Decision making in shaping racking constructions in storage areas of industrial warehouses

1. STORAGE AREAS IN INDUSTRIAL WAREHOUSES

1.1. Storage area – buffer for supply chain

Industrial warehouses are crucial elements of supply chains. Warehouses foster smooth material flow and favour stabilization of basic processes; consumption and production by regulating material flow intensity. This is possible due to buffering capabilities – accumulating excessive material flow volumes and releasing reserves in absence of supplies. Buffering capability serves also levelling differences in material flow intensities related to order quantities, suppliers lead times, material flow velocity, rotation, and demand forecasts. Another important function of warehousing facilities is making long time reserves. All these functions require two interconnected elements: storage areas and handling systems. This paper discusses common decisions in shaping storage areas and provides a mathematical method of optimizing space utilization of storage areas.

1.2. Storage areas – technical conditions

Storage areas dispose appropriate space, technology, organization and devices to:
- store homogenous units of materials (in most cases), with particular attention paid to efficient space usage,
- provide proper storage conditions,
- ensure accessibility to stored materials (according to specified rules).

Many different technologies can be applied to store materials, but the most common in all businesses is using racking systems for palletized load units. Storage areas with racking systems dispose space for material handling and space for storage. Material handling space is limited to transport aisles, and – as well as storage space – is shaped by racking construction and area dimensions. Transportation space is dependent on internal transport technology, types of handled units, and height of area (see Gue and Meller 2009, [9]). Dimensions of storage space results from unit’s parameters, area height, and material flow velocity. Space in storage area is partitioned by racking systems, and by pillar grids (Ratkiewicz, 2013 [13]). Space within racking system is partitioned by construction elements of racks like frames, longitudinal beams, and spreads. These elements cut out uniform cuboidal spaces – rack cells in which units of material are stored. Vertically stacked rack cells are rack columns. Rack columns positioned next to each other create rack walls. Two rack walls with work aisle (Ast) in the middle are racking corridor. Combined racking corridors form storage area (Figure 1).

Rack cells are bins for units of material – items. Setting rational dimensions of rack cells should take into account parameters of items, accessibility to the units and standard elements of racking constructions offered by warehouse developers. It can be stated as a rule of thumb, that parameters of stored items change quicker than parameters of rack cells, so rack cells must be universally set to fit changeable structure of material flows. Rack cell can be then threatened as a smaller possible element of storage area to decide about.

--

1kle@wt.pw.edu.pl
Logistyka - nauka

Figure 1. Scheme of racking system in storage area.
Source: own work

Storage of materials generates costs related to freezing capital in stored materials, loss of value in use of materials, space maintenance, operation costs, investment expenditures and efficiency-related costs of material handling. These parameters are strongly dependent on storage area configuration. The main decision issues in that area are presented in following part.

1.3. Decisions in shaping storage areas

Decisions about storage areas are taken when new objects are erected or existing systems are reengineered, and embrace a broad range of problems related to different designing stages. Decisions in shaping storage areas touch the following aspects:

I. Technological:
   a) Storage capacity – related to material flow velocity and structure of supplies – usually is determined at the beginning of designing process.
   b) Material handling technology – used internal transport systems, translates into area height and space utilization according to working aisle width.
   c) Storage technology – used type and configuration of racking construction (or block storage).
   d) Number of work-aisles – strongly related to area length and width, appropriate number of work aisles foster avoiding congestion and lowers average travel time.
   e) Work-aisle width – the most significant parameter describing handling technology and area space utilization index.
   f) Items accessibility – supporting FiFo and LiFo to the nearest single unit, SKU/series or rack line/channel, resulting from storage technology.
   g) Supported logistics processes – other processes that can be performed in the area – mostly order picking in different technologies.
   h) Standardization of stored units – using standard logistics units (like ISO pallets), results from physical features of products, packaging systems, and supply chain configuration. Standardization allows using standard handling equipment and racking constructions, and therefore minimizes handling and maintenance costs.

II. Architectural and constructional:
   i) Area footprint – a group of determinants describing space limits for area in aspect of layout, location of other functional areas of warehouse or land price.
   j) Area height – together with area footprint constrain number of work aisles, technology, internal transport system and other elements of design.
k) **Grid of pillars** – influences allocating racking walls in the area. Pillars can’t cut the racking construction elements and can’t be placed within working aisles, so they constrain free placement of racking system.

l) **Storage area forehead** – responsible for accessibility to the area, and indirectly area efficiency, strongly related to number of work-aisles and area footprint.

m) **Pre-designed racking system elements** – using standard construction elements offered by warehouse developers forces constructing racking structures with pre-designed components, what – theoretically – restricts configurability of the area, but – practically – lowers construction costs.

n) **Locations of racking systems elements relative to floor slab construction** – orientation of floor slabs and dilatations to the rack frame grids, detailed standards of floor flatness and smoothness required by forklifts operating in the area, and permissible forces put on floor from rack.

III. **Organizational:**

o) **Unification of units** – number of types of units handled in a warehouse – is important for storage and handling equipment configuration. Unified material units are desirable according to universalism of storage area.

p) **Slotting** – items’ location pattern reflecting rotation of materials and structure of clients’ orders determining average distances travelled by transport equipment.

q) **Addressing and zoning** – the way of describing storage locations by addresses used for operation directing and Warehouse Management Systems.

IV. **Maintenance:**

r) **Racking durability and stability** – resulting from selecting proper racking system for expected loadings and work pace, anchoring racking frame to the floor, interconnections between elements, technical condition of rack elements and servicing quality, not exceeding allowed loads.

s) **Safety and servicing** – related to the safety of people working in the area, goods stored and racking system itself – anti-collision equipment, bumpers, surface markings, safety signs, servicing programs, sprinkler systems, periodic technical inspection, expert opinions and other.

Above named issues are frames of decision problems touching storage area. In practice, those problems merge and are strongly correlated. One of the most important issues is related to configuration of racking system by selecting dimensions of racking construction to 1/ handle all types of items and 2/ minimize consumed space.

2. **RACKING SYSTEM CONFIGURATION**

2.1. **Literature review**

Rack cells must be fitted to stored materials and are composed of standard construction elements. Setting best possible rack cell for given set of items is not clearly discussed in literature, but many related works can be found (Lee et al. 1999 [12], Lee et al. 2005 [11]). Important impulse for research in rack system configuration area was implementing AS/RS in warehouses (compare Chang and Ven 1997 [5], Lee et at. 1999 [12]). Formally, many publications touch racking system configuration in different aspects. Dimensions of rack cells are usually fixed in a wide range of designing problems, and are parameters of optimization models influencing the final result of research. At this stage of research rack cells are determined. In most cases models are to solve layout design problems and routing issues (Roedbergen et al 2014, [16], Gue and Meller 2009, [9], Ratkiewicz 2012, [14] or comprehensive review papers like Dukic and Opetuk 2012, [7]). Rack designing problems in aspect of AS/RS configuration are touched for example by de Koster, Le-Duc, and Yugang (2008, [6]) or Lee et al (1999, [11]), in aspect of warehouse layout design by Gue et al (2012, [8] – and many before), in aspect of stock location and travel time models by Yu, and de Koster (2009, [17]), and others. Berry (1968, [3]) discusses basic requirements of warehouse layouts, and points the necessity of minimizing space utilization by dimensioning blocks of stacking units by manipulates functional blocks as wholes. Bassan et al (1980, [2]) determine optimal storage area dimensions, and the number and parameters of storage racks, but doesn’t investigate the problem of rack columns and rack walls definition. Rack bays...
are configured by Roberts and Reed (1972, [15]) to minimize costs of handling and construction. They provide methods of bay configuration in the sense that adjacent bays must have common corners, but don’t discuss the problem of walls and racking corridors configuration. Chan and Chan (2011, [4]) discuss the efficiency of picking process according to warehouse layout and racking system dimensions. Ambroziak and Lewczuk (2009, [11]) present set of evaluation criteria for storage area used in multicriteria evaluation. Klodawski and Żak (2013, [10]) discuss the effectiveness of functional areas of warehouse according to dimensions of the areas which result from racking configuration. Very interesting approach to designing storage areas is presented by Ratkiewicz (2013, [13]), which includes a grid of pillars as a determinant of constructing storage areas.

Most of presented approaches base on efficiency maximization and not strictly focus on supporting decision making about storage area construction in early designing stages, when future work patterns and work-loads are unknown, so the area must be fitted to the universal services.

2.2. The problem

A few decision points named in previous chapter touch the problem of racking system configuration. The configuration can be done according to different criteria, but fundamentals are to find proper depth, height and length or rack columns, walls, and the area to fully utilize space, meet the requirements of safety and handling technology and store all materials. According to that, a research problem is formulated as follows:

For a given set of rack cells – as cuboids of known dimensions, one must determine their positions in rack system to reveal dimensions of rack columns and walls constituting storage area and to minimize consumed space according to given technological constrains. The position of rack cells is unrestricted. Additional elements can be taken into account like a grid of pillars of the building and time-travelling requirements.

Rack cells are cuboids that are stacked one to the other to form a rack column. Column height is a sum of heights of stacked cells. Its depth is equal to the deepest cell assigned to the column, and length is equal to the longer one. Exactly the same is with rack walls. Rack wall height is equal to the highest column assigned to, its length is equal to the sum of lengths of assigned columns and its depth is equal to the deepest column (Figure 2.)

Figure 2. Construction of racking blocks: a) rack cell, b) rack column, c) rack wall, d) storage area. 
Source: own work
For different rack cells various feasible solutions are possible. Selecting best solution can be done with optimization task.

3. FORMAL MODEL

3.1. Model parameters

Proposed model describes the problem of setting best possible arrangement of given rack cells to minimize space required for storage area, and under specified constrains. The model is formulated as follows:

Let the following indexes be defined:

- $c$ – number of a rack cell; $c \in C$
- $C$ – total number of rack cells,
- $b$ – number of a rack column; $b \in B$
- $B$ – total number of obtained rack columns,
- $w$ – number of a rack wall; $w \in W$
- $W$ – total number of constructed rack walls,

and the model parameters:

- $d_c, l_c, h_c$ – depth (width), length, and height of $c$-th rack cell,
- $d_b, l_b, h_b$ – depth (width), length, and height of $b$-th rack column,
- $d_w, l_w, h_w$ – depth (width), length, and height of $w$-th rack wall,
- $d_a^{\text{max}}, l_a^{\text{max}}, h_a^{\text{max}}$ – maximal depth (width), length, and height of storage area,
- $\text{Ast}$ – work-aisle width,

the decision variables are:

- $\alpha_c^b$ – binary variable determining assigning $c$-th rack cell to $b$-th rack column, $A = [\alpha_c^b]_{c \times B}$
- $\beta_w^b$ – binary variable determining assigning $b$-th rack column to $w$-th rack wall, $B = [\beta_w^b]_{B \times W}$.

Particular rack cells can be assigned to only one rack column, and obtained rack columns can be assigned to only one rack wall:

$$\forall c \in C \quad \sum_{b=1}^{B} \alpha_c^b = 1$$  (1)

$$\forall b \in B \quad \sum_{w=1}^{W} \beta_w^b = 1$$  (2)

Number of arranged rack walls should be even to compose technically proper storage area. Single rack wall requires access space (work-aisle) that is not fully utilized because it serves only one side. This constrain is not mandatory, but practical observations indicate its grounds:

$$W \mod 2 = 0$$  (3)

Rack columns dimensions result from dimensions of particular cells included into that column:

$$\forall b \in B \quad d_b = \max_{c \in C} \{d_c \alpha_c^b\}$$  (4)

$$\forall b \in B \quad l_b = \max_{c \in C} \{l_c \alpha_c^b\}$$  (5)
\[ \forall b \in B \quad h_b = \sum_{c=1}^{C} h_c \alpha_c^b \quad (6) \]

Rack column height must keep the limit:
\[ \forall b \in B \quad h_b \leq h_a^{\max} \quad (7) \]

Rack walls dimensions result from dimensions of particular columns included into that wall:
\[ \forall w \in W \quad d_w = \max_{b \in B} \left\{ d_b \beta_w^b \right\} \quad (8) \]
\[ \forall w \in W \quad l_w = \sum_{b=1}^{B} l_b \beta_w^b \quad (9) \]
\[ \forall w \in W \quad h_w = \max_{b \in B} \left\{ h_b \beta_w^b \right\} \quad (10) \]

Rack wall length must keep the limit:
\[ \forall w \in W \quad l_w \leq l_a^{\max} \quad (11) \]

Consequently, storage area parameters are:
\[ d_a = \sum_{w=1}^{W} (d_w + 0.5Ast) \quad (12) \]
\[ l_a = \max_{w \in W} \{ l_w \} \quad (13) \]
\[ h_a = \max_{w \in W} \{ h_w \} = \max_{b \in B} \{ h_b \} \quad (14) \]

Storage area depth must keep the limit:
\[ d_a \leq d_a^{\max} \quad (15) \]

Finally, the criteria function minimizes cubic capacity \( V_a \) of storage area:
\[ d_a l_a h_a \rightarrow \min \quad (16) \]
or maximizes effective usage of space:
\[ \sum_{c=1}^{C} (d_c + 0.5Ast) l_c h_c \cdot \frac{1}{d_a l_a h_a} \rightarrow \max \quad (17) \]

Fully expanded version of formula (16) takes form:
\[ \max_{w \in W} \left\{ \sum_{b=1}^{B} \max_{c \in C} \left\{ l_c \alpha_c^b \beta_w^b \right\} \cdot \max_{c \in C} \left\{ h_c \alpha_c^b \right\} \right\} \cdot \sum_{w=1}^{W} \left\{ \max_{b \in B} \left\{ h_w \beta_w^b \right\} \cdot \max_{c \in C} \left\{ d_c \alpha_c^b \right\} \right\} + 0.5Ast \rightarrow \min_{A, B} \quad (18) \]

Particular difficulty is related to parameters \( B \) – total number of obtained rack columns, and \( W \) – total number of constructed rack walls. These two parameters result from values of decision variables \( \alpha_c^b \) and \( \beta_w^b \), and only lower and upper boundaries are known. Lower boundary of \( B = 1 \) when all rack cells are gathered in a single rack column, lower boundary \( W = 1 \) when all rack cells are gathered into one rack wall. Upper boundaries of both parameters are: \( B = C \) when each rack cell constitutes its own rack column and \( W = C \) when each rack column is assigned to a single rack wall.
4. SOLVING MATHEMATICAL MODEL

For practical cases where about 2 000 – 10 000 rack cells of about 2 – 4 different types must be set into rack walls, decision can be done even intuitively, but situation is getting complicated when number of types of rack cells is more than 5 – 10 like in order picking areas. Exact methods of solving proved to be not efficient for those cases. Using tools like branch-and-bound with global solver doesn’t give applicable results in reasonable time. Examples doesn’t considered as large were unsolvable for LINGO solvers in proposed way, mainly due to parameters $B$ – total number of obtained rack columns, and $W$ – total number of constructed rack walls that must be set for maximal possible values before solving.

A simple heuristic was proposed to get feasible and rational solution. The heuristic bases on estimating position of rack cell in a rack wall according to its dimensions. The general algorithm of the method consists of following steps:

1. Sort all rack cells in ascending order of depths, then lengths and heights.
2. Stack rack cells into columns starting from the smallest – if column height will exceed $h_{u}^{\text{max}}$ in next stacking stage, then start new column.
3. Count depths, lengths and heights of all rack columns (Figure 2).
4. Sort all rack columns in ascending order of depths, then lengths and heights.
5. Form rack walls from columns starting from the lowest possible value – if wall length will be greater than $l_{a}^{\text{max}}$ in next repetition, then start new wall.
6. Count depths, lengths and heights of all rack walls (Figure 2).
7. Combine rack walls into storage area (Figure 1 and Figure 2) – if area width is greater than $d_{a}^{\text{max}}$ then no feasible solution can be found – go to 14.
8. In each wall find column with the greatest depth and move all columns of that depth from the wall to the beginning of the next one.
9. Check the length of wall over-longed in point 8, and move as many columns from the end of that column to the beginning of the next one, as necessary to maintain the condition of maximal wall length. Create a new wall if necessary to keep truncated columns.
10. For each wall repeat points 8 and 9.
11. Check the width of the storage area – if $d_{a}^{\text{max}}$ is exceeded then restore configuration from 7.
12. If number of walls is not even then shorten first wall by one column and move it to the beginning of next wall (then each following wall must be shorten appropriately by two, three and more columns – while checking the length condition for lengthened wall) in order to form additional wall.
13. Form rack walls into storage area – if area width is greater than $d_{a}^{\text{max}}$ then restore configuration from point 7.

The above algorithm is very generic and provides feasible solution of quality better then random solutions, and is consistent with intuitive way of constructing. Proposed algorithm can be easily modified and detailed to gain higher quality solutions, but it is firstly a frame for manual work with the storage area. In more complicated cases it can be easily implemented into computer application. The problem can be efficiently solved by genetic programming according to fundamental features of the problem.

5. CONCLUSIONS

Discussed pack of rack construction issues related to storage area dimensioning is common in designing practice. Usually it is solved intuitively, but complex cases require supporting in decision making. Especially order picking areas with thousands of locations of different types are predestined to apply presented concepts.
Combining rack cells into columns, and then walls, always leads to excess of space in racking system in comparison to actual needs. The column will be as depth as the deepest rack cell (Figure 2b), so proper allocating of rack cells allow minimizing wasted space. Therefore the algorithm bases firstly on depth of rack cells and columns. This is related to the characteristics of units stored in typical pallet warehouses which usually are supported by two longitudinal beams. Stacking rack cells with the same depth to make columns and connecting columns with the same depth to walls foster manipulation of pallets without additional devices like decking systems, but on fitted beams.

The paper is a contribution for development of designing methods applied in standard designing procedures. The general decision areas named in point 1.3 are frame for further research. Many of presented points base on rack configuration, so this issue seems to be fundamental for proper conception of storage area. The necessary works that would supplement research are: including grid of pillars to the model, and applying genetic programming to solve it efficiently.

Abstract

The paper gathers and discusses basic issues related to decision making in designing storage areas and racking constructions in modern industrial and distributional warehouses. Storage areas (or order picking areas) are most space consumptive and have a great impact on warehousing efficiency. Proper design of those areas should take into account types of handled units, handling technologies, architectural conditions (i.e. grid of pillars), disposed equipment, costs and other issues named in the paper. The research on proper space shaping can lead to significant improvement in space utilization. The problem of constructing proper rack system was then discussed and identified as crucial for designing storage areas. The mathematical model of shaping storage area was presented and supplemented by solving heuristic. Paper contains conclusions and directions for further research.

Keywords: storage area, decision making, industrial warehouse, optimization

Podejmowanie decyzji w zakresie kształtowania konstrukcji regałowych w strefach składowania w magazynach przemysłowych

Streszczenie

W artykule zestawiono i omówiono podstawowe zagadnienia związane z podejmowaniem decyzji w projektowaniu obszarów składowania i konstrukcji regałowych w nowoczesnych magazynach przemysłowych i dystrybucyjnych. Obszary składowania (lub obszary komisjonowania) wymagają dużych przestrzeni obudowanych oraz mają bardzo duży wpływ na wydajność procesu magazynowego. Poprawne projektowanie tych obszarów powinno uwzględniać rodzaje obsługiwanych jednostek, technologie transportu wewnętrznego, uwarunkowania architektoniczne (np. siatkę słupów), dysponowane wyposażenie, koszty oraz inne aspekty omówione w artykule. Badania nad poprawnym kształtowaniem przestrzeni mogą prowadzić do znacznej poprawy stopnia jej wykorzystania. Z tego względu problem konstruowania układu regałów magazynowych został zidentyfikowany i przedstawiony jako kluczowy przy projektowaniu obszarów składowania. Model matematyczny kształtowania obszaru składowania został zaprezentowany i uzupełniony o heurystykę rozwiązyującą. Artykuł kończy się podsumowaniem i wskazuje kierunki dalszych badań.

Słowa kluczowe: obszar składowania, podejmowanie decyzji, magazyny przemysłowe, optymalizacja

Acknowledgement

The paper was prepared partly as a statutory work of Department of Logistics and Transport Systems on WUT Faculty of Transport, and partly under the project “Modelling warehousing processes for designing and organization of logistics systems – II” realized on Warsaw University of Technology, Faculty of Transport

BIBLIOGRAPHY


