SIMULATION ANALYSIS OF PALLET RACK SYSTEM WITH SHUTTLE TRUCKS

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Abstract

The paper presents analysis and simulation studies on pallet rack system with shuttle trucks - version of shuttle-based storage and retrieval system (SBS/RS). The main attention was paid to systems based on Pallet Radio Shuttle technology. Paper concerns research and analysis of technical and organizational parameters selection in storage system Pallet Radio Shuttle type. For this purpose was developed FlexSim simulation model. Various structural and organizational variants of racking system were investigated. Individual variants were distinguished by different numbers of rack bays, storage levels, depth of the tunnels, as well as the number of shuttles.

Keywords: FlexSim simulation, shuttle truck, pallet rack system, SBS/RS

1. INTRODUCTION

Different technologies are applied to store materials, but four factors are always considered: 1/ efficient space usage, 2/ maintaining proper storage conditions, 3/ maximizing accessibility to materials, 4/ maximizing throughput. Racking systems of different types serve these four conditions to a different extent.

Striving for better space utilization and higher input / output rates led to storage systems combing dense storage like drive-in or drive-through racking with automated storage and retrieval systems based on robotized units for material handling. This is how pallet racks with shuttle trucks (PR-ST) appeared. PR-ST are considered as space effective, but considerably expensive solution. The cost of one autonomous shuttle can reach 20 000 euros what makes PR-ST expensive in comparison to classic racking systems. This is why PR-STs must be carefully configured to achieve proper effectiveness and productivity but there are no general rules for that. Consequently simulation can be used as a strong support in configuration. The purpose of this paper is to evaluate throughput performance of an PR-ST using simulation with **FlexSim** software. The performance of the studied system is evaluated in terms of average cycle, time (for dual command), which is expressed by the system throughput capacity and number of handled units (cycles per hour).

PR-ST is a type of shuttle-based storage and retrieval system (SBS/RS) discussed in [4], [5], [6] or [8] and defined as system of tier-captive shuttle carriers, multiple elevators with a lifting table, and racks. Lerher et al. (2015, [4]) present a simulation-based performance evaluation of SBS/RS. Performance comparison of the studied SBS/RS is contrasted with alternative storage rack configurations. The same authors present (2015, [5]) analytical travel time model for SBS/RS confirming their simulation experiments. Ning et al (2015, [6]), examine SBS/RS by simulation and propose efficient simulation model that can be auto-remodeled for different rack configurations. Model allows to test a large number of rack alternatives and to determine the optimal solution efficiently. Eder and Karting (2016, [7]) examine geometry of the rack for shuttle system as a critical factor influencing throughput. Similarly Ekren et al. (2015, [8]) look for best rack design for shuttle-based storage and retrieval system, but under class-based storage policy (CSP). They evaluate by simulation performance of the system in terms of utilizations of lifts and storage / retrieval devices and cycle times of storage / retrieval transactions. In other place Ekren (2016, [9]) provide a graph-based solution for performance evaluation of SBS/RS, under different number of bays, aisles and tiers for the rack design and arrival rate of storage / retrieval. Zou et al. (2016, [10]) investigate the same problem and propose a parallel processing policy for the system, under which an arrival transaction can request the lift and the vehicle simultaneously. The concept is validated by simulation. Güller and Hegmanns (2014, [1]) discuss miniload multishuttle system which is similar to pallet version. Authors propose agent-based simulation approach to evaluate the performance of the system. Perotti et al. (2014, [2]) study Automated Vehicle Storage and Retrieval Systems by analysing their performance through analytical modelling and simulation. Chen and Li (2015, [3]) check the double-shuttle system with AS/RS and prove by simulation its effectiveness. Jacyna et al. (2015, [12]) as well as Lewczuk (2012, [12]) place a PR-ST in warehouse design procedure and discuss the role of storage systems in warehousing.

2. PALLET RACK SYSTEM WITH SHUTTLE TRUCKS (PR-ST)

PR-ST is automatized version of block storage of palletized goods in racks. It has inherited advantages of conventional drive-in, push-back and gravity flow racks but eliminated some of their disadvantages. The basic idea of block storage is to store large stock of palletized goods while extra warehouse space is freed by eliminating work aisles from the system. Using racking constructions ensures safe storage of delicate and instable goods which can't be stacked.

PR-ST is considered as last step in block storage and as a successor of drive-in racking systems. Both systems are based on the storage by accumulation principle, which enables the highest use of available space. Two operation versions are possible: the drive-in system, with only one access aisle, and the drive-through system, with access to the load from both sides of the rack. In both options rack is fed and emptied by a truck entering the racking construction (**Figure 1**). In the first option first loaded unit is placed on position 1. and rack is fed from bottom to top and from back to front (**Figure 1a**). Emptying happens in reverse from front to back and from top to bottom. Loading and emptying sequence is realized according to LIFO. In drive-through racking systems loading and emptying is done from opposite sites according to FIFO (**Figure 1b**).

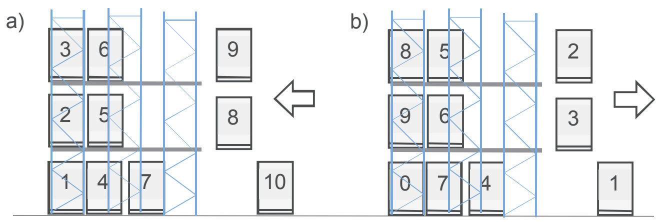

Figure 1 Drive-in rack operation scheme

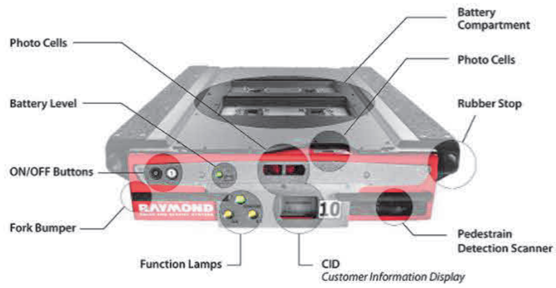

Figure 2 Schema of shuttle truck
Source: http://www.radioshuttle.co/

Push-back is another technology of block storage in racks. Push-back uses flow-through racking system which is loaded and emptied from one side only. This technology ensures high space utilization by eliminating work aisles, but it supports only LIFO principle and is limited by number of wheeled carts in rack. To feed push-back rack palletized load is placed on a cart and pushed against gravity inside the rack. Wheeled carts are stacked inside each other (usually 3 to 5) and wait on the rack forehead to be pushed inside with a pallet on it. To empty the rack the first pallet in a line is retrieved so the gravity forces other carts down. Empty carts stack together.

Gravity flow rack uses tunnels with rollers to make gravity flow of pallets possible. It is fed from one side and emptied always from the other one. Construction is limited only by durability of pallets while the first one in line is squeezed by the rest pushed by gravity. Gravity flow rack is not expensive and supports only FIFO.

All discussed constructions can be superseded by PR-ST. Pallet rack system with shuttle trucks consists of specialized rack frame and remotely controlled transfer (satellite, shuttle) trucks. Racks form multilevel structure with tunnels (or lines) for palletized products. Typically whole tunnel is intended for single, homogenous product. Pallets are handled in tunnels by shuttle trucks (**Figure 2**), which are disposed to the front or rear of tunnel by standard forklift truck in semi-automated system or by pallet crane in fully automated system. Loading and unloading pallets is done automatically by shuttle truck while work-orders are transmitted to the truck remotely. Shuttle truck travels under the pallet line on special rail system and lifts selected units up to move them according the work-order. After accomplished task truck returns to the initial position and can be disposed to other tunnel by forklift truck or pallet crane.

PR-ST can be configured in different ways to support different flow-strategies;

- FIFO - feeding and emptying tunnels on opposite sides,
- LIFO - feeding and emptying tunnels from the same side,
- pick tunnel - combination of PR-ST with a dynamic pallet flow case pick tunnel (higher levels of rack handled by shuttle trucks are used as reserves for picking areas on lower levels),
- mezzanine for staging (PR-ST system in combination with a structural mezzanine) - **Figure 3**.

Unlike conventional drive-in or drive-through racking, the operations guided by shuttle trucks eliminates any unwanted entry of material handling equipment or human into the racking structure, thus ensuring higher safety of material, equipment and people.

Figure 3 Examples of configuration pallet rack system with shuttle trucks.
Source: http://www.radioshuttle.co/

Drive-in racking accommodates a large number of pallets for each SKU. High-density of storage favors PR-ST systems for compact storage, cold storage, and buffers for temporary storage of replenished materials or ready-to-ship units. It is good for cold storage since it maximises the use of the cold store volume, reduces manoeuvring times and eliminates human factor from harmful environment. So PR-ST system is an ideal solution for FMCG, pharmaceutics, electronics etc. It is typically used where huge volumes of standard type products are stored. System is even more efficient when used in conjunction with automated feeding and emptying systems. The advantages of PR-ST compared to conventional compact systems are the following:

- Reduced pallet loading and unloading times.
- Different SKUs can be stored in each lane, and one SKU can be in different tunnels.
- Storage tunnels can be more than 40 m deep.
- Single work aisle is needed regardless of tunnel depth.
- Productivity can be increased by adding more shuttles.

- No need to drive forklifts into the racks (safety, lower rack damage risk, lower risk of accidents).
- Less forklifts and their operators.
- Elements of AS/RS.
- Better stock control.

The disadvantages of PR-ST systems compared to conventional compact systems are the following:

- Expensive automated shuttle trucks are necessary for operation.
- Some space is wasted for technical tunnel for shuttle truck.
- Materials are not immediately accessible from the front of rack like in gravity flow or push-back rack.
- Insufficient number of shuttles reduces productivity of storage.

The advantages and disadvantages listed above name the basic problems with PR-ST to be solved:

- What is the rational number of shuttle trucks to make the process reliable and smooth?
- How deep, wide and high should be racking construction to keep the stock and be effective?
- How many forklift trucks or cranes must be used to support PR-ST?
- Is the PR-ST really cost-effective in analysed case?

3. ASSUMPTIONS FOR SIMULATION ANALYSIS

Model of pallet rack with shuttle trucks (PR-ST) developed in FlexSim is composed of (**Figure 4**):

- single pallet rack for block storage, rack height, length and depth can be arbitrarily modified,
- set of shuttle trucks for handling pallets in rack tunnels,
- set of cranes to dispose shuttle trucks between tunnels and transport pallets to / from tunnel forehead,
- sources of entries and dispatches, and mouths for pallets leaving the racking system.

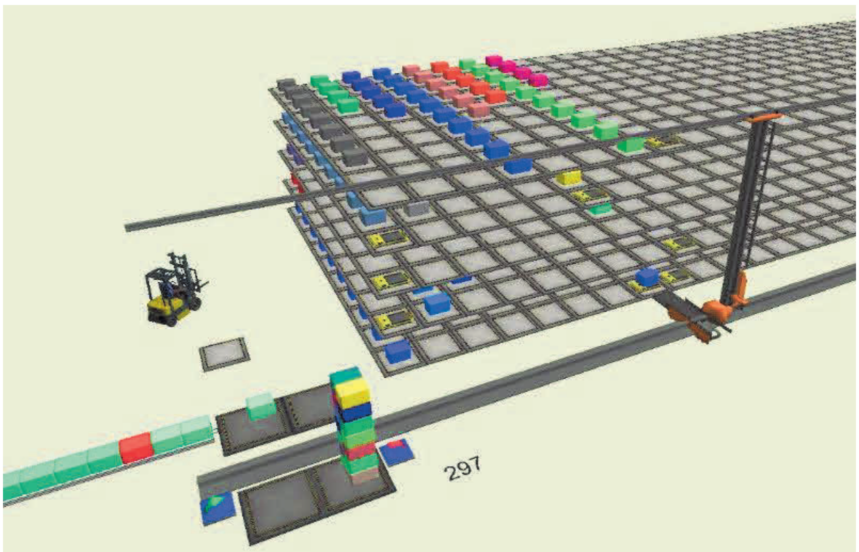

Figure 4 Model of PR-ST in FlexSim

System is initially empty. Time of enter of batches of units is given by Poisson distribution time. The number and type of units in a batch is set by uniform distribution (2 to 10 units of one of 50 types). Units are assigned to tunnels where other units of the same type are actually placed. The tunnel for new type of unit is selected according to location sequence. All units for which there is no place in rack are moved to temporary buffer where they wait for re-disposal. Dispatching orders are generated in accordance with normal distribution. Type and number of dispatched units follow the same distributions as entries. If demanded SKU is awhile not on stock order is added to the list of waiting orders where it stay until appropriate SKU enters the system. Modeled racking system supports LIFO. Each tunnel can keep only one SKU at the time.

The procedure of putting units into rack is realized as follows:

- Unit is assigned to the location in a specific tunnel when task enters the system.
- Algorithm browses all tunnels starting from the closest one (locations sequence). If the same SKU was found in and there is free place in that tunnel unit is assigned to. If that SKU is not on hand at the time or tunnel if full algorithm takes the closest empty tunnel and assigns unit to.
- Successful assignment pushes task to realization list while failed assignment pushes it to waiting list. Tasks from waiting list take priority in realization over new tasks appearing in a system.
- When task is picked from realization list, the algorithm checks availability of crane and shuttle truck on the forehead of the tunnel assigned to the unit.
- The closest free crane (in Cartesian coordinate system) is selected.
- If shuttle truck is available and in the place, crane puts the unit on the forehead of tunnel. Shuttle truck takes unit and transports it to the location in a rack.
- Empty truck returns to the tunnel's forehead and waits for disposal. Crane doesn't wait until truck returns.
- If shuttle truck is not available in tunnel it must be moved from other tunnel. The closest free shuttle truck (in Cartesian coordinate system) is moved to the assigned tunnel's forehead by crane and waits for unit.

Retrieval procedure is similar to presented above.

4. SIMULATION RESULTS

Analyzed case covered 8 scenarios for 2 different variants of racking system. Each scenario involves different number of shuttle trucks (from 1 to 8). I the first variant racking system is constructed of 10 columns with 5 levels (50 tunnels) 30 units depth. In the second variant racking system embraces 30 columns with 5 levels (150 tunnels) 10 units depth. Simulation was replicated 20 times for all scenarios in both variants. Model was set for 24 hour work-day. Rack is initially empty. Entering starts from the beginning while dispatching starts in 6th hour of simulation (time shift necessary for saturating rack with units).

The evaluation criteria was total sum of stored and dispatched (serviced) units. Productivity of PR-ST system was reported for 18 hours, since 6th hour of simulation when both entering and dispatching processes burden system. Simulation results are presented in **Figure 5** and **Figure 6**. It can be noticed that in both variants of racking construction total productivity of the system reaches quickly maximum and doesn't grow despite an increase in number of shuttle trucks. In the first variant maximal productivity is reached with 4 trucks (but maximal average value is reached with 5 trucks for 90% confidence). In the second variant maximal productivity is reached with 2 shuttle trucks (but maximal average value is reached with 4 trucks for 90% confidence). In both variants significant increase in productivity is noticed when system switches between 1 and 2 shuttle trucks. Productivity in following scenarios doesn't grow so intensively (see **Figure 5** and **Figure 6**). The situation is clear since only one crane is used to dispose shuttle trucks and handle pallets.

One crane can operate efficiently only limited number of shuttle trucks. Potential usage of other trucks is hampered while system is limited by crane. The number of shuttles equal to number of tunnels eliminates re-disposing shuttles between tunnels so the productivity reaches the highest level and depends only from crane and units assignment pattern. Of course it is not economically justified.

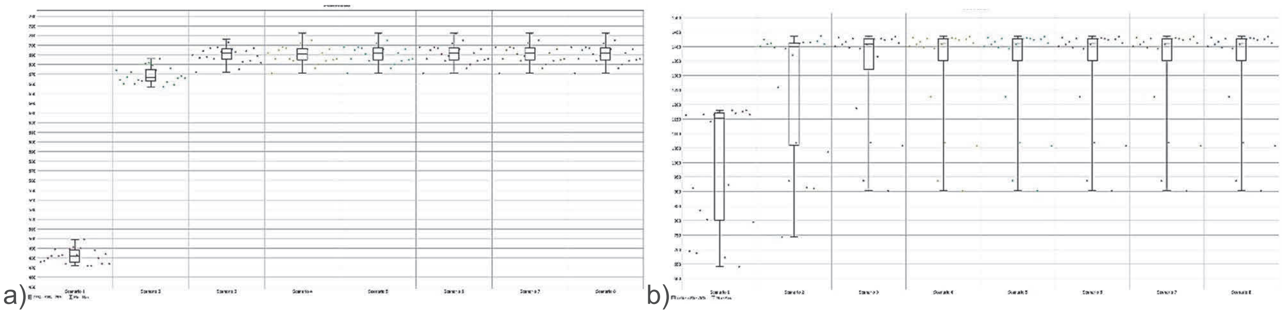

Figure 5 Number of serviced units: a) - variant I, b - variant II

a)

	Mean (90% Confidence)					Sample Std Dev	Min	Max
Scenario 1	479.1	<	481.9	<	484.8	7.4	472.0	499.0
Scenario 2	665.7	<	669.0	<	672.3	8.5	657.0	686.0
Scenario 3	687.0	<	690.4	<	693.7	8.6	672.0	706.0
Scenario 4	686.8	<	690.6	<	694.4	9.9	671.0	712.0
Scenario 5	687.3	<	691.1	<	695.0	10.0	671.0	712.0
Scenario 6	687.3	<	691.1	<	695.0	10.0	671.0	712.0
Scenario 7	687.3	<	691.1	<	695.0	10.0	671.0	712.0
Scenario 8	687.3	<	691.1	<	695.0	10.0	671.0	712.0

b)

	Mean (90% Confidence)					Sample Std Dev	Min	Max
Scenario 1	908	<	990	<	1073	213	641	1180
Scenario 2	1170	<	1259	<	1347	228	743	1436
Scenario 3	1248	<	1317	<	1386	178	902	1434
Scenario 4	1253	<	1322	<	1392	179	902	1434
Scenario 5	1253	<	1322	<	1392	179	902	1434
Scenario 6	1253	<	1322	<	1392	179	902	1434
Scenario 7	1253	<	1322	<	1392	179	902	1434
Scenario 8	1253	<	1322	<	1392	179	902	1434

Figure 6 Number of serviced units, analytical results: a) - variant I, b - variant II

Another important issue is a number of handled (put and retrieved) units, which is almost twice higher in all scenarios of second construction variant. The first variant compared to second one had fewer longer tunnels (50 tunnels with 30 locations in first variant and 150 tunnels with 10 locations in second variant). It means that average entering time was much longer in first option. That loss of time was not offset by shorter routes on the rack forehead in second variant. Therefore, the first construction variant is characterized by longer in-rack operation-times and consequently reduced availability of shuttle trucks for tasks.

5. CONCLUSION

Simulation study has shown that productivity of examined PR-TS is not proportional to the number of used shuttle trucks. The number of installed shuttle trucks is crucial, since it is strongly correlated with frequency and intensity of entries and dispatches, racking system configuration, number of disposing equipment (cranes) and task sequencing strategy for the selection of shuttle trucks. Racking configuration influences productivity of whole system. Productivity is higher in configurations with shorter rack tunnels, when shuttle trucks are more accessible because spent less time on in-rack operations.

Automated storage with pallet shuttle trucks allows a significant increase in productivity. When transfer cars are installed to work independently on each level, the number of incoming and outgoing pallets is increased exponentially, but configuration must be investigated before expensive trucks are bought.

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