Novel approach to semi-automated warehouse for manufacturing: design and simulation

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Abstract. The purpose of this paper is to present a novel design of semi-automated warehousing system for manufacturing applications. The approach bases on a new type of storage of carriers, called drawer racks. This concept adopts a modified shelving system based on single or double sections of row racks rotated by 90 degrees. Each drawer rack can move perpendicularly to the transportation corridor. The motion of the rack is possible thanks to the automatically guided vehicle that translates under the line of racks. In the paper, we show a comparison between the designed new system and conventional storage solutions for manufacturing. This indicates that the drawer racks require less space per pallet place without a significant interference with a building infrastructure. In this work, we discuss various design solutions for key components of the drawer-rack and AGV that can operate a rack of 40 pallet places. The designed system was tested if it meets the assumed performance level. The simulation model was created in discrete event system environment. We compared the warehouse layout and material flow for conventional row racks with the newly proposed system. We found out that the new system operates at the higher efficiency but requires less space.

1. Introduction
A recent development in automation has lead to creation of new solutions in warehousing and logistics. This trend has been triggered by an increased cost and a decreased availability of skilled workforce as well as a limited space and a greater availability of commercial technical solutions at a reasonable cost. The other key issue is the growth of e-commerce sector what requires to process a large amount of orders for individual clients within the shortest possible lead time. This new challenge may result in substitution of manual picking with semi- or fully-automated systems, [1]. A discussion of automated storage and retrieval (AS/RS) systems can be found in, [2]. The advancement in automated guided vehicle has resulted in the appearance of autonomous vehicle storage and retrieval system (AVS/RS). These systems can improve the fulfillment process, [3]. Compared to the traditional AS/RS systems, the AVS/RS offers more flexibility and under certain conditions, the AVS/RS performs better than an AS/RS, [4-5].

Due to the limited amount of space for already existing facilities, there have been endeavours to better utilize the resources by an introduction of compact storage systems [6]. A review and synthesis of existing approaches was described by de Koster et al, [7]. Generally, these solutions allow manipulation
of stored units in 3D space along three perpendicular directions: vertical, horizontal, and cross-aisle direction, by using different material handling systems (like S/R cranes, conveyors, shuttles, AGVs or elevators).

The performance of warehousing system can be determined based on analytical or simulation models [8]. The first group include empirical [9], continuous [2] and statistical [10] travel-time models. These models fail to be effective for multi-aisle environments. The simulation studies involve discrete event system approach [11], Petri nets [12-13] and others. There is a recent trend to apply agent-based simulation (ABS) for AVS/RS systems [14-15].

In this paper, we present a novel design of semi-automated warehousing system for manufacturing applications that allows better utilization of space in comparison with traditional racks. We call this new design drawer racks. The performance of the proposed solution is tested via simulation and compared with most standard solution, namely, row racks. A brief description of most common non-automatic and semi-automatic approaches for warehousing were described by Kunc et al. [16]. The model is built in Discrete Event System (DES) environment and features the ABS simulation technique, in which the overall behaviour of a system is modelled through the use of autonomous system components (called agents) that communicate with each other [17]. By programming an agent’s behaviour we can determine its interaction with other agents and environment. This behaviour can be adjustable [18]. Agent based modelling is a relatively novel technique when compared to system dynamics and discrete event systems. It offers a modeler another way to study the system from agent’s perspective. It is possible to start building the model by identifying the objects (agents) and defining their behaviours. Next, it is possible to connect the created agents and allow their interaction or put them into an environment with its own dynamics. The global behaviour of the system emerges from many concurrent individual behaviours [19].

The paper is organized in four sections. In section 2 we describe the design of the proposed system. Section 3 contains a description of simulation models for two types of warehouses: the novel drawer racks and conventional row racks. The solution is based on cyclic and agents approach. It also provides results of simulation for the two systems and their discussion. Section 4 includes conclusions and plans for further research.

2. Design of the system

We propose a new type of storage of carriers called drawer racks (DR). This concept adopts a properly modified shelving system based on single or double sections of row racks rotated by 90 degrees. Each set of drawer racks can move perpendicularly to the transportation corridor. The depth of the rack and the number of storage levels are adjustable to the users’ requirements. The motion of the rack is possible thanks to the automatically guided vehicle (AGV) that translates under the line of racks. We name this rack the drawer as an analogy to the piece of furniture in which in order to get access to stored goods one is to pull the grip. Each rack is placed on a frame that constitutes the interface between rack and AGV as well as allows storing pallets. Once the AGV transfers itself under a rack, it lifts it and moves together in the corridor, similarly to a drawer. This allows the forklift to reach stored goods and places. When this operation is complete, the AGV goes backwards, lowers the rack and transfers itself to another location (figure 1). We call this AGV a transfer unit (TU) as it allows manipulation of the position of rack and transfers itself under racks. TU consists of following modules (figure 2):

- 4 wheel units which allow moving a rack/drawer in the corridor (1),
- outer frame that connects all wheel units (2),
- inner cart which main role is to translate under racks (3),
- mast responsible for moving the rack (either pushing or pulling) (4),
- hydraulic drive (5),
- control system (6),
- energy chain (7).
Figure 1. Visualization of Transfer Unit under rack frame.

The TU has the possibility of precise movement in two directions. The passage along the row of racks to the specified location is possible thanks to the use of the elevator guide anchored to the warehouse floor and the guide wire of the trolley supply (figure 3). The TU moves on the sets of wheels mounted in the inner frame. The motion of a given rack is possible after lifting it, when the wheels of the inner frame loose contact with the floor, and the wheel of the outframe are lowered. This process is visualized in figure 4. The TU reaches the intended location (figure 4(a)). Then, the hydraulic actuators, installed in the wheel units, start. As a result, the internal frame is raised and the wheel units are lowered. When these wheels touch the floor, further extension of the hydraulic cylinders results in lifting the platform with the rack (figure 4(b)). When hydraulic cylinders reach their final position, it is possible to start the mast drive. Thanks to the attachment to the guide in the floor, TU push itself with lifted rack into the corridor (figure 4(c)).

The TU and rack frame were designed to operate a rack of maximal 40 pallet places (5 levels of 8 pallets each). This means that the total static load is expected to reach 400 kN. For this reason, we considered two types of drives for lifting: electrical and hydraulic. In case of electric, the drive has to be transmitted from motor to lifting mechanism. Four lifting mechanisms were analyzed in terms of their applicability: screw; belt, chain or rope; rack and pinion; crank, knuckle or eccentric mechanism.

The drive by the screw mechanism is usually a low efficiency system. However, it ensures full safety in the event of a power failure. The friction arising between the screw and the nut will cause rapid wear of the mechanism, as well as the formation of clearances, which can lead to unstable lifting and in the extreme case, damage to the screw during lifting.

In case of linear drive via rope, belt or chain stretched between two wheels, cable, its high efficiency makes it necessary to equip the mechanism that prevents the rack from falling down by gravity.

If the drive is to be transmitted via rack and pinion, there is a generation of noise and the need for precise running of the pinion in reference to the rack. Another problem is related to the clearance, which would cause unstable lifting. As in the case of previous solutions, it would be necessary to equip the system with mechanisms preventing the rack from falling down.

Crank, knuckle or eccentric mechanism can also be used when connected to a high reduction gear (preferably self-locking, so there will be no need for an additional brake). The undoubted advantage of this kinematic system is approximation to the sinusoidal course of speed when lifting, which will ensure a calm start and stop.
As for hydraulics application we consider hydrostatic drive as, potentially, it is the simplest and most convenient solution due to the high pressures used in these systems. In addition, the advantages include:

- a very low compressibility of the working fluid, ensuring stability of movement,
- small dimensions of hydraulic cylinders,
- no need to use mechanical gears to obtain linear motion and generate very high forces
- a possibility of supporting the rack in several points with independent synchronized drives,
- a simple control of speed and dynamics of movement,
- a high durability and reliability,
- a relatively low cost of the system compared to the mechanisms that transmit drive from electrical motor,
- a possibility of using one hydraulic power supply for horizontal drives and auxiliary movements,
- a trouble-free operation of the system in a wide temperature range,
- an easy transfer of power transfer through hydraulic hoses.

All things considered, we decided that the most suitable solution to the designed system would be hydrostatic drive.

The new type of storage rack can be flexibly adapted to the variable demand for storage space by expanding or reducing it to further drawers without the need to perform heavy-duty work in the floors or foundations of storage facilities. The only elements that are anchored to the floor are guideways and footplates for frame rear legs. These are shorter than front in order to avoid collision of the frame with energy chain and guideway.

Communication between the forklift operator, the rack control system and the WMS (Warehouse Management System) system allows the drawer to be pulled out shortly before reaching the position by the forklift, which can possibly decrease the time for loading or unloading. Installing or changing the arrangement of shelves does not require building infrastructure in the warehouse floor. Since the rack moves in the area where an operator can be present, we propose a safety system which consists of two safety scanners that monitor the area in rack neighbourhood during its motion. If any objects is detected within the safety zone, the safety systems cuts off the power. This is to ensure that no harm can be done to the operator and prevent critical situation like hitting or compressing body part.

The designed solution optimizes the storage space by reducing the number of transport corridors. As a result, there is an increase in the storage capacity of goods at the same storage area. Customers are able to reduce their storage space, which directly translates into a reduction in the cost of investment in the construction of logistic centers as well as more efficient use of internal transport [16].

![Figure 2. Main components of the Transfer Unit: 1 – wheel unit, 2 – outer frame, 3 – inner cart, 4 – mast, 5 – hydraulic drive, 6 – control system, 7 – energy chain.](image-url)
**Figure 3.** Method for TU guidance: 1 – elastic rollers, 2 – guideway, 3 – chain.

**Figure 4.** Moving a rack: a) positioning TU under selected rack, b) lifting the rack, c) moving the rack in the corridor.
3. Simulation model

3.1. Agent Based Simulation approach

The motivation for creating a simulation model is to compare the two types of warehousing systems: novel drawer racks and conventional row rack. To form the basis to solve, defined in previous section, problem we used our earlier experiences [20, 21]. To build the logic of designed simulation model we have concentrated on:

- levels of control and analysis,
- using cyclic and agents approach.

We identify work cycles on following levels:

- level of automation (PLC - programmable logic controller)
- level of rack transfer unit and cooperating forklift,
- level of control/management – MFC/WMS (MFC – Material Flow Control system, WMS – Warehouse Management System).

Agent approach involves describing and implementing the logic of system operation in a distributed and autonomous way (as it is in reality). Central control and management (equivalent of MFC/WMS) is treated as an agent’s operation as well. To build the simulation logistics model, it is not necessary to focus on the level of automation. So we focus on level of transfer unit and forklift. We defined the rules for TUs, forklifts and for the level of control/management [17]. We used a script language implemented in FlexSim Simulation Software. In [18] it was presented the methodology for layout and intralogistics redesign using simulation. This methodology is dedicated for assembling system and is available as LogABS Simulation Program. In this study, we have developed LogABS for this kind of warehouse that uses designed drawer racks. The first step was to extend the script language defined in [17] by two commands: PickUp and Lower. Figure 5 presents the corridor with drawer racks, transfer units and forklift as part of simulation model built in LogABS/FlexSim 3D environment.

![Figure 5. The view 3D of simulation model in LogABS/FlexSim with one corridor, transfer carriers and forklift.](image)

3.2. Model design

The developed simulation tool allows automatic generation of simulation models for both types of systems. In this study, we prepared three experimental scenarios for low capacity warehouses in order to show the fundamental differences in their operation. As a reference we assume a DRS (Drawer Rack System) of 400 pallet capacity. This consists of two rows with 4 drawers on each side and 2 lateral fixed racks (a total of 20 shelves), each shelf has 5 levels and 4 locations horizontally - which gives the storage capacity \((10 + 10) * (5 * 4) = 400\) pallet spaces. The view of the simulation model of the aforementioned system can be found in figure 6.
Figure 6. Overview of drawer rack system of 400 pallets capacity generated in LogABS software.

This reference model was compared with three different row rack warehouses arranged in two extreme and one intermediate configuration as shown in figure 7. Each of them had the same parameters as in a drawer system, i.e. the same size, structure and capacity:

- variant A - racks arranged along one corridor (extreme version where minimum number of corridors is achieved),
- variant B - intermediate - arrangement of shelves on a rectangular plan,
- variant C - shelves arranged along 10 corridors (the largest number of corridors possible to be obtained with such system (extreme version - maximum number of corridors).

Figure 7. Overview of three various row racks scenarios generated in LogABS software.
Experiments involved four transport orders - the pallet was collected by the forklift from the point furthest away from the point determining the place of placing the pallet on the rack. This is marked with arrows in figure 7.

| Object               | Velocity [m/s] | Acceleration/Deceleration [m/s²] |
|----------------------|----------------|----------------------------------|
| TU (transfer alone)  | 2.0            | 1.0/1.0                          |
| TU (with rack)       | 0.2            | 0.04/0.04                        |
| Forklift             | 2.0            | 1.0/1.0                          |

The following measures have been adopted to show the differences between those scenarios:
- time of completing 4 transportation orders,
- the distance travelled by the forklift during the implementation of 4 transport orders.

The parameters of transfer units and forklifts are presented in table 1. Lifting/lowering time for TU is assumed to last 10 seconds.

3.3. Results and discussion
The results of simulation are shown in table 2. As expected, the highest values of both parameters were achieved for the most extreme layouts of row racks: variants A and C. The multiplication of number of corridors is less efficient in comparison with single corridor scenario. Variant B (intermediate) exhibits similar results to Drawer Rack system. There is a slight advantage observed in the favor of drawer rack as this approach ends up with 7% decrease in the time of completion and 9% drop the distance covered. We are aware that these are preliminary results and the model has to be expanded if a more solid statement is to be declared. However, those numbers can suggest that drawer rack system can operate at the similar performance level at conventional system. The main advantage of the proposed design is a fact that for the same number of pallet places, it requires less space. The simulated drawer rack system needs 180 m², whereas row rack (B) 220 m², what is a 20% advantage.

| Variant            | Time of completion [s] | Distance travelled by forklift [m] |
|--------------------|------------------------|-----------------------------------|
| A                  | 171.5                  | 296.7                             |
| B                  | 120.7                  | 195.1                             |
| C                  | 220.7                  | 395.1                             |
| Drawer Rack        | 112.9                  | 177.6                             |

4. Conclusions
In the paper, we show a comparison between the designed new system and conventional storage solutions for manufacturing. This indicates that the drawer racks require less space per pallet place without a significant interference with a building infrastructure. This is can be of great importance for manufacturers who can easily adapt their workspace for either production or storage, depending on the current demand. In this work, we discuss various design solutions for key components of the drawer-rack and AGV that can allow to operate a rack of 40 pallet place capacity and maximum load of 400kN. This includes lifting mechanisms, applications of electric- or hydraulic-powered drive.

The designed system was tested via simulation to verify if it meets the assumed performance level. The simulation model was created in discrete event system (DES) environment with Agent Based technique (ABS). In the model, we implemented the actual geometry of the rack and AGV, their
technical parameters as well as control and safety rules. We compared the warehouse layout and material flow for already existing conventional row racks with the newly proposed system. The experiments were designed to determine the time of completing transportation orders and the distance travelled by forklifts for both types of warehouses. We found out that the new system operates at the slightly higher efficiency as the conventional systems but requires 20% less space. Our hypothesis is that the advantage of the proposed system will be more evident for more complex systems.

The results we show are preliminary but they constitute a prospect for future. The designed drawer rack systems is now installed in the test facility in Poland. Our next steps in this research will concentrate on testing the performance of the system and creating simulation models for real-life material flow and stored goods allocations. That model would be used to determine that actual advantage of the drawer rack system in comparison to conventional pallet racks.

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