of AR. Two servo motors work for the lifting operation, and another servo motor is used for carrying. Lifting motors have a power of 3 kW power, a speed rate of 2000 rpm, and a torque of 14.3 Nm. The carrying motor has a power of 1.5 kW, a speed rate of 2000 rpm, and a torque of 7.16 Nm. Three servo motors are controlled via the Mechatrolink-II motion network by the Trajexia control unit. The block scheme of AR's working algorithm is shown in Figure 7.

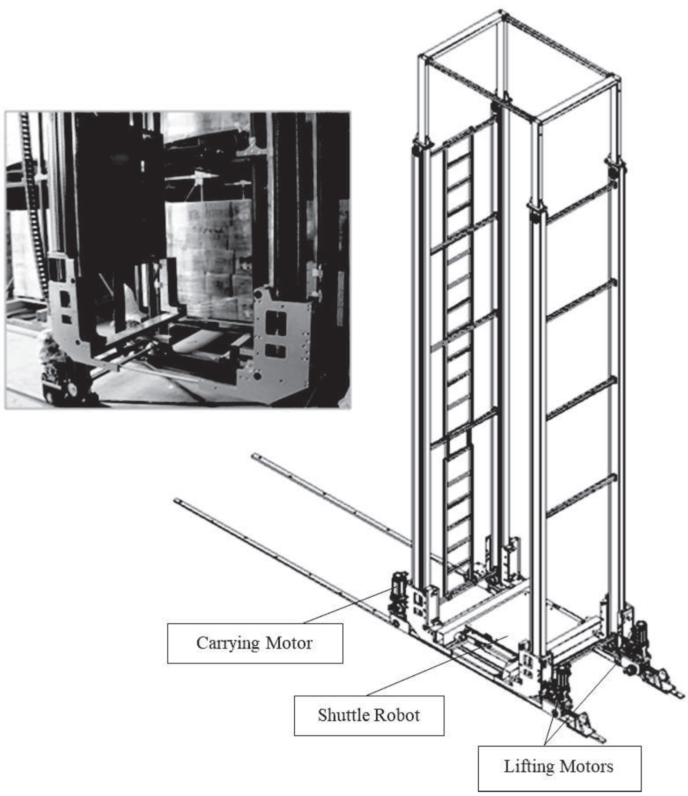


Figure 6. Aisle robot and its components.

<u>Components of Aisle Robot:</u>

- Steel Construction: suitable for loads of 1000 kg.
- Carrying Cabin: steel component, connected to lifting motors by gear and chain to provide z-axis motion.
- Transmission Components of Lifting Mechanism: gear and chain group that connect two lifting motors to the carrying cabin and provide balanced lift.

- Transmission Components of Carrying Mechanism: gear and chain group that connect carrying motor to wheels for linear motion.
- Servo Motors: electric machines that provide means of carrying and lifting (2 lifting, 1 carrying).
- Servo Motor Drives: control units that enable the motors to reach their specified velocity, torque, or position.
- Encoders: acquire feedback data including velocity and position values from motors.
- Proximity Sensors: acquire data when a specific position is reached.
- Position Verification Sensors: assist encoders to provide sensitive position control.
- PLC: control unit, runs and transmits storage/retrieval algorithm to servo drives.

Network Adapter: provides communication of PLC and server PC.

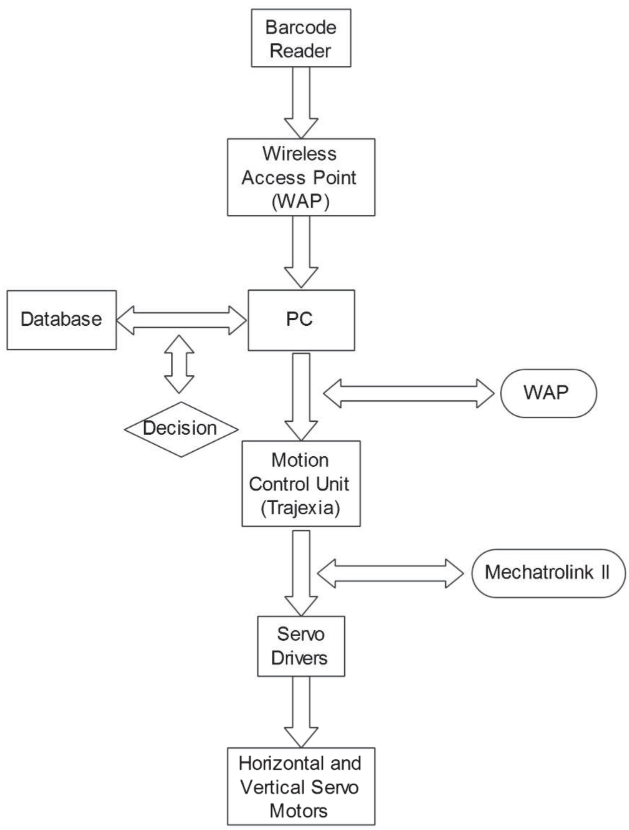


Figure 7. Block scheme of AR (Soyaslan *et al.* 2012).

Another component of the system is SR. SRs are vehicles that carry pallets in racks much like a traveling operator. Some SRs are left to wait at the charging station to assist fully charged SRs. The remaining SRs are used for storage and retrieval operations at needed locations in the system. The produced SR and its solid model are shown in Figure 8.

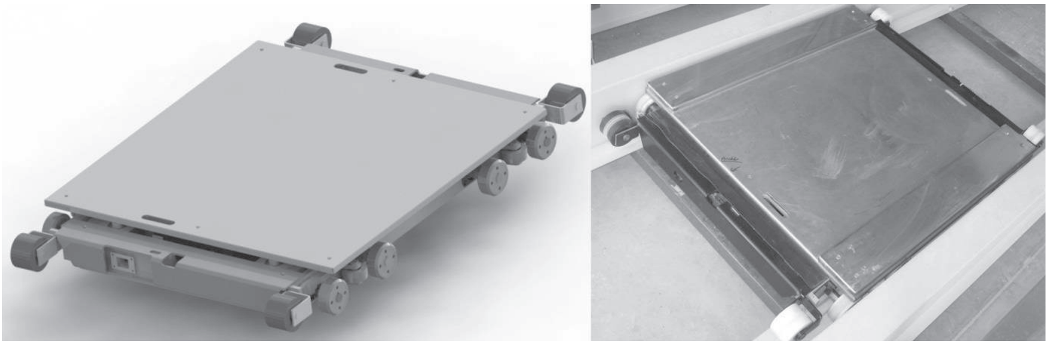


Figure 8. 3D drawing and real application of shuttle robot.

SR has 2 servo motors to perform lifting and carrying operations. The lifting motor has a power of 0.24 kW, a speed ratio of 2500 rpm, and a torque of 2 Nm. The carrying motor has a power of 0.26 kW, a speed ratio of 1300 rpm, and a torque of 4 Nm. If SR does not operate for 3 minutes, it automatically switches to the standby mode, thus preventing unnecessary battery consumption. Figure 9 shows the block scheme of the working algorithm of SR.

Components of the Shuttle Robot:

- Steel Case: designed for ability to withstand loads of 1000 kg.
- Transmission Components of Lift Mechanism: gear and chain group that connect
- the lifting motor to four corners and provide a balanced lift.
- Transmission Components of the Carrying Mechanism: gear and chain group,
- provide transmission from motor to four wheels for linear motion.
- Mechanical Brakes: 4 mechanical systems prevent faults due to sensors, drivers, or racks and are located at the tips of SR.
- Electrical Motors: 2 electric machines for lifting and carrying operations.
- Servo Motor Drives: control units, provide motors to reach the specified velocity,
- Torque, or position.
- Encoders: acquire feedback data including velocity and position values from motors.
- Proximity Sensors: acquire data when a specified position is reached.
- Position Verification Sensors: assist encoders to provide sensitive position control.
- PLC: control unit, runs and transmits storage/retrieve algorithm to servo drives.
- Network Adapter: provides communication of PLC and server PC.
- Battery Group: power supply for motors, PLC, servo drives, encoders, sensors, and network adapter.
- Battery Charge Input : input connected to charge station when battery decreased to charge level.

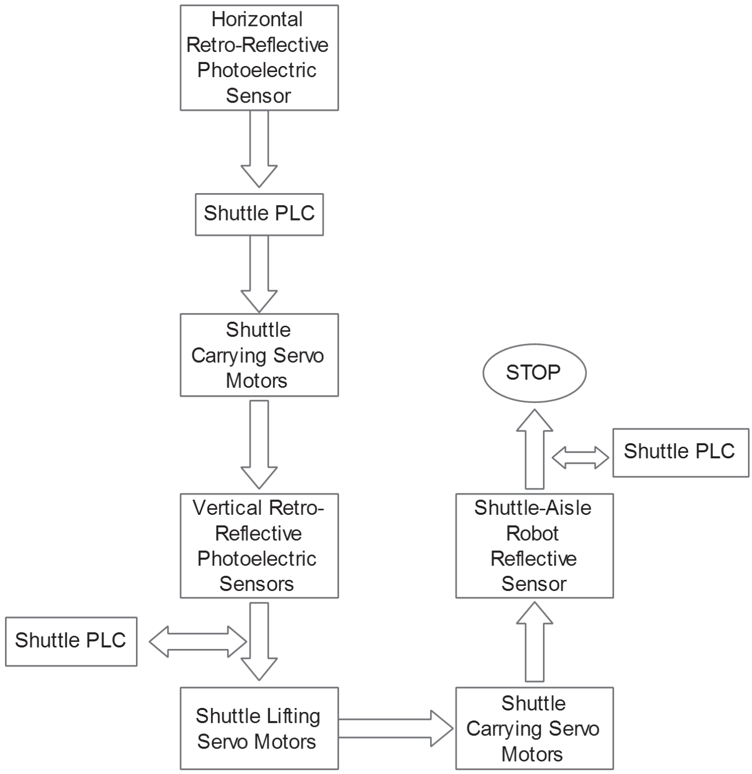


Figure 9. Block scheme of SR (Soyaslan *et al.* 2012).

MODEL DESCRIPTION

Order picking principles and algorithm

There are many issues to be considered during the collection of products from the shelves. The location of the best matching item must be selected in the software. The instant information of the tubes and cell addresses are stored and updated in the database of the company. Consumed energy and cycle time values can be easily calculated according to the selected algorithm, and the best method can be selected according to the company order's density. AR and SR are directed to the desired cell address according to the optimization method. Then, the current coordinate information must be recalculated depending on the new shelf layout. The update process should be repeated after every retrieval process of products. The time based algorithm of order picking is shown in Table 2, and the energy based algorithm of the order picking process is shown in Table 3.

Table 2. Time based optimization algorithm of order picking process.

Start

Determine for which truck order picking process will be done.

Locate the truck coordinate.

Determine the desired order sort (a, b, c, d, e, f) and quantity for selected truck.

Determine the coordinates of same sort products.

If (Product‘y’coordinate = 2 and |product ‘x’coordinate – truck ‘x’coord.|≥ 4) or

(Product‘y’coordinate = 3 and |product ‘x’coordinate – truck ‘x’coord.| ≥ 8) or

(Product‘y’coordinate = 4 and |product ‘x’coordinate – truck ‘x’coord.| ≥ 12) then

Calculate only ‘**x**’ and ‘**z**’ coordinates time to go.

Else

Calculate only ‘**y**’ and ‘**z**’coordinates time to go.

End if

Create solutions for the first pallets of the same kind of products.

Go to the best solution coordinate and bring the product to T_x (truck output station) entry.

While if same sort of products don’t finish **do**

Update ways.

Create new solutions.

Go to the best solution coordinate and bring the product to T_x entry.

End while

Repeat the same procedure for the other sort of products.

End

There are two options to calculate only the x, z and only the y, z coordinates in the time based algorithm shown in Table 2. Product pallet coordinates will be (X_p, Y_p, Z_p), whereas truck coordinates will be $(X_t, 1, 0)$. Trucks will be in the same line in front of the reserved area, so only the x coordinate will change while the y and z coordinates remain constant. X_{te}, Y_{te} , and Z_{te} are the time periods that elapse for one unit to be carried in the *x-, y-, z*-axes. The lifting and lowering elapse time of SR (SR_l) is 3 seconds. This value is used for cycle time calculations in all equations.

AR operates simultaneously moving along the *x*-axis and rising along the *y*-axis. The moving time rate is $4 * X_{time} = Y_{time}$. So moving along the *x*-axis 4 units is equal to rising along the y-axis one unit. If the cell address is higher than 4 in the *x*-axis and one unit in the *y*-axis, it is enough to calculate only the *x*-axis. These coefficient numbers for the other floors of the y-axis are 8 and 12. 'If command group' in Table 2 has been established according to this situation. Figure 10 shows the AR and SR's movement directions and default positions.

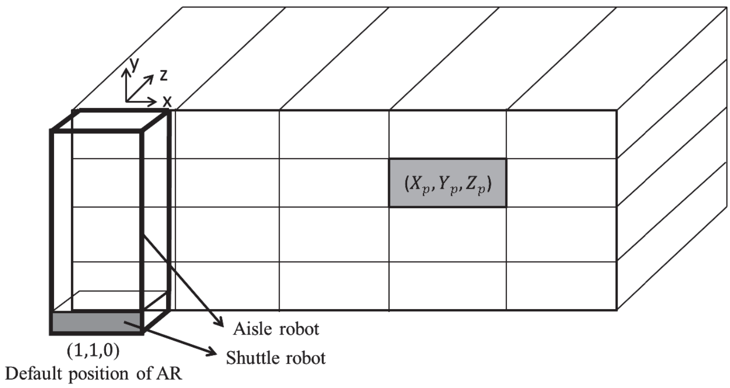


Figure 10. AR and SR's movement directions and default positions.

The general equation for calculating travel time along the *x*- and *z*-axis is formulated in Eq. 1. According to Eq. 1, the X_p coordinate of the pallet is higher than the $4 * Y_p$ coordinate; therefore, the time that elapses going along the *x*-axis is greater than going along the *y*-axis. This means the AR's *x*-axis travel time, SR's *z*-axis travel time, and the lifting and lowering time are enough for the elapsed time calculation for going to the pallet's coordinate.

$$T_{x,z} = 2 * \left[\left|X_p - X_t\right| * X_{te} + Z_p * Z_{te} + SR_l\right] \quad (1)$$

According to AR and SR speeds, which are acquired from real time warehouse data, the moving time periods for only the *x*- and *z*-axis are formulated in Eq. 2. The time that elapses for one unit product pallet to be carried along the *x*-axis is 1,93 (X_{te}) seconds, one unit lifting along the *y*-axis takes 6,3 (Y_{te}) seconds, and one unit entering into the tube along the *z*-axis takes 2,14 (Z_{te}) seconds. When these values are plugged into Eq. 1, the result is Eq. 2. Thus, Eq. 2 gives the real application elapsed time in seconds for the movement of AR and SR in the warehouse when the X_p coordinate of the pallet is higher than the $4 * Y_p$ coordinate.

$$T_{x,z} = 2 * \left[\left|X_p - X_t\right| * 1{,}93 + Z_p * 2{,}14 + 3\right] \quad (2)$$

The general equation for travel time along the *y*- and *z*-axis is formulated in Eq. 3. According to Eq. 3, the X_p coordinate of the pallet is less than the $4 * Y_p$ coordinate, so the time elapses going along the *x*-axis is smaller than going along the *y*-axis. This means the AR's *y*-axis travel time, SR's *z*-axis travel time, and the lifting and lowering time are enough for the elapsed time calculation for going to the pallet's coordinate. (The truck's Y coordinate is always 1 because it is on the first floor.)

$$T_{y,z} = 2 * \left[\left|Y_p - 1\right| * Y_{te} + Z_p * Z_{te} + SR_l\right] \quad (3)$$

According to the AR and SR speeds, which are acquired from real time warehouse data, the moving time periods for only the *y*- and *z*-axis are formulated in Eq. 4. The time that elapses for one unit product pallet to be carried along the y-axis takes 6,3 (Y_{te}) seconds and one unit entering into the tube along the z-axis takes 2,14 (Z_{te}) seconds. When these values are plugged into Eq. 3, the result is Eq. 4. Eq. 4 gives the real application elapsed time in seconds for the movement of AR and SR in the warehouse when the X_p coordinate of the pallet is less than the $4 * Y_p$ coordinate.

$$T_{y,z} = 2 * \left[\left|Y_p - 1\right| * 6{,}3 + Z_p * 2{,}14 + 3\right] \quad (4)$$

The calculated elapsed time values are multiplied by 2 for moving to take the pallet and coming back to unload the pallet as one-cycle time in all conditions.

Table 3. Energy based optimization algorithm of order picking process.

Start

Determine for which truck order picking process will be done.

Locate the truck coordinate.

Determine the desired order sort (a, b, c, d, e, f) and quantity for selected truck.

Determine the coordinates of same sort products.

Create solutions for the first pallets of the same kind of products based on energy opt.

Select the coordinate which has the best energy efficiency.

Go to the best solution coordinate and bring the product to T_x entry.

While if same sort of products don't finish **do**

Update ways.

Create new solutions.

Go to the best solution coordinate and bring the product to T_x entry.

End while

Repeat the same procedure for the other sort of products.

End

The energy consumption of all moving motors in the *x*-, *y*-, and *z*-axes is different in energy based optimization. X_{ec}, Y_{ec} and Z_{ec} are the energy consumption in the *x*-axis, *y*-axis, and *z*-axis for one unit movement. Therefore, the general energy based equation is written in Eq. 5. SR_{ell} is the energy consumption, while SR is lifting and lowering a pallet.

$$E_{x,y,z} = 2 * \left[\left| X_p - X_t \right| * X_{ec} + \left(Y_p - 1 \right) * Y_{ec} + Z_p * Z_{ec} + SR_{ell} \right] \quad (5)$$

According to the AR and SR motor parameters, in addition to the measured energy consumption values acquired from real time warehouse data, one unit carrying energy consumption along the *x*-axis is 0,80 Watt (AR), one unit lifting energy consumption along the *y*-axis is 10,50 Watt (AR), and one unit entering into tube energy consumption along the *z*-axis is 0,15 Watt (SR). Eq. 6 was obtained according to Eq. 5 and the real time energy consumption values.

If the *x*-axis energy consumption is calculated, it will be better understood. The cell size of the warehouse system is 1,35x1,9x1,5 meters. This indicates that one unit of AR in the *x*-axis is 1,35 meters. The carrying power of AR can be seen in Table 5b as 1,5 kWh and time elapsed for 1,35 meters movement of AR is 1,93 seconds (1,35/0,7). So, when one hour (3600 seconds) of energy consumption (1500 W) is proportioned to 1,93 seconds, 0,80 W is the result. This is the energy consumption value of the AR's moving one unit along the *x*-axis.

$$E_{x,y,z} = 2 * \left[\left| X_p - X_t \right| * 0{,}80 + \left(Y_p - 1 \right) * 10{,}50 + Z_p * 0{,}15 + 0.2 \right] \quad (6)$$

The time and energy values calculated using time and energy formulas are examined in section 5. The flowchart of the movements of AR and SR according to the automation system is shown in Figure 11.

Truck based order picking optimization

The main goal during the order picking process is to load the products on the trucks with an optimal energy efficiency and minimum travel time. Another important goal is to avoid possible loading and unloading faults as well as accidents in companies that use operator based order picking.

Orders are prepared for different trucks according to the requests of the distribution unit after the products are stored in the warehouse. The preparation of these orders has revealed problems with regard to time and energy according to the location of the products on the shelves. It is necessary to calculate the shortest route with the least energy consumption for each truck according to the requested orders to solve this problem and to make an accurate process.

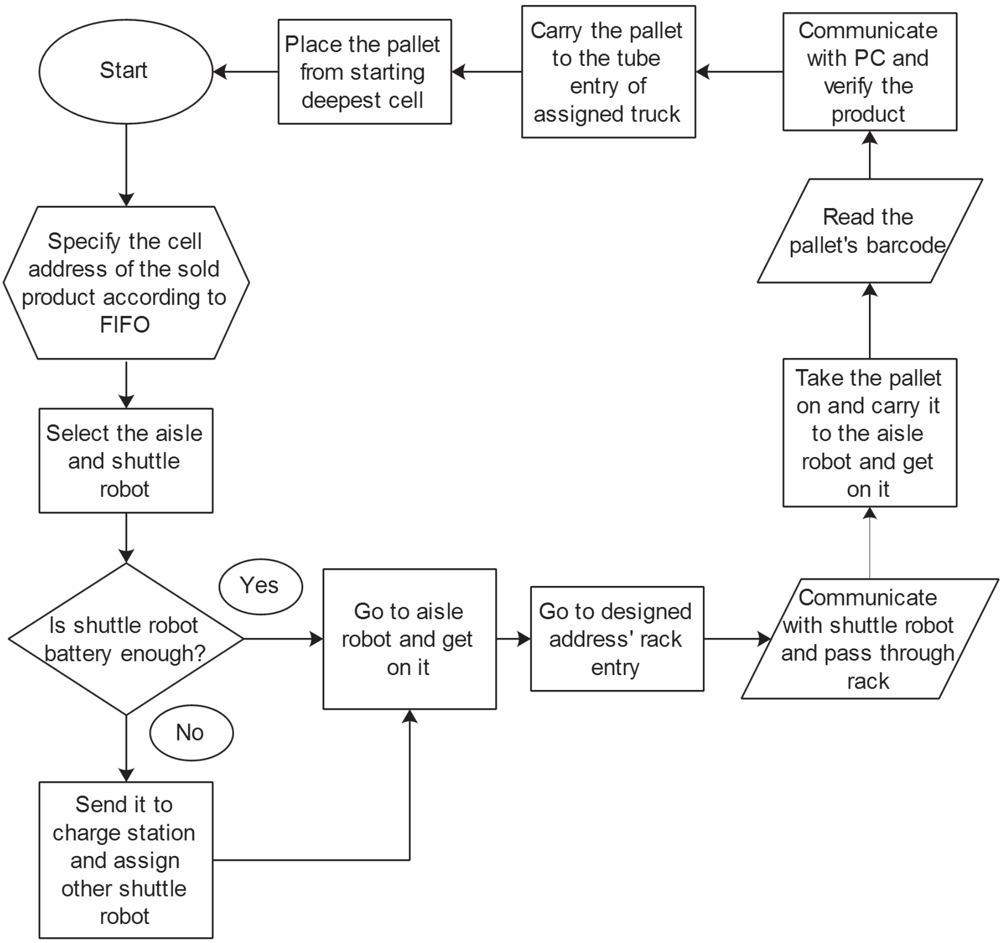


Figure 11. Order picking automation process of AS/RS (Fenercioglu *et al.* 2011).

The performed system is called high density deep-lane AS/RS in the literature and is often used in companies that store high-tonnage product pallets. Various products are located in each tube in warehouse storage shelf system. Therefore, it can be thought of as a matrix from the front view. The matrix information is stored in the database and shows how many pallets are there in each tube. The 30 pallets of storage area on the first floor are reserved for trucks, so this area is not used for general storage. AR2, which picks the pallets from the tubes, collects the products in the reserved area according to the order data of trucks.

When 20 trucks are to be loaded at the same time, 600 pallets must be picked from the tubes and sorted to the reserved area according to truck orders. Energy consumption along with process cycle times increases significantly if the energy or time optimizations are not carried out. Hence, the storage area is considered to be a matrix for easy calculation in the performed optimization study. Time based and energy based cycle times and consumption energy values are calculated according to AR and SR motor powers and speeds.

There are 56 tubes on the 2nd, 3rd, and 4th floors in 20 storage columns. The warehouse can be considered as a matrix of 4 lines by 20 columns. AR2 stands on the x-y-axis, and when it is in the left corner, the x-y-z coordinates are (1,1,0). So it is assumed that the *z*-axis begins with tube depth. Product pallets are filled randomly to the tubes. The order picking and loading processes to the reserved area according to the order data of trucks are optimized via analytical methods. The notations of product pallets are shown in Table 1.

Order picking method

Product pallets are stored randomly at the storage area. If the storage area is considered to be completely loaded, 20 tubes (reserved tubes) must be loaded from 60 tubes (2nd, 3rd, and 4th floors) according to truck orders when the order picking process is desired.

Figure 12 shows what product pallets are stored in the storage area. Thirty pallets that comprise part of the 1st floor tubes are reserved, and the remainder 26 pallets are used for temporary storage. The product pallets are stored according to the aforementioned coding. For example, 4f12e means that the product stored at the 4th floor, f block, and 12th cell address is cherry juice (e).

e	e	X	d	c	c	e	e	f	c	c	e	d	X	e	f	a	a	c	a	a	f
c	a	X	a	d	d	b	b	b	d	d	b	b	X	e	c	c	a	c	a	b	b
c	a	X	b	b	c	c	b	d	a	a	a	b	X	b	c	c	e	d	d	a	a
		Reserved Area For Truck Based Order Picking																			

Figure 12. Stock area and the product types.

Product information of the first three trucks is shown in Table 4. For example, T1 represents the truck that will come to the output station number 1. When the T1 matrix is analyzed according to the notation in Table 4, the orders of T1 are eight pallets of apricot juice (a), eight pallets of peach juice (b), five pallets of mixed juice (c), six pallets of milk (d), and three pallets of cherry juice (e). As x6 data is 0, apple juice pallet (f) has not been ordered for T1 truck.

Table 4. The product information of the first 3 trucks.

Truck Number	Number of pallets a	b	c	d	e	f
T1	8	8	5	6	3	0
T2	7	5	5	3	8	2
T3	9	7	4	5	3	2

APPLICATION RESULTS

Various parameters for AR and SR are measured following the tests carried out in the company. These values are shown in Table 5. The energy and time values depending on these parameters are evaluated according to the information of truck orders. The order picking data are then compared with the predicted analytical model.

Table 5. (a) Measured SR and AR speeds under load and no load conditions.

Robot/Speed	Carrying Speed (m/s)	Lifting Speed (m/s)	Load Status
SR	0,62	0,01	Loaded
	0,78	0,01	No Load
AR	0,69	0,32	Loaded
	0,7	0,34	No Load

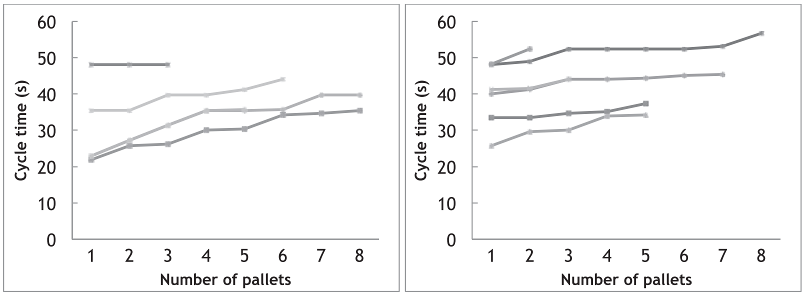
Table 5. (b) Motors parameters and values.

Motor Parameters/Type	SR Carrying	SR Lifting	AR Carrying	AR Lifting
Power (kWh)	0,26	0,24	1,5	3x2=6
Nominal speed (Rpm)	2000	2000	3000	3000
Nominal moment (Nm)	2,5	1,2	4,9	9,8

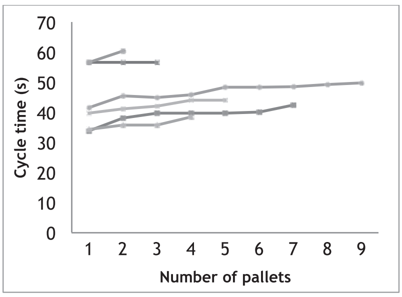
In light of the data from Table 5, the SR average carrying and lifting speeds are 0,7 m/s and 0,001 m/s, respectively, in loaded and unloaded conditions. The AR average carrying speed is 0,7 m/s and the lifting speed is 0,3 m/s in the loaded and unloaded conditions. The cell size of the warehouse system is 1,35x1,9x1,5 meters. Accordingly, total time and energy values can be calculated for orders when cycle times are calculated. According to movement speeds, the time that elapses for one unit to be carried along the *x*-axis is 1,93 seconds, one unit lifting along the *y*-axis takes 6,3 seconds, and one unit entering into the tube along the *z*-axis takes 2,14 seconds. When the energy calculation is performed in accordance with Table 5b, one unit carrying energy consumption along the *x*-axis is 0,80 Watt, one unit lifting energy consumption along the y-axis is 10,50 Watt, and one unit entering into the tube energy consumption along the z-axis is 0,15 Watt.

The first position of AR is assigned as (1,1,0), and the (x,y,z) values refer to the cells in the horizontal, vertical, and orthogonal directions, respectively. For example, if the order address is 4f12, this means 4th floor (y value), f block (x value), and 12th cell (z value). Figures 1 and 2 should be well analyzed for the movement of AR to this cell address. In this case, the coordinate points are (6,4,12). In order to reach the product pallet at that address, AR has to move to the 6th block and lift the SR to the 4th floor. The SR then has to leave the AR, enter the tube, and move to the 12th cell. The SR takes the product pallet and returns to the AR and gets on it. The AR then takes the SR to the desired truck entry on the 1st floor according to the order data. These procedures are applied in the same way for all pallets to be retrieved.

Two different methods can be noticed upon examination of the retrieval process of product pallets. The first is time based and the second is the energy based order picking method. The objective of the time based order picking algorithm is to retrieve the products in optimum cycle periods. The objective of the energy based order picking algorithm is to retrieve the products with optimum energy consumption. The results of these optional algorithms for T1, T2, and T3 trucks are shown in Figures 13-16, and the comparison of time and energy based optimization is shown in Figure 17. These figures are discussed in the conclusion section.



(a) T1 truck **(b)** T2 truck

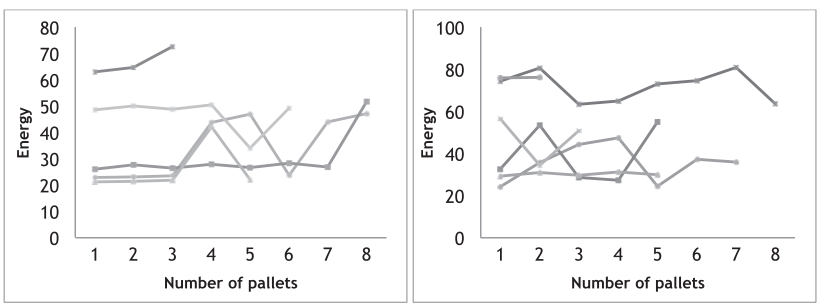


Truck No	Total Cycle Time	
	seconds	minutes
T1	1038,8	17,31
T2	1274,9	21,25
T3	1338	22,3
Total	3651,7	60,86

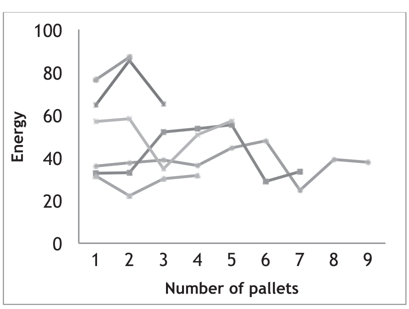
(d) Total Cycle Time

(c) T3 truck

Figure 13. Cycle time graphics for time based optimization.



(a) T1 truck **(b)** T2 truck

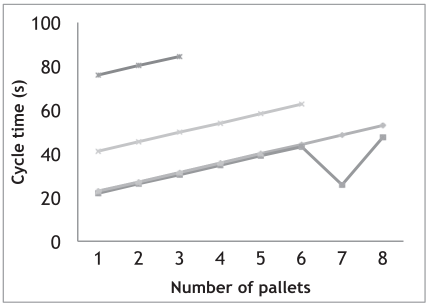


Truck No	Energy (W. cycle time)
T1	1127,45
T2	1466,18
T3	1384,67
Total	3978.3

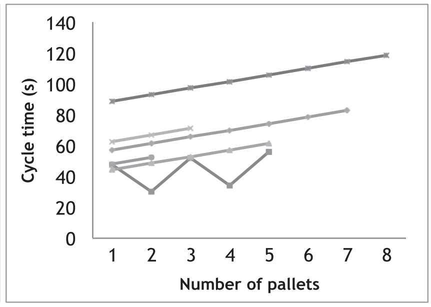
(d) Total consumed energy

(c) T3 truck

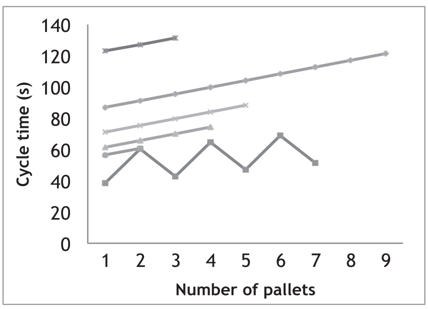
Figure 14. Consumed energy graphics for time based optimization.



(a) T1 truck



(b) T2 truck

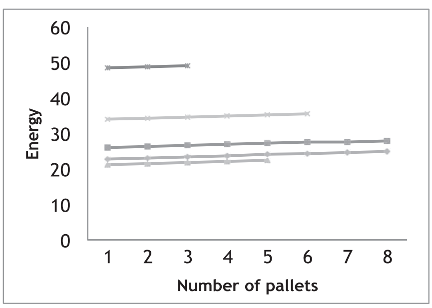


(c) T3 truck

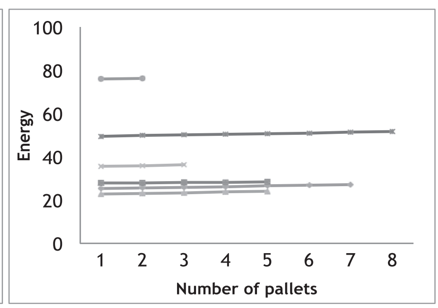
Truck No	Total Cycle Time	
	seconds	**minutes**
T1	1280,4	21,34
T2	1274,9	21,24
T3	2480,72	41,34
Total	5036,02	83,92

(d) Total Cycle Time

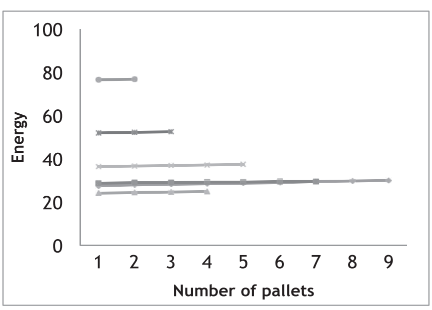
Figure 15. Cycle time graphics for energy based optimization.



(a) T1 truck



(b) T2 truck



(b) T3 truck

Truck No	Energy (W. cycle time)
T1	872,24
T2	1105,05
T3	1053,5
Total	3030,79

(d) Total consumed energy

Figure 16. Consumed energy graphics for energy based optimization.

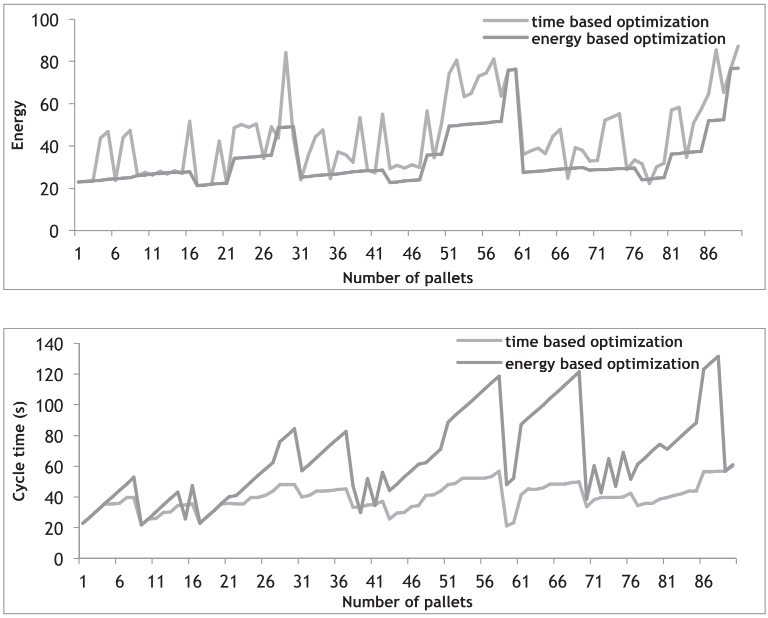


Figure 17. Comparison of time and energy based optimization for 90 pallets.

Figure 13 displays the cycle time graphs for the T1, T2, and T3 trucks according to time based optimization. This means that the algorithm works for the minimum time values of picking pallets to the specified truck based area. There are six types of beverage, and truck orders have different quantities. The stock area and product pallet allocations are shown in Figure 12. Figures 13(a), 13(b), and 13(c) show the cycle time values of AR and SR, respectively, for T1, T2, and T3 truck orders. According to these coordinates and truck orders, it can be seen from Figure 13(d) that it takes 60.86 minutes for picking the pallets to the reserved area.

While Figure 13 shows the time based cycle time graphics and total cycle times, Figure 14 shows the consumed energy graphics and total consumed energy values for time based optimization. According to movements of AR and SR for the time based algorithm, the total consumed energy value is shown in Figure 14(d) as 3978,3 W. This value is the total consumed energy for the order pickings of T1, T2, and T3 trucks.

Figure 15 shows the cycle time graphs for T1, T2, and T3 trucks according to energy based optimization. This means the algorithm works for the minimum consumed energy values of picking pallets to the reserved stock area. While Figures 15(a), 15(b), and 15(c) show the cycle time values of robots, respectively, for T1, T2, and T3 truck orders, Figure 15(d) shows that it takes 83.92 minutes for picking the pallets to the reserved area when the pallets' coordinates are selected according to the energy based algorithm.

The consumed energy graphics and total values for energy based optimization are shown in Figure 16. According to these values, the total consumed energy value is 3030,79 W when the energy based algorithm is selected. Figure 17 shows the comparison of time and energy based optimization in two graphics. The first one is consumed energy values and the second one is time values for picking pallets.

CONCLUSION

Throughput travel time and energy consumption of random orders in warehouse systems is an important measurement of the efficiency of an order picking process. The faster the order can be picked, the sooner it can be ready for loading to the truck and hence for shipment (Yu M. and Koster, 2009). However, it is not implied that the energy consumption decreases with fast travel time. Hence, these situations are examined separately for this system. Different cycle time and consumption energy results are obtained from time and energy based optimizations graphs.

If time based optimization is selected, the total cycle time is 60,86 minutes and the total energy consumption is 3978,3 W. If energy based optimization is selected, the total cycle time is 83.92 minutes and the total energy consumption is 3030,79 W. These values show that there are two different cases for order picking, and they have different values for travel times and energy consumption.

The travel time difference between time and energy based optimization is determined as 23,06 minutes for three trucks by the experiments carried out. When this value is proportioned to 20 trucks, 153,73 minutes is the result. The energy consumption difference between energy based and time based optimization is 947,51 W for the three trucks. Again when this value is proportioned to 20 trucks, 6316,73 W is the result. These values show that time and energy optimization is inversely proportional. When time based efficiency is selected, approximately 6316,73 W more energy is lost in comparison with energy based optimization for a 20-truck order picking operation. When energy based efficiency is selected, the operation is finished approximately 153.73 minutes later than that in the time based optimization. These value changes occur because of the motor parameters of AR and SR. Therefore, the operator must select the most suitable method for the warehouse and orders when using the optimization system. The sales office of the company estimates delivery time calculations of orders to markets. If there is no time problem, the energy based algorithm is selected. However, the workload density of the company peaks during the summer months, and delivery time calculations of orders to markets must be carried out within the shortest amount of time possible. Thus, it always uses the time based algorithm. The picking sequence in truck orders does not have an impact on the algorithms because it does not matter which beverages are picked first to the reserved area. Their tubes are in the different coordinates and the AR and SR must go along their coordinates at all times. If it considered a multi-objective optimization, new cell coordinates will emerge according to the energy and time values of SR and AR's motors. It is obvious that these coordinates will differ from the coordinates that are presented in this study. In such a case, the cycle time and consumed energy values will be in average ranges between time based and energy based optimization. Further research about this project could be a hybrid optimization method that includes both time based and energy based algorithms.

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