Augmented Reality System for Instructed and Visualized Pallet Loading

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Abstract: Optimally loading pallets is a challenge and can be a time-consuming task for many industrial and logistics applications. To help solve this problem, we proposed an augmented reality (AR) application that assists warehouse workers during the pallet loading process. For this reason, an algorithm for solving the Pallet Loading Problem (PLP) was defined first. All input data (name, dimensions and quantity of boxes that need to be loaded on the pallet), which actually form a loading order, are then transferred to the warehouse with the generated QR code. A warehouse worker scans the QR code and gets a visual representation of how to load the boxes onto the pallet on the lens of their smart glasses. The experimental results show that the proposed system successfully facilitates and speeds up the process of shipping products from the warehouse to customers.

Keywords: pallet loading; augmented reality; packing problem; optimization

1 Introduction

When delivering a certain amount of products to customers, PLP often occurs. It is often the case that requests are received from several customers at the same time or that one customer requests the delivery of several different types of products. In order to optimize costs and meet multiple requirements with one delivery, suppliers try to make maximum use of the available cargo space of a pallet, truck or other means of transport [1]. Therefore, it is necessary to carefully plan the loading of transport boxes on pallets. However, usually the time for loading pallets is very limited because the customer expects delivery within the appropriate time. In the background, many optimization methods need to be applied to define the best way to load pallets, which can be done by workers in production facilities, who are usually counted as "unskilled labour". The goal is

for the worker to receive simple, unambiguous instructions on how to load the transport boxes onto the pallet, and all this in a very short time.

By carefully searching the literature and following modern technological achievements, it can be concluded that AR is emerging as a promising solution [2, 3]. Through the integration of virtual objects into the real space, workers in warehouses can be provided with clear guidance on the placement of shipping boxes in a simple way.

In order to successfully develop a system that would meet all the mentioned requirements, it is, first of all, necessary to have a good and efficient algorithm that solves the PLP. By searching the literature, it is possible to find a few of them, which will be discussed in Section 1.1. The algorithm used in this paper, with all constraints and defined optimization criterion is presented in detail in Section 2.1.

For the successful functioning of any algorithm, it is necessary to provide appropriate input data. In this paper, the input data is contained in a QR code generated by a desktop application as a part of a loading order, which is then forwarded to the worker. The developed desktop application that generates loading orders is presented in Section 2.2.

Finally, it is crucial to visually show the worker how to load the boxes on the pallet. In this paper, this is made possible by the use of AR, through the developed AR application. Upon receiving the loading order, the worker runs the AR application and scans the QR code, starting the algorithm, which is then executed in the background of the application.

A detailed description of the developed AR application is given in Section 2.3. Testing of the developed applications and the most important results of the research are shown in Section 3, along with the discussion and directions for further research. The most important conclusions are given in the last Section.

1.1   Literature Review

AR has emerged as a transformative technology in the logistics sector, offering innovative solutions to enhance process optimization, efficiency, accuracy, and overall operational flexibility and effectiveness [4-6]. Significant contributions can be observed in various activities, such as:

1) *Warehouse management*: AR facilitates real-time inventory tracking and management. By providing instant information about stock levels and locations, AR helps in reducing stockouts, overstock situations, and streamlining the replenishment process. In addition, AR is employed for hands-free picking and packing in warehouses. Workers equipped with AR devices, such as smart glasses, receive real-time information on item locations, reducing errors and increasing productivity [7].

2) *Navigation and route optimization*: AR assists in route planning and navigation for logistics and transportation. By overlaying digital information on the real environment, AR aids drivers in identifying optimal routes, reducing delivery times, and minimizing fuel consumption [8].

3) *Maintenance and repairs*: In field service operations, technicians use AR to access relevant information and step-by-step instructions while on-site. This ensures accurate and timely execution of repairs and maintenance tasks, minimizing downtime [9].

4) *Training, onboarding and collaborative operations*: AR is employed to train logistics personnel, offering immersive experiences for simulating diverse scenarios and thereby enhancing skills and preparedness for real-world situations. Additionally, AR fosters collaboration within logistics teams by enabling remote experts to deliver real-time guidance to on-site workers through AR devices. This not only improves communication but also enhances problem-solving capabilities [10].

5) *Quality control*: AR empowers inspectors to overlay digital information onto physical products, facilitating the identification of defects and ensuring strict adherence to quality standards [6].

6) *Augmented packaging*: AR is used to enhance packaging processes. By overlaying digital instructions on packaging materials, workers can ensure accurate and efficient packing, reducing errors and optimizing the use of packaging materials [3].

Overall, AR is based on the insertion of virtual objects into real 3D human space. The user perceives the inserted virtual objects as if they were real. A variety of practical applications within warehouse settings are explored in existing literature, showcasing the diverse potential uses of AR in this context.

Porter et al. used spatial AR for prototyping new human-machine interfaces, such as control panels or car dashboards [11]. Within the prototyping system projectors are used to present the visual appearance of controls on a product prototype. In order to provide real-time interactions with the controls, finger tracking is applied. This kind of technology can be used for the quick and inexpensive creation and evaluation of device interface prototypes.

One of the possible applications of AR for material and product handling purposes is shown in [12], where AR is proposed as a helpful tool for picking the items listed on the order. A simulation was given, using Head Mounted Displays (HMDs) and virtual storage for this purpose. Schwerdtfeger and Klinker performed a similar experiment where a real storage environment and smart glasses were used by many participants, in order to obtain useful data regarding the adaptation of people to AR and new technologies [13]. It is proven that users were quick to adapt to AR technology.

Study [14] shows an application of AR in a warehouse, designed to facilitate the work of the driver that needs to be focused both on their surroundings while driving, and the process of loading pallets. The driver gets information about their position in space via a 3D model, the path to follow, and the contents of the pallet that needs to be loaded.

In the realm of intralogistics, the application of AR holds potential benefits, particularly in the context of palletization. The literature encompasses diverse approaches and suitable algorithms for solving PLP, suggesting opportunities for guidance and optimization within this field.

Martins and Dell analysed Multidimensional Packing Problems, such as Bin Packing problem, Knapsack Problem, Strip Packing Problem, and PLP in order to understand the differences among the execution times of the algorithms created for solving the mentioned loading problems [15]. In the case of PLP, the items of the same height are loaded in vertical layers. Therefore, the problem is reduced to finding the two-dimensional (2D) arrangement which maximizes the number of packed items in a layer. It is also considered that PLP is an example of an unconstrained 2D Knapsack Problem. Considering dimensionality, the type of assignment, the assortment of boxes, and the assortment of small items, the PLP is identified as 2D. When solving the problem, the aim is to minimize unused space and find the optimal arrangement of the boxes. Heuristics and approximation algorithms are discussed, which also include a tree search with Graph-theory. In this case, the PLP is classified as a non-deterministic polynomial time (NP) problem.

A real-world application intended for packing boxes of heterogeneous size, shape, and weight is discussed in [16] to optimize their arrangement. Constraints such as geometry (border of pallet, overlap, height threshold), stability, and fragility are taken into account. To solve the PLP, a metaheuristic framework is used to try to escape from local minimums, and achieve reasonable response time. Also, it is said that by using only heuristic techniques, the algorithm will get trapped in a local optimum. To find an optimal solution, a hybrid genetic algorithm is used.

The PLP is defined as the problem to find the optimal layout for packing a set of identical boxes on a rectangular pallet in [17]. Furthermore, it is said that it is justified to consider the height of the boxes as fixed, which reduces a three-dimensional (3D) problem to a 2D PLP. As a result, the PLP algorithm is applicable in logistics where distributed goods need to be packed in layers on uniform pallets. Also, pallet area utilization and stability were marked as important, with an emphasis on stability. An Integer Programming (IP) formulation of PLP is used.

Ha and Nananukul analysed an air cargo 3D packing model with constraints: overlapping, the practical position of cartons, cargo priority, and weight limitation applied on a forwarder [18]. The idea was to improve the model to be able to operate with a large number of input data in a short time. The improvement of the

original model is achieved by relaxing the original constraints, in order to address unsolved cases from the original model. As small deviations are now allowed, minor movements of the box are made in order to meet the additional criteria.

A carton-to-pallet loading problem is discussed in [19]. Products are grouped in boxes. Also, boxes containing similar products (soft drinks and beer) are grouped together in one class. These boxes have similar dimensions as well. In this way, different groups of products are loaded on the same pallets. When an order from a customer is ready to be packed, boxes of similar size form a group which is then used as input to the algorithm, reducing the number of possible combinations. The algorithm sequentially allocates product boxes to pallets using ten sub-steps. Each box, when allocated to a pallet, will take up a certain percentage of the pallet volume. A product group/class minimal percent rule is given.

Constraints of dynamical stability are taken into account in [20], so that there is no box movement caused by forces such as gravity and horizontal forces that occur during the transportation of the container. To solve this problem, an approach based on the metaheuristic BRKGA (Biased Random-Key Genetic Algorithm) is used in order to analyse the geometrical structure of the problem. Static and dynamic stability is discussed. During loading/unloading and transportation, it is important to pack the cargo in a physically stable manner, forbidding the movement of the cargo, especially rotating or falling.

To define the positioning of the boxes in [21] a coordinate origin in the bottom-left-behind of the bin (Bin packing problem) is used. Solving the loading problem begins with tackling it in sub-problems. It is necessary to define the box location and the optimal way to place it in the defined location. Constraints that are taken into account are stability, rotation, weight, different products, and product agglomeration. An algorithm based on Extreme Points (EP) is used. The height of a layer depends on the first box loaded in the layer. The weight constraint reflects in placing boxes with heavier products at the bottom, to prevent them from crushing the lighter ones. There are, however, some deviations where heavier boxes do not need to necessarily be at the bottom. In loading with extreme points, instead of packing single boxes, the boxes are grouped and packed in rows whenever possible. The floor boxes are the ones whose top is at the same level as the EP where the present box is to be stored.

Different ways of loading are given in [22]. The loading problem is divided into manufacturer's and distributor's problems. The task is to find a loading pattern using identical boxes for each layer of the pallet. A more complex formulation brings the Distributor's PLP (DPLP), which implies loading non-homogeneous items onto one or more pallets. The paper is based on solving the distributor's problem. In order to minimize delivery costs, each pallet must be loaded efficiently with respect to maximal volume utilization and inner-layer support, making it stable for safe transport. An algorithm for loading different types of rectangle-shaped boxes onto a pallet is defined as NP-hard. The main objective

was to maintain stability in addition to volume utilization with a nested beam search.

The PLP characterized as a 3D packing problem with additional requirements to ensure that pallets are stable and that cargo may be handled and transported safely is discussed in [23]. The DPLP and Manufacturer's PLP (MPLP) are both considered. The DPLP considers shipment from a distribution centre to retailers where pallets are composed of mixed cases. On the other hand, MPLP considers shipment from a manufacturer to a distribution centre and deals mostly with similar cases. It is similarly concluded as in [22], that the DPLP deals with heterogeneous items, while the MPLP deals with homogeneous items. It is indicated, to build stable pallets that it is essential to guarantee adequate bottom support for all items. The recommendation is to use 70% of bottom support.

What is particularly interesting for analysis is how to apply the PLP solution in real working conditions, i.e. how to help and show the worker to properly load the boxes on the pallet or how to visualize the packaging solution [24]. AR can be used for this purpose [25].

2   Method

This section presents the entire method for creating AR system for instructed and visualized pallet loading is presented. This method starts with the PLP algorithm in order to solve DPLP where different products are loaded into boxes of different sizes according to customer requirements [26]. Based on this algorithm, two applications were developed: Desktop application for creating the LOADING ORDER and AR application for pallet loading, which then together enable guided and visualized loading of pallets.

2.1   PLP Algorithm

The state of the art indicates the complexity of the PLP issue. Various researchers take into account a number of different factors, such as the dimensions of the boxes, their masses, the position of the centre of mass, the orientation, the order in which the boxes are removed from the pallet, etc.

For the efficiency of the real-time execution of the algorithm, only the planar problem is considered in this study. Precisely, all rectangular boxes are assumed to have at least one edge of the same length, be it length, width, or height. This reduces the 3D problem to 2D one [17]. Given that the PLP resolution process consists of consecutive steps, the flow diagram of instructions is presented in Figure 1.
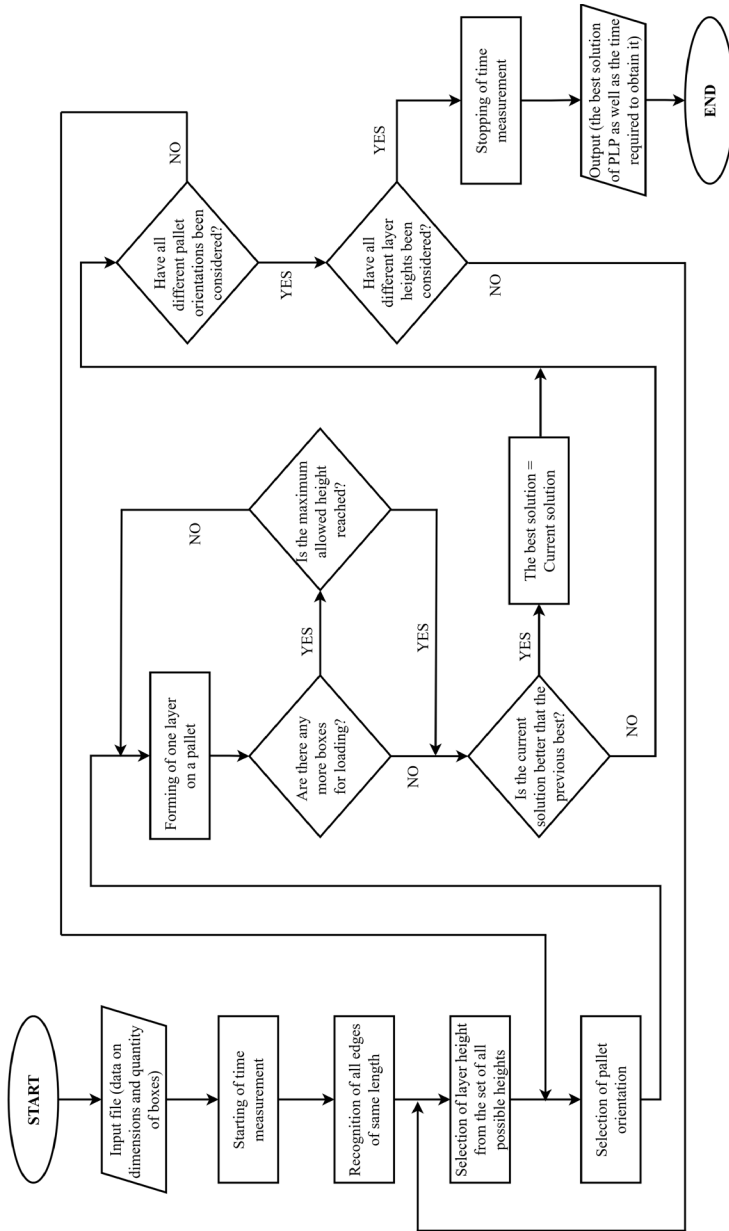
Figure 1
Instructions flow diagram

As can be seen from Figure 1, a series of steps is undertaken:

1) In the first step, the algorithm recognizes all edges that have the same length. These edges represent the potential height of some layers of boxes on the pallet.

2) In case all the boxes have more than one edge of the same length, the algorithm shows all those edges as a result in the background.

3) For each of the recognized edges (height of the layers), a pallet loading simulation (layer by layer) is performed for two different pallet orientations, until the maximum allowed height is reached or until all the boxes are loaded. The maximum height is predefined in the desktop application.

4) After the first performed simulation, the current solution is declared as the best possible one.

5) In the case that the next solution is better than the current one in terms of the best utilization of the pallet volume, i.e. the existence of the minimum possible "empty space", that solution is declared the best possible.

6) The simulation is repeated until all combinations have been tested.

7) At the very end, the algorithm returns the final optimal solution as a result, as well as the time required to obtain it.

As noted earlier, when the boxes are properly oriented and loaded on the pallet, their common dimension actually becomes the height of a single layer of loaded boxes. In this way, the problem of loading boxes on a pallet is reduced to finding the optimal layout for placing different-sized rectangles on the surface of the pallet or a previous layer of loaded boxes. The idea is to minimize the free space, or "slots" that could occur after placing these rectangles on a given surface. To achieve this, the box with the largest base area is placed first in the new layer of boxes. The formation of one layer ends when no new boxes can be added to it. As discussed earlier, the pallet is then loaded layer by layer until all the required boxes are loaded on the pallet or until the maximum height of the loaded boxes is reached. An example illustrating these algorithmic steps is presented, specifically showcasing the sequence for loading four boxes, as presented in Figure 2. Two different dimensions of the given boxes (a, b) are shown in Table 1. The third dimension of these boxes is the same and as such represents the height layer.

Table 1

Contains the result of comparing in pairs with the final result

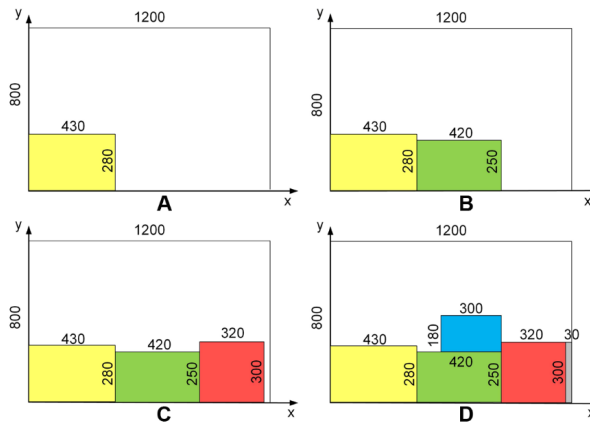| Dimensions (mm)		Colour
a	b	
430	280	Yellow
420	250	Green
320	300	Red
300	180	Blue

Figure 2
Algorithm functioning - forming one layer on the pallet

The algorithm first selects one of the pallet edges. Since EUR-pallet is used, the dimensions of the pallet are 1200 mm x 800 mm. The box with the longest edge is selected first when forming the layer of boxes, and its long edge is aligned with the long edge of the pallet, i.e. the x axis (Figure 2A). As it can be seen from the Table 1, the box that meets this condition is the yellow box with a 430 mm long edge. This step is repeated, placing new boxes with their long edge parallel to the x axis next to each other, until no more boxes can fit in the current row of the layer. Accordingly, Figure 2A and 2B show the addition of the boxes that have the second and third longest edge – the green box with the edge of 420 mm and the red box with the edge of 320 mm, respectively. After adding these three boxes, a gap, i.e. "slit" appeared between the third box and the edge of the pallet, visible in Figure 2C. As the length of this gap is 30 mm and there are no boxes with appropriate dimensions that could "fill" the gap, it is obvious that no other boxes can fit in the first row and new boxes are to be added to the second one. Further, the first box of the following row needs to be placed above the box from the previous row whose shorter edge, i.e. the dimension parallel to the y axis is minimal, in this case 250 mm (Figure 2D). If this isn't feasible because of the difference in the longer edge values of the two boxes, the algorithm seeks the box with the next higher value of the shorter edge in the previous row.

If it is detected that placing the next box in the row would result in exceeding the pallet dimensions, the box cannot be added to the row as described. In these cases, the algorithm searches for the next shorter edge that would not exceed the pallet dimension when added to the row, which can either be the short edge of the given box, or any edge of some of the other boxes. In case the short edge of the current box is chosen as optimal, the box is rotated for 90 degrees and placed onto the pallet, making its short edge parallel to the x axis. Otherwise, the observed box is no longer considered for placement in the current row and the next box to be

added to the row is searched for among remaining boxes in the same way. Also, if the dimensions of a single box exceed the pallet dimensions, the algorithm does not allow the addition of that box to the pallet.

2.2   Desktop Application for Creating the LOADING ORDER

To seamlessly incorporate the PLP algorithm into an AR application, it is crucial to establish the methodology for generating input data. These inputs include the name, dimensions and quantity of boxes that need to be loaded onto the pallet. If there is a need, it is possible to add different information to each article depending on the needs of the warehouse itself. The colour of the virtual boxes has also been added for easier identification. Based on the input data, a loading order is created, which is then sent to the worker in the warehouse, either electronically or in paper form. To achieve this, a desktop application was developed to generate loading orders whose main menu is shown in Figure 3.

In the first step, the user needs to select the item name from the drop-down list (Figure 3, position 1) and enter the number for each of the selected items (Figure 3, position 2). The general term "item" is used, while the actual product names are entered for each warehouse/production facility individually. One item refers to one shipping box. After entering the item name, the corresponding data related to the dimensions and colour of the boxes are generated in the background. In the same way, after entering the item quantity, the required amount of boxes is generated. In cases of incorrect data entry, e.g. by entering decimal numbers or characters in the "NUMBER OF ITEMS" field, a warning appears and the input field is cleared for re-entry. Confirming the entry of one item is done by clicking the "ENTER" button (Figure 3, position 3), after which a message about successful entry appears on the display. The user needs to confirm that they have read the message by clicking on "OK" or on "X" to close the window. Following this step, the input fields are cleared and the application is ready to enter a new item. By clicking on the "SHOW THE LIST OF ITEMS" button (Figure 3, position 4), the user can view the entered items (Figure 3, position 5) at any time. After completing the list of items, the user generates a QR code by clicking the "GENERATE QR CODE" button (Figure 3, position 6) and the QR code appears on the main form (Figure 3, position 10). The key thing in this step is to generate the QR code that contains the input data for the algorithm related to the products placed inside the boxes. In this way, the QR code represents a means of communication between the desktop application in the back office of the warehouse and the AR application in the warehouse itself. Before generating a QR code, the list of items needs to be displayed at least once. If the user tries to generate a QR code before all items are displayed the user will be warned that execution is not possible and that it is necessary to display the content of the loading order first. Also, if the user tries to enter an already entered product, the application will notify them that the item has already been entered, and that the number of these items can be changed in the entry table named "CURRENT

INPUT". Some items that have been entered by mistake can easily be deleted from this table by simply deleting the row in which the item is located.

The *LOADING ORDER* is generated by clicking the "GENERATE A LOADING ORDER" button (Figure 3, position 7). Clicking on the "NEW ORDER" button (Figure 3, position 8), all data is deleted and a new loading order is created. In case the user wants to close the program, they need to click on the "EXIT" button (Figure 3, position 9).
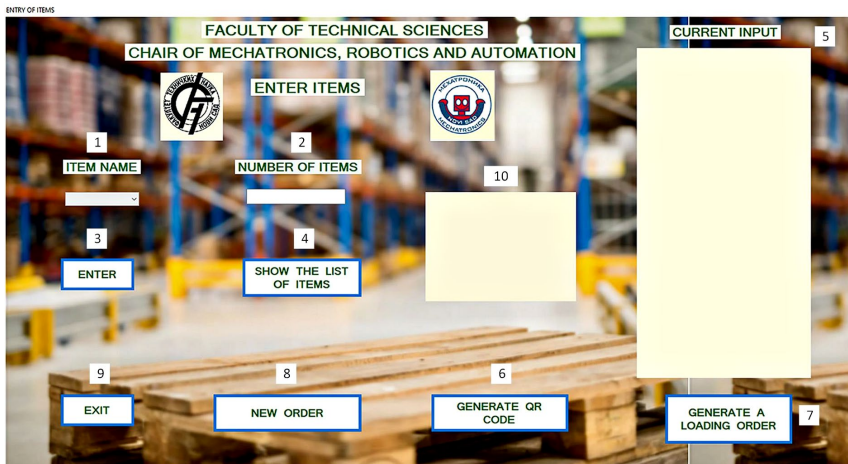

Figure 3
Main menu of the desktop application

The desktop application with entered items (products) and the generated QR code is shown in Figure 4.
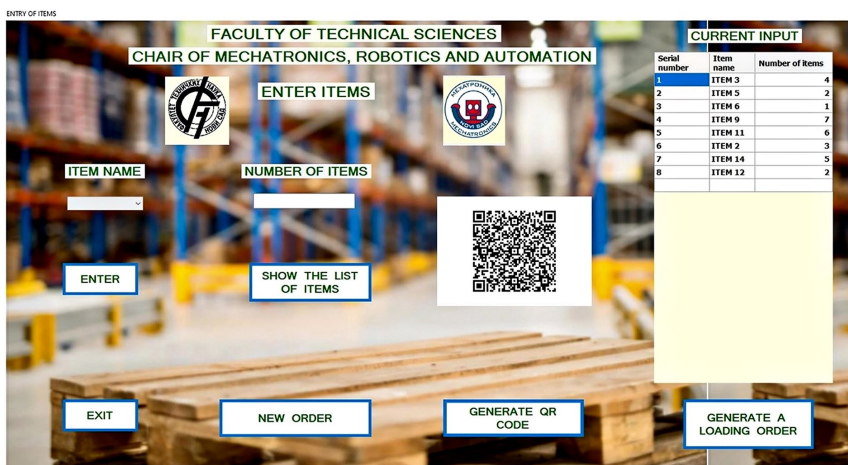

Figure 4
Desktop application with entered items and generated QR code

As a result of, executing the desktop application, a "LOADING ORDER" document is generated (Figure 5) containing all the entered data. This document appears in a new window and allows the user to view the order before clicking the "SAVE/PRINT" button (Figure 5, position 1). By selecting the printer icon, it is possible to save the order in *.pdf format or print it on paper. If the user wants to create the next order, they must first return to the main form by clicking the "BACK" button (Figure 5, position 2), and then select the "NEW ORDER" option.

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SAVE /
PRINT

1

LOADING ORDER

Place of issue:	Novi Sad	Serial number	Item name	Number of items
Date of issue:	30.09.2022	1	ITEM 3	4
Currency:	RSD	2	ITEM 5	2
Traffic date:	30.09.2022	3	ITEM 6	1
		4	ITEM 9	7
Warehouse: Lager		5	ITEM 11	6
Address: Trg Dositeja Obradovica		6	ITEM 2	3
Previous documents:		7	ITEM 14	5
		8	ITEM 12	2

BACK

2

Issued the Goods   Received the Goods

Accounted   Company Stamp   Responsible Person

Figure 5
Output document "LOADING ORDER" with generated QR code

2.3   AR Application for Pallet Loading

The AR application for Android platform was created using the *Unity* programming environment and the *Vuforia* plugin which enabled creating recognition markers. The marker is a CAD model of a standard EUR-pallet. Depending on the used smart device, it is possible to use different markers that imply different pallet views. For the initial testing of the application, in order to check only the functionality, the pallet marker 1 was created (Figure 6A) [27].

On the other hand, under the real working conditions, the real boxes hid the pallet marker which resulted in impossibility of tracking the marker. For this reason, the pallet marker 2 with a changed view was created (Figure 6B).
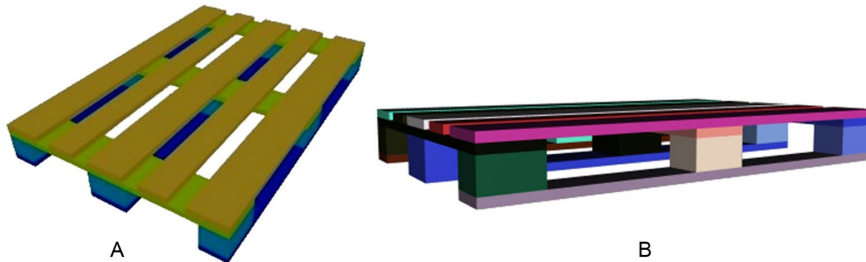

Figure 6
A) Pallet marker 1 and B) Pallet marker 2

The camera of smart device should be oriented in a way that the spatial orientation of the pallet matches the spatial orientation of the markers created based on the CAD model. In other words, it is necessary that the view of the pallet obtained from the camera coincides with the view of the marker created within the application. A certain deviation from the complete coincidence of the two views defined within the scope of recognition is allowed. Once the marker is spotted using the correct camera orientation, there is an area within which the marker will still remain recognized, although there is a slight change in the camera angle relative to the pallet [27]. For both pallet markers, the recognition angle in relation to the vertical axis is from -180° to + 180°, and the recognition angle in relation to the horizontal axis from 0° to 60°.

During testing, the importance of the angle at which the camera is directed towards the pallet was confirmed. If the orientation of the pallet in relation to the camera position is not appropriate, the pallet markers will not be recognized and the display of AR elements will not be generated. If the user moves the camera so that it cannot capture the pallet markers, the display of the AR elements on the screen is lost, but the captured state is preserved. When the user points the camera back at the pallet, the previously recorded state of the application is displayed again on the screen.

As a result of, the application of the PLP algorithm, after recognizing the appropriate marker, the developed AR application provides a display of the positions for placing the boxes on the pallet. These positions are represented as virtual square boxes that are sharp and coloured and as such are easily distinguishable from real boxes. Each virtual box corresponds to exactly one real box.

When the generated "Load Order" document arrives at the warehouse, the worker turns on the glasses and puts them on and then scans the QR code on the document by clicking on the button "Scan QRCode" (Figure 7A).

Confirmation of successful code scanning appears in the form of a new button on the screen labelled "Generate algorithm from code" (Figure 7B). At that point, the AR application starts executing. The content of the application is displayed on the screen located on the right lens. The final version of the AR application titled "Slaganje na paletu" is implemented on Vuzix Blade 494 smart glasses [28]. The advantage of using smart glasses, compared to other smart devices such as smartphones or tablets, is that the user's hands remain free to manoeuvre [25].

Based on the scanned QR code, the application reads the data necessary to generate the algorithm (dimensions, quantity, colour of the boxes). After the successful generation of the algorithm, the process of loading the transport boxes on the pallet begins. To enable the display of virtual boxes on the screen, the pallet marker needs to be detected. A new virtual box is displayed with each new click on the "Update Boxes" button (Figure 7C). It is important to note that boxes that have identical dimensions also have the same colour. The number of identical packing boxes corresponds to the quantity of the item in the loading order.

When the "Update Boxes" button disappears from the application, it means that all boxes have been successfully arranged or the layer height limit has been reached. In this way, it becomes visually clear to the worker that there is no possibility of adding new boxes, i.e. that all boxes are arranged according to the application's algorithm.

All screenshots of the smart device are taken indirectly, from the computer using the "Vuzix View" software [29].
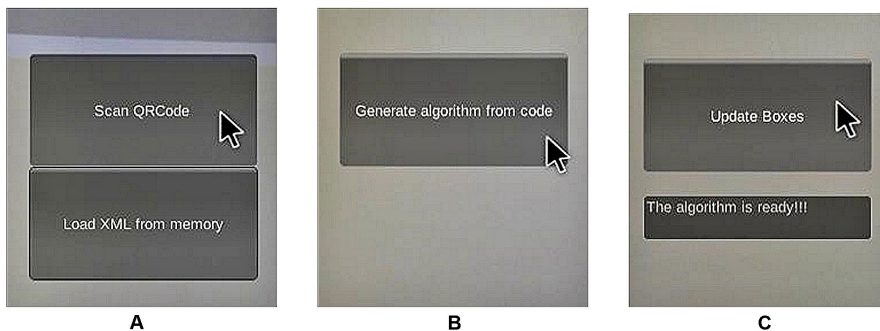

| A | B | C |

Figure 7
Sequence of steps in the AR application for pallet loading

3   Results and Discussion

The research related to the application's functionality is divided into two phases. The first phase involved the development and testing of the first version of and algorithm that provides the display of virtual boxes. Pallet marker 1 was developed for this purpose [27]. Algorithm execution ran flawlessly while executing the guidance and visualizing loading of the virtual boxes. However, a problem arose with placing the first real box on the pallet. The placed box partially covered the pallet marker 1 and thus prevented the detection of the marker and the execution of the algorithm. For this reason, the second version involved first the development of an additional marker (pallet marker 2), and then testing the developed applications in reality.

3.1   The First Version of the Developed AR Application

After following all the necessary steps to successfully launch the AR application and recognize the pallet marker 1, the application was tested using different cardboard boxes (Figure 8). The first set of test data is randomly defined and is given in Table 2. The common dimension of all boxes is equal to *200 mm*. Figure 8A shows the first two boxes (since boxes that have identical dimensions are represented by the same colour and there is no obvious boundary between the boxes, it may not be apparent) and the cursor that allows the user to add the next box. An illustration of the third box added to the pallet, identical to the previous two, is given in Figure 8B. It should be noted that the combination of the first three identical boxes was not chosen intentionally, but such a combination was determined by an algorithm according to the set of input data. Figure 8C shows the first two layers of boxes (four cyan and four yellow boxes) loaded on the pallet, and Figure 8D shows the pallet after loading four layers. The final result, after loading all the boxes given in Table 2, is given in Figure 8E.

Table 2
First set of test data

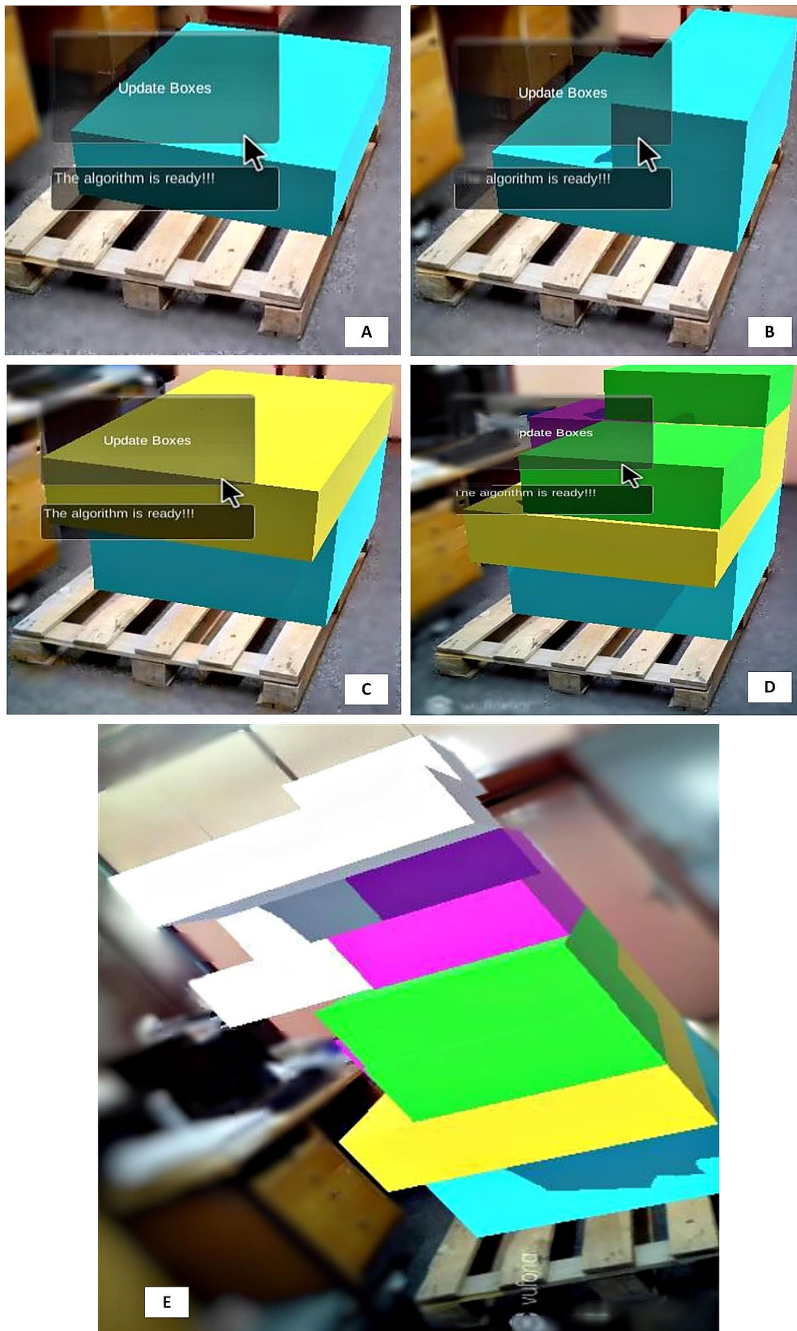| Item	Dimensions [mm]			Number of items	Color
	Width	Length	Height		
Item 1	900	200	360	4	Cyan
Item 2	440	460	200	2	Navy
Item 3	200	330	600	5	Yellow
Item 4	490	420	200	4	Magenta
Item 5	580	200	500	3	Lime
Item 6	200	380	460	6	White

Figure 8
One example of the first test of an AR application

Relying on pallet marker 1 was found to be unreliable. There was an interruption in the operation of the AR application, due to the marker being covered by real boxes in real working conditions. To overcome these issues, within the second version of the AR application, all tests were conducted using pallet marker 2.

3.2   The Second Version of the Developed AR Application

The goal of the second version of the application was to enable the simultaneous display of real boxes loaded on a pallet and virtual boxes on the screen of smart glasses.

The second set of test data was obtained by collecting real boxes. Deviations ranged from several millimetres to one centimetre are neglected, as they do not impair the stability of a formed layer. The second set of test data is given in the Table 3. The QR code containing the data related to these boxes was generated. By scanning this QR code, the algorithm in the background application receives the data and is ready for operation.

In this case, the virtual boxes are set to be transparent so that the positions of real and virtual boxes can be compared, otherwise the virtual boxes would overlap or cover the real boxes loaded on the pallet. Additionally, unlike the first case, the transparency of the boxes allows the user to see the boundaries between boxes of the same colour (identical boxes). The result of applying the second set of input data is given in Figure 9. The successfully solved PLP in this case can be seen in Figure 9E (virtual boxes are shown in different colours). Using this approach, the actual loaded box corresponds to the virtual box. A white line is also added as the contour line of the virtual boxes. A view of the physically loaded boxes is given in Figure 9F. The arrow points to the user's point of view when displaying the loading sequence given in Figure 9E as well.

Table 3
Second set of test data

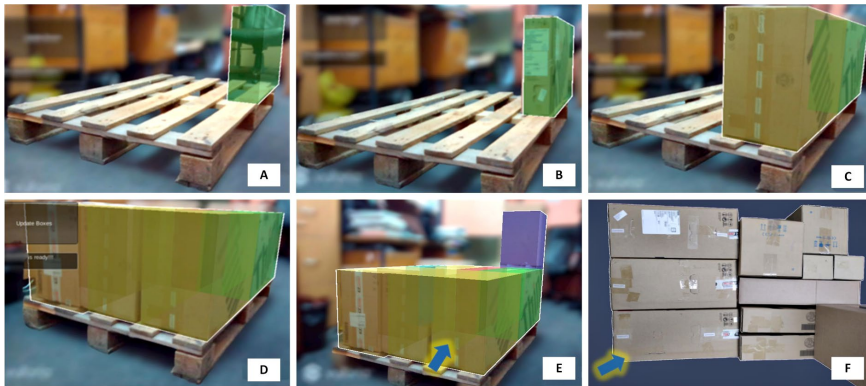| Item	Dimensions [mm]			Number of items	Color
	Width	Length	Height		
Item 1	400	580	140	1	Red
Item 2	280	400	280	2	Orange
Item 3	400	530	240	3	Yellow
Item 4	130	630	400	2	Green
Item 5	400	250	250	1	Blue
Item 6	130	400	160	2	Cyan

Figure 9
One example of the second test of an AR application

3.3   Discussion

By testing the developed applications in real working conditions, it can be said that AR can be successfully implemented in material handling processes in production plants, distribution centres, warehouses, etc. Further analysis can confirm that AR can be used as support to solve the PLP. In real working conditions, the execution time of the proposed algorithm for solving PLP is relatively short (several tens of milliseconds) [27] which provides the fast implementation of the algorithm into the AR application, where "step-by-step" movement occurs. This movement allows the warehouse worker to display one box at a time, then to pick it up and place it on the pallet (before displaying another box). For this purpose, the best solution is using smart glasses because in that case the worker has free hands to manipulate the real boxes. It should also be noted that the virtual boxes in the current version of the AR application are displayed in the corresponding colours, which implies the fact that the worker knows which virtual box (which colour) corresponds to which real box. To address the issue where the worker is unaware of the correspondence between the colors of virtual boxes and real boxes, it is possible to improve the application and automatically providing the worker with information about the real box after displaying the virtual box.

Live testing pointed out that the recognition angle of the desired marker is crucial to the app's functionality. One pallet marker was not enough to run the application smoothly, so two were created. Comparing these two markers, it can be seen that the pallet marker 1 is more often observed in real situations, so the upper surface is the dominant part of the marker. However, by placing the boxes on the pallet, they obscure the marker and the application is very prone to interruptions. For this reason, it was necessary to develop the pallet marker 2. The dominant part of the pallet marker 2 is the lateral side, so that the load boxes do not affect the loss of display. It was also observed that it is more difficult to recognize the marker the

first time due to the viewing angle and to make an initial connection in this case. The positive thing is the preservation of the captured state of loaded boxes, so the application continues to work from the step where it stopped as soon as the marker is detected again.

One limitation in the current version of the AR application is the absence of feedback regarding whether the worker correctly positioned and oriented the actual box on the pallet. In the event of an error, which could occur randomly, subsequent steps may result in overlapping boxes, making it impossible to place the next box accurately. When such an error is detected, the worker would need to reset the system. Following this, they would have to revisit all previous steps, rectifying the position and/or orientation of the inaccurately placed box in the ongoing work.

Future research will be related to the improvement of the implemented algorithm for PLP solving. In this observed case, a planar problem is practically considered since all the boxes have one common dimension, that is, the 3D problem is reduced to 2D. In reality, many boxes may have different dimensions. In that case, it would be necessary to create a new optimality criterion, i.e. take into account other parameters, such as the mass of the boxes, the position of the centre of mass, orientation, etc. Furthermore, the desktop application for generating the loading order would have to be changed so that the newly formed QR code contains all the necessary information. In addition, the AR application will be enhanced with integrated feedback on whether the worker placed the actual box in the correct position and orientation.

It is extremely important to follow the described methodology when developing an AR environment regardless of specific conditions in a plant/warehouse. This development path consists of three steps: 1) user algorithm; 2) a desktop application for creating loading order and 3) an AR application. Depending on the case, only partial adjustments are allowed. These adjustments imply adaptation to the requirements of specific users in some of the mentioned steps.

Conclusions

The main goal of this paper is to provide insight into how AR can be used to support material handling processes. A realistic setup was prepared and experimental proof was confirmed by implementing the AR application with the integrated algorithm for the pallet loading process. This novel application includes two user applications: 1) a desktop application, and 2) an AR application for pallet loading.

Desktop application generates a loading order with a QR code, which contains all the necessary information for the successful execution of the algorithm. The proposed algorithm provides one way of solving PLP. The AR app scans this QR code, executes the algorithm in the background and visually show the worker how to load the boxes onto the pallet.

Experimental testing has shown that AR is competitive both in terms of time efficiency (several tens of ms) and error rates (thereby increasing production). Using the developed system facilitates and speeds up the process of shipping products from the warehouse to customers. In real working conditions, during loading boxes, there is a possible situation in which a worker places one box and then removes it from the pallet, realizing that a box of other dimensions fits better. Applying the proposed solution avoids this situation.

Of particular interest is the adaptability of the PLP algorithm for application in various scenarios, particularly in "pick and place" operations executed by industrial robots. In these situations, implementation of the algorithm would solely require integration during the programming phase of the robot's operation.

Augmented reality can be a viable option for pallet loading, especially where more information needs to be displayed. Future work will be related to the development of a new algorithm that allows overcoming existing limitations, in a way that provides the possibility of loading boxes of completely different dimensions, possibly also shapes. In addition, future research will be related to improvement of AR application in order to allow a feedback information.

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